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Evaluation of Portable Soil Test Kits Promoted for Use by Smallholder Farmers to Make Site-Specific Fertilization Decisions

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Table of Contents

Tables

Figures

Acronyms and Abbreviations

Ca	Calcium
DI	Deionized
DSSAT	Decision Support System for Agrotechnology Transfer
EC	Electrical Conductivity
FY	Fiscal Year
GPS	Global Positioning System
IFDC	International Fertilizer Development Center
K	Potassium
MCP	Monocalcium Phosphate
Mg	Magnesium
MIR	Mid-Infrared Reflectance
MOP	Muriate of Potash
N	Nitrogen
Na	Sodium
NAPT	North American Proficiency Testing
NH_4	Ammonia
NO_3	Nitrate
OM	Organic Matter
P	Phosphorus
RCBD	Randomized Complete Block Design
S	Sulfur
SSA	Sub-Saharan Africa

Evaluation of Portable Soil Test Kits Promoted for Use by Smallholder Farmers to Make Site-Specific Fertilization Decisions

Executive Summary

Recently, there is growing interest in updating fertilizer recommendations for crops in most developing countries, particularly in sub-Saharan Africa (SSA) and southern Asia. Many farmers in this part of the world have been correctly advised that investment in fertilizer inputs should be preceded by proper analysis of soil chemical and physical properties in order to ascertain which nutrients are suboptimal. Currently, the most frequently used approaches to soil analysis are those offered by standard soil analytical laboratories, mostly through wet chemistry, using various extraction and digestion methods. Given the constraints associated with standard soil analytical labs for smallholder farmers, a simpler and quicker approach is needed for soil tests at the farm level in the developing countries. Portable soil test kits with their mobile features and low costs offer attractive options capable of providing tailored and real-time fertilizer recommendations for smallholder farmers in remote regions and in areas without functional laboratories. Many soil test kits are available on the market in most parts of SSA and southern Asia. Their predictive capacity of soil fertility is not consistent, which suggests the need for proper testing, calibration, and validation of the kit outputs against reference wet chemistry laboratory data and response curve of the crop to fertilizer. The overall objective of this work was, therefore, to evaluate selected soil test kits in terms of their performance against standard soil analytical labs to ascertain the reliability of data generated with these kits. Specific objectives were to: (a) evaluate selected soil test kits with respect to their ability to accurately analyze the macronutrients (nitrogen [N], phosphorus [P], and potassium [K]) and pH; (b) compare them with respect to crop performance (dry matter and nutrient uptake); and (c) based on the results obtained, make recommendations for smallholder farmers, taking into account the above objectives.

The following soil test kits were evaluated against standard laboratory tests: Hach, SoilDoc, and Kasetsart University soil test kits. The Kasetsart and Hach soil test kits were chosen based on their ease of use, performance, and cost. They have been used in several different projects in

Rwanda, Ghana, Afghanistan, and Thailand and are currently being promoted by several projects in SSA and southern Asia. The third kit – SoilDoc – was added due to its widespread and aggressive introduction and use in SSA. Eight benchmark soils of different physicochemical properties were used to evaluate the soil test kits. During the second half of the FY16 project year, the soils were characterized by IFDC's soil analytical lab and validated by Auburn University's soil testing lab. Additionally, 40 archived soil samples from the North American Proficiency Testing (NAPT) Program (Soil Science Society of America quality control program for soil testing) were obtained from Auburn University. These samples were strategically selected to capture variations in soil texture, pH, and organic matter content and used to evaluate the accuracy of the portable soil test kits. Finally, a greenhouse experiment was set up to validate the soil test results coming from both the wet chemistry procedures of the soil analysis lab and those of the portable soil test kits by matching the soil nutrients, as determined by the soil test kits, to plant nutrient uptake.

The study confirmed that the Kasetsart soil test kit was user friendly for most smallholder farmers. Proper use of the SoilDoc kit, on the other hand, would require the user to have considerable chemistry knowledge and experience in soil testing. The accompanying training manual did not provide some specific, detailed steps. This oversight could have led to erroneous results for people inexperienced in soil testing. However, it should be noted that SoilDoc advocates that its users participate in an intensive one-week training course prior to independent use. At the current stage of development, the SoilDoc kits should be handled by professional chemists familiar with soil testing or by personnel well-trained in using the kit.

Results obtained from the analyses of the IFDC benchmark soils showed a good correlation (between the soil test kits and the standard wet chemistry analyses) for soil pH. Nitrate-N (NO_3-N) showed reasonable correlation between standard chemistry and the soil test kit. However, in acidic soils, NO_3-N values obtained with all three test kits were outside an acceptable range as determined by the KCl method for standard wet chemistry analysis. The results obtained for "available" P did not produce good correlations and were highly pH-dependent. With soils of near-neutral pH, all three soil test kits produced P concentration values that were within an acceptable range of values for the standard lab analysis, but the kits performed poorly in acidic soils. The Hach soil test kit performed reasonably well for P with alkaline soil, whereas the other two performed poorly. Only the SoilDoc soil kit performed well for the determination of K.

For the archived NAPT samples, the pH values determined using the three soil test kits were not significantly different from the pH values obtained by standard laboratory procedure. Of practical significance, the soil test kits more accurately differentiated among strongly acidic soils, acidic soils, near-neutral soils, and alkaline soils represented in the NAPT soil samples compared to IFDC's benchmark soils.

Although there was a very high correlation of the results of the nitrate analysis done with the SoilDoc soil test kit with those of the standard soil chemistry procedure ($R_2 > 0.96$) for the NAPT samples, the actual values obtained from the SoilDoc soil test kits were consistently orders of magnitude greater than those obtained from the standard wet chemistry procedure. On the other hand, there was a poor correlation of the P concentration values with the standard laboratory Pi procedure. However, for the soil samples with near-neutral pH, there was a rather strong correlation of the "available" P values between the SoilDoc results and those of the standard laboratory procedure. Similarly to the soil nitrate determination with SoilDoc soil test procedure, the actual phosphorus values obtained were orders of magnitude (an average of six times) greater than those obtained from the standard wet chemistry procedure. For potassium determination, the SoilDoc was the only test kit that produced relatively good results, relative to the other two soil test kits. However, contrary to the results observed for nitrate and phosphorus, the actual potassium values obtained with the SoilDoc soil test kits were consistently smaller (about one-half) than those obtained from the standard wet chemistry procedure. The combined results suggest the need for a critical look into the extraction procedures for the various elements and the algorithms being used for the calculations within the SoilDoc software.

As observed with the benchmark soils, the pH of the NAPT soils had a significant effect on the nitrate analysis using the Hach soil test kits. With the exception of the soils having strongly acidic pH, there was a very high correlation between the values obtained with the Hach soil test kits and those of the standard wet chemistry procedure. However, the actual soil nitrate concentration values from the Hach soil test kits were relatively smaller (an average of 65%) than those obtained with the standard wet chemistry procedure. For "available" P determination, the Hach soil test kit was the only one that produced good results. With the exception of the strongly acidic soil, determinations on most of the weakly acidic, near-neutral, and weakly alkaline soils produced values that were within the limits of those observed with the standard wet chemistry procedure. However, as observed with the benchmark soils for exchangeable K, the Hach soil test kit was not good enough to produce acceptable K values, compared with values obtained with the wet chemistry analysis.

The results obtained with the Kasetsart soil test kit for the archived soil samples were rather inconsistent, as observed for the benchmark soils. For soils with medium to high nitrate concentrations, there was a partial match with the results of the standard wet chemistry procedure. However, there were several soil samples that were classified by the Kasetsart soil test kits as having very low to low nitrate concentrations that were contrary to the values obtained with the standard wet chemistry procedure. Similarly, for "available" P and potassium determinations, the kit produced good results for the soils with high concentrations but not for those with low to medium concentrations. There were samples with inherently low P and K concentrations that were designated as having high to very high concentrations when the Kasetsart soil test kits were used (and vice versa for some samples). This anomaly could be attributed to the soil pH and the organic matter content of the soil. The acidity of the soil likely affected the chemical extraction of the nutrients from the soil, but since the procedure used by the Kasetsart kit for analysis is entirely colorimetric, the organic matter content of the soil likely compromised the color of the soil extract, which affected the reading of the extract to determine elemental concentrations. Thus, the ranges of pH and organic matter content of soils within which the Kasetsart soil test kits produce accurate and acceptable values must be evaluated and specified in the user's manual. Also, it is important to align the "available" P level designations by the Kasetsart soil test kits with the range of "available" P concentration values to be consistent with levels assigned by researchers for most soils.

Thus, for now, soil fertility recommendations using portable soil test kits are not realistic. The value of these three kits is limited to giving baseline information on soil properties, particularly for pH, NO_3-N, and "available" P for soils with a near-neutral pH. Also, by using the kits, farmers could, at least, identify the limiting and abundant nutrients within their field, assuming costs were minimal. Even if a consistently well-performing kit is eventually identified, before it can be widely used, field validation should be required based on a soil test kit approach that includes the blanket recommended fertilizer as a control to which the soil test kit recommendation is compared in terms of yield-enhancing efficiency and economic profitability. The economic feasibility of such an approach is questionable, particularly in light of the recent focus on spectral analysis as a replacement for standard wet chemistry. Regardless, for the immediate future, laboratory wet chemistry will remain the standard for identifying soils' fertility and for improving fertilizer recommendations.

Background and Rationale

Imbalanced application of fertilizers and blanket fertilizer applications have resulted in low fertilizer use efficiency, stagnation of yields, and environmental pollution. To minimize or eliminate this problem, fertilizer recommendations, therefore, must be more specific to crops' complete nutrient needs and soil and climatic conditions. To achieve this, soil testing is needed to determine the right fertilizer that crops need in a given soil context and to correct for inhospitable soil conditions. Recently, there is growing interest in updating fertilizer recommendations for crops in most developing countries, particularly in SSA and southern Asia. Farmers in this part of the world have recognized that investment in fertilizer inputs should be preceded by proper analysis of soil chemical and physical properties in order to ascertain which nutrients are suboptimal. Currently, the most frequently used approaches to soil analysis are those offered by standard soils analytical laboratories, mostly through wet chemistry, using various extraction and digestion methods. An emerging method of soil testing is the mid-infrared reflectance (MIR) spectroscopy, which has potential for fast, accurate, and considerably cheap soil analysis with particular application in the field. The technology can provide good quality prediction of most soil properties. However, some soil parameters, such as extractable P, sulfur (S), and N, are poorly predicted due to their low concentration in the soil matrix. While MIR is seen as a technology for the future, with applications that augment conventional soil testing and decision support and that are capable of measurements in the field, for the near future (about five to 10 years), improved recommendations at the farm-level will continue to be dependent on wet chemistry procedures offered by the standard soil analytical labs.

When the standard soil analytical labs are well-equipped with qualified personnel and modern equipment, they can deliver accurate soil and plant analytical results, especially when they abide by the quality standard procedures (including participation in frequent proficiency testing of reference samples). However, the turnaround time for delivering sample results is usually long, and in most cases, without the provision of data interpretations and/or recommendations along with the analytical results. To exacerbate this problem, frequent disruptions in electricity and water supply and the poor quality of reagents are issues confronting some wet chemistry laboratories in SSA, which tend to compromise the results obtained from these labs. These factors, in combination with poor laboratory procedures and lack of qualified and experienced personnel, consequently lead to the generation of inaccurate results and eventually lead to erroneous recommendations. Apart from these problems, accessibility to these labs for resource-poor smallholder farmers in very remote areas is another big challenge that limits the usage of these labs.

Given the constraints associated with standard soil analytical labs, a simpler and quicker approach is needed for soil tests at the farm level in developing countries. Portable soil test kits with their mobile features and low costs are therefore attractive options capable of providing tailored and real-time fertilizer recommendation for smallholder farmers in remote regions and in areas without functional laboratories. Currently, there are a range of mobile kits proposed for soil testing on the market and, given that results generated by these kits can be variable, there is a need to evaluate the accuracy of the information provided by the kits. This should be done in comparison with reference wet chemistry lab data and, if possible, data generated by the soil test kits also should be reconciled with crop response to fertilizer data available in the agro-ecologies where the kits are being tested. Therefore, before these portable test kits are promoted and recommended for widespread use, there is the need for further testing and calibration for the kits to produce credible results. The kits must also be readily available, users should be adequately trained to interpret results, and a conducive business environment should be in place for entrepreneurs to invest in the provision of services.

Given that the plant is the best index of the complex system of soil and climate, reflecting all factors that affect its nutrition, nutrient omission trials have sometimes been used to detect the most limiting elements in soils. All testing methods at most offer a good approximation of the nutrient level extractable by plant roots. However, it is essential to correlate the results from the soil test kits with plant nutrient uptake. The overall objective of this work was, therefore, to evaluate selected soil test kits in terms of their performance (regarding ease of use and data generated through the respective procedures) against standard soil analytical labs to ascertain whether these portable soil testing kits are reliable enough for wide-scale application or if their results need further evaluation against those obtained from the traditional wet chemistry methods. The specific objectives of the study were to: (a) evaluate the kits' analysis of the main nutrients (N, P, and K) and pH; (b) compare results to crop performance (dry matter and nutrient uptake); and (c) based on the results obtained, make recommendations for smallholder farmers, taking into account the above objectives

Methodology and Soil Test Evaluation Procedure

Soil Test Kits

Based on the recognition that portable soil test kits could facilitate smallholder farmers to have an onsite capability for soil analyses, the following soil test kits were evaluated against standard laboratory tests: Hach, SoilDoc, and Kasetsart University soil test kits. The Kasetsart and Hach soil test kits were chosen based on their ease of use, performance, and cost. They have been used in several different projects in Rwanda, Ghana, Afghanistan, and Thailand and are currently being promoted by several projects in SSA and southern Asia. The third kit – SoilDoc – was added due to its widespread and aggressive introduction and use in SSA.

The Kasetsart soil test kit is among the cheapest and, while it has limited capability, it still has the ability to analyze for ammonia-N in addition to nitrate-N, P, K, and pH (Table 1). The Hach and SoilDoc soil test kits are a lot more expensive but with more capabilities. The Hach soil test kit has the ability to analyze for N, P, K, calcium (Ca), magnesium (Mg), sodium (Na), acidity, salinity, and gypsum and lime requirement. The SoilDoc's major quality is that feedback and recommendations are done through a digital media (tablet). It can analyze nitrate-N, Ca, Mg, P, K, acidity, sulfate, electrical conductivity (EC), and active carbon (Table 1).

Table 1. Basic Information About the Soil Test Kits Evaluated

	 **Kasetsart**	 **SoilDoc**	 **Hach SW-1**
Capabilities	pH, NO_3, NH_4, P, K	NO_3-N, Ca, Mg, P, K, acidity, sulfate, EC, and active carbon	Inorganic N (NO_3 + NH_4), P, K, Ca, Mg, Na, acidity, salinity, gypsum and lime requirement, sulfate, EC, and active carbon
Retail Price	$150	$4,000	$1,300

Benchmark Soils Used

Eight benchmark soils of different physicochemical properties were used to evaluate the soil test kits. These soil were (a) Brownfield soil, (b) Greenville soil, (c) Lakeland sand, (d) Hiwassee soil, (e) Demopolis soil, (f) Fayette soil, (g) Crowley soil, and (h) Hartsell soil. During the second half of the FY16 project year, the soils were characterized by IFDC's soil analytical lab and validated by Auburn University's soil testing lab. These benchmark soils represent a wide range of soil pH, organic matter (OM) content, and texture. Selected physicochemical properties of the soils are presented in Table 2.

Table 2. Selected Physical and Chemical Characteristics of the Benchmark Soils Used to Evaluate the Soil Test Kits

Benchmark Soil	Soil Texture	pH	%OM
Brownfield	Loamy Sand	6.87	0.92
Crowley	Loam	7.36	0.85
Demopolis	Sandy Clay Loam	7.92	2.88
Fayette	Loam	6.26	2.57
Greenville	Loam	6.35	1.58
Hartsell	Sandy Loam	4.73	2.18
Hiwassee	Sandy Clay Loam	5.50	2.71
Lakeland	Sand	5.97	0.85

Soil Analysis

1. Wet Chemistry Analysis

Selected soil chemical analyses were conducted on the benchmark soils, based on the minimum capabilities of the soil test kits and the recommendation by the manufacturers to enable comparison of the results. Since all the soil test kits being evaluated had the capabilities to analyze for soil pH, nitrate, "available" P, and exchangeable K, only these nutrients were analyzed through the wet chemistry procedure for analysis for comparison with values obtained using the portable soil test kits. The soil pH was analyzed, as stated in all the soil test kits and also as standard analysis in the lab, using deionized (DI) water at a 2:1 water:soil ratio. Soil nitrate was analyzed using the KCl extraction procedure (Keeney and Nelson, 1982). "Available"

P was analyzed using the Pi soil P test method (using strips of iron oxide) (IFDC, 1989), and exchangeable K was determined using the ammonium acetate method.

2. Analyses with Soil Test Kits

The various analyses were carried out following the procedures described the by manufacturers in the operating manual for each soil test kit. The various steps of the procedures are summarized in Figure 1.

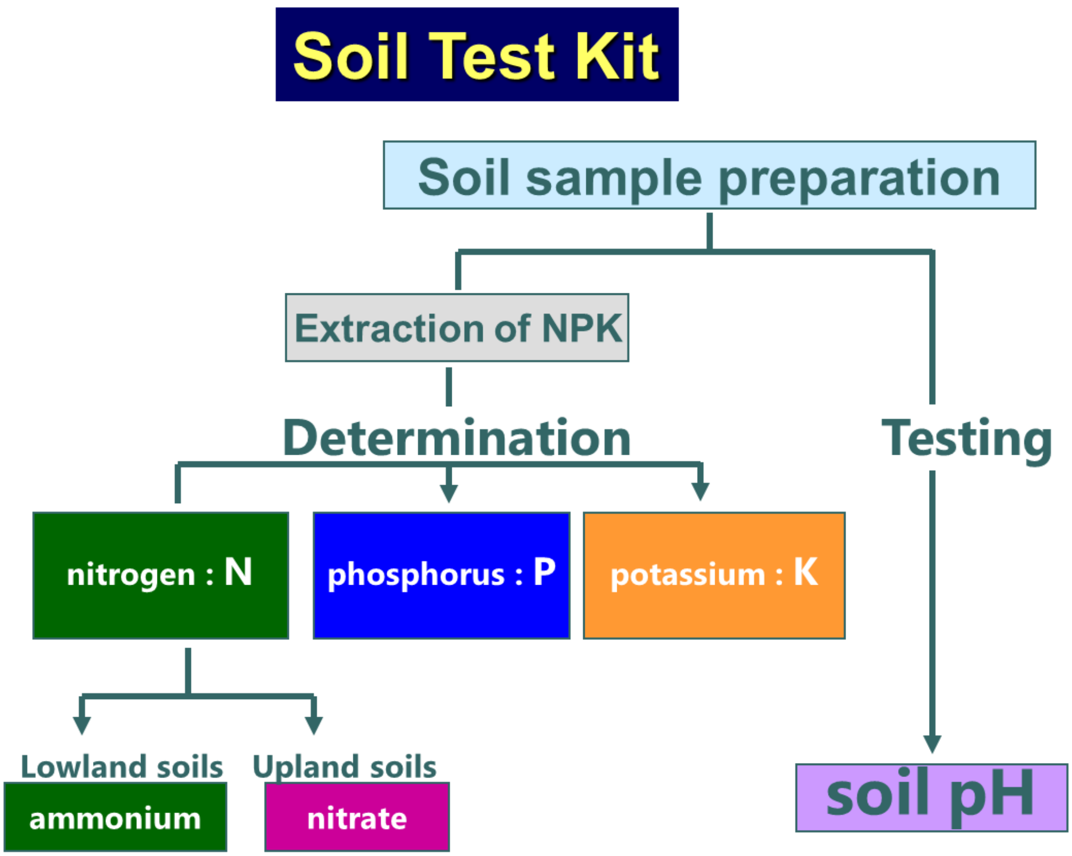


Figure 1. Schematic Description of the Soil Test Procedure for the Test Kits Evaluated

Validation of Results from Analysis of Benchmark Soils

The results of the soil analyses of the eight benchmark soils were validated using: (a) chemical analysis of archived soil samples obtained from the laboratories of the North American Proficiency Testing (NAPT) Program; and (b) a greenhouse study to determine plant nutrient (N, P, and K) uptake from the benchmark soils.

a. ***Chemical Analyses of the Archived NAPT Soil Samples***

Forty soil samples of varying physical and chemical properties were obtained from the laboratories of the NAPT Program. (NAPT is a program of the Soil Science Society of America that assists soil, plant, and water testing laboratories in their performance through inter-laboratory sample exchanges and a statistical evaluation of the analytical data with the aim of standardizing methods and developing nutrient recommendations for soil and plant analysis methods within the U.S. and Canada.) The soils were strategically selected to capture the effects of texture, pH, and organic matter content on the accuracy of the portable soil test kits. The textures of the soils were clay (two samples), clay loam (two samples), loam (seven samples), sandy loam (eight samples), silt loam (14 samples), and silty clay loam (eight samples) (Table 3). These soils range from strongly acidic (pH 4.8-5.5; four samples), acidic (pH 5.6-6.4; 11 samples); near-neutral (pH 6.5-7.5; 15 samples), and alkaline (pH > 7.5; 10 samples). The organic matter content of the soil ranges from very low (~0.7%) to very high (> 8%) (Table 3).

The soils were analyzed for pH, nitrate nitrogen, "available" P, and exchangeable K using both standard laboratory procedures and the three soil test kits described above.

Table 3. Selected Physical and Chemical Characteristics of the Archived NAPT Soil Samples Used

	Soil	Texture	pH	% OM
1	Soil 2009-114	Silt Loam	6.4	6.28
2	Soil 2009-115	Sandy Loam	8.0	4.06
3	Soil 2009-116	Silty Clay Loam	6.5	4.13
4	Soil 2009-118	Silt Loam	6.3	6.05
5	Soil 2009-119	Clay Loam	8.1	1.80
6	Soil 2010-111	Sandy Loam	6.2	6.20
7	Soil 2010-112	Sandy Clay Loam	8.1	8.10
8	Soil 2010-113	Silty Clay Loam	7.2	7.21
9	Soil 2010-114	Loam Sand	4.8	4.78
10	Soil 2010-115	Sandy Loam	5.4	5.41
11	Soil 2011-106	Clay	7.7	1.36
12	Soil 2011-107	Silt Loam	8.0	1.93
13	Soil 2011-108	Loam	5.5	3.95
14	Soil 2011-109	Silt Loam	7.2	3.31
15	Soil 2011-110	Sandy Loam	6.1	0.91
16	Soil 2012-116	Silt Loam	7.0	1.88
17	Soil 2012-117	Sandy Loam	6.6	0.70
18	Soil 2012-118	Silt Loam	5.8	3.24
19	Soil 2012-119	Sand	6.9	0.74
20	Soil 2012-120	Silt Loam	5.7	1.83
21	Soil 2013-101	Silt Loam	6.3	1.90
22	Soil 2013-102	Clay	7.7	4.17
23	Soil 2013-103	Silt Loam	6.6	1.50
24	Soil 2013-104	Silt Loam	7.2	3.53
25	Soil 2013-105	Sandy Clay Loam	8.2	1.05
26	Soil 2014-111	Clay Loam	8.0	2.12
27	Soil 2014-112	Silt Loam	5.8	1.88
28	Soil 2014-113	Silt Loam	7.0	3.30
29	Soil 2014-114	Loam	5.7	1.61
30	Soil 2014-115	Loam	7.3	1.00
31	Soil 2015-106	Sandy Loam	8.2	1.68
32	Soil 2015-107	Loam	5.7	1.54
33	Soil 2015-108	Silty Clay Loam	6.5	3.35
34	Soil 2015-109	Sand	6.3	1.09
35	Soil 2015-110	Loam	6.9	2.10
36	Soil 2016-101	Silt Loam	6.5	3.04
37	Soil 2016-102	Loam	7.3	4.20
38	Soil 2016-103	Silty Clay	8.1	1.90
39	Soil 2016-104	Silt Loam	5.3	3.21
40	Soil 2016-105	Loam	7.2	1.07

b. ***Greenhouse Experiment***

A greenhouse experiment was set up to validate the soil test results coming from both the wet chemistry procedures of the soil analysis lab and those of the portable soil test kits by matching the results with plant nutrient uptake. The experiment was carried out with six treatments (Table 4). Maize was used as the test crop and was grown using three of the benchmark soils

(Brownfield, Hiwassee, and Greenville soils). Selected chemical properties of the soils are presented in Table 5. The crop was harvested at six weeks after seedling emergence to determine yield and nutrient uptake.

Table 4. Treatments Applied to the Greenhouse Experiment

Treatment	Treatment ID
1	Unfertilized soil (Control)
2	Recommend fertilizer rate
3	Minus N
4	Minus P
5	Minus K
6	Minus micronutrients

Table 5. N, P, and K Concentrations of the Benchmark Soils Used for the Greenhouse Experiment

Soil	Test Method	NO_3-N (ppm)	Pi-P (ppm)	K (cmol/kg)
Brownfield	Wet Chemistry*	0.73	2.05	0.63
	SoilDoc	9.50	31.3	0.16
	Hach	0.00	0.00	0.33
	Kasetsart	VL(0-10)	L(1-3)	L(0-40)
Greenville	Wet Chemistry*	11.08	7.86	0.13
	SoilDoc	8.90	42.10	0.0
	Hach	12.00	6.60	0.22
	Kasetsart	VL(0-10)	M(4-6)	L(0-40)
Hiwassee	Wet Chemistry*	0.25	3.77	0.32
	SoilDoc	0.09	0.00	0.1
	Hach	0.00	13.20	0.22
	Kasetsart	VL(0-10)	L(1-3)	L(0-40)

***** NO_3-N was determined with the KCl method, “available” P by the Pi method, and exchangeable K by the ammonium acetate method.

Except for the nutrient omission treatments, the maize plants received a recommended fertilizer rate as follows: 200 milligrams N per kilogram (mg N kg^{-1}) (50 mg N kg^{-1} as ammonium sulfate [21% N] and 150 mg N kg^{-1} as urea [46% N]), 150 mg K kg^{-1} as muriate of potash (MOP, 52% K), 100 mg P kg^{-1} as monocalcium phosphate (MCP, 24.6% P), and 57 mg S kg^{-1} supplied in ammonium sulfate (24% S). All fertilizers, except urea, were applied basally by incorporating them thoroughly into the entire soil before planting. Urea was surface applied two weeks after planting as supplemental N to complete the N dosage. A complete micronutrient solution was applied at adequate levels so that, except for the nutrient omission treatments, there was no limiting nutrient on crop growth. The experimental design was a randomized complete block design (RCBD) with four replications per treatment. The maize plants were harvested six weeks after seedling emergence. All harvested samples were dried at 60°C, weighed to determine dry matter yield, and analyzed for N, P, and K.

Results and Interpretation

Attributes of the Soil Test Kits

Table 6 summarizes the kits' positive characteristics, constraints to their use, methods used to obtain results from the analysis, and how the interpretation of results and recommendations were made.

Table 6. Summary of the Attributes of the Three Soil Test Kits

Attributes	Kasetsart Test Kit	SoilDoc	Hach
Positives	Very easy to handle and quick analysis	Modern test kit with large database for recommendations	Considerably easy to use
Constraints	Color scheme slightly difficult to see Small qualitative range	Expensive for a smallholder farmer Requires extensive laboratory skills	Expensive for a smallholder farm
Results	All the analyses are colorimetric and provide semi-quantitative results	Send to virtual lab Increase soil database based on GPS coordinates	Most results based on colorimetric color chart
Recommendations	Kasetsart University developed an app that uses crop modeling (DSSAT) to provide recommendations for smallholder farmers (Thailand)	Specific soil nutrient recommendations in real-time through a tablet	Booklet recommendations based on calibrations for yield in specific crops

Soil Analyses

Results from the soil analyses from the portable soil test kits were compared with the values obtained from the standard laboratory analysis through wet chemistry. The comparisons were limited to pH, nitrate, “available” P, and exchangeable K.

Soil pH

All the three portable soil test kits evaluated produced pH values not significantly different from one another or from those determined through the standard lab procedure (Figure 2). All three portable soil test kits correctly identified the acidic, near-neutral, and alkaline soils among the eight benchmark soils used.

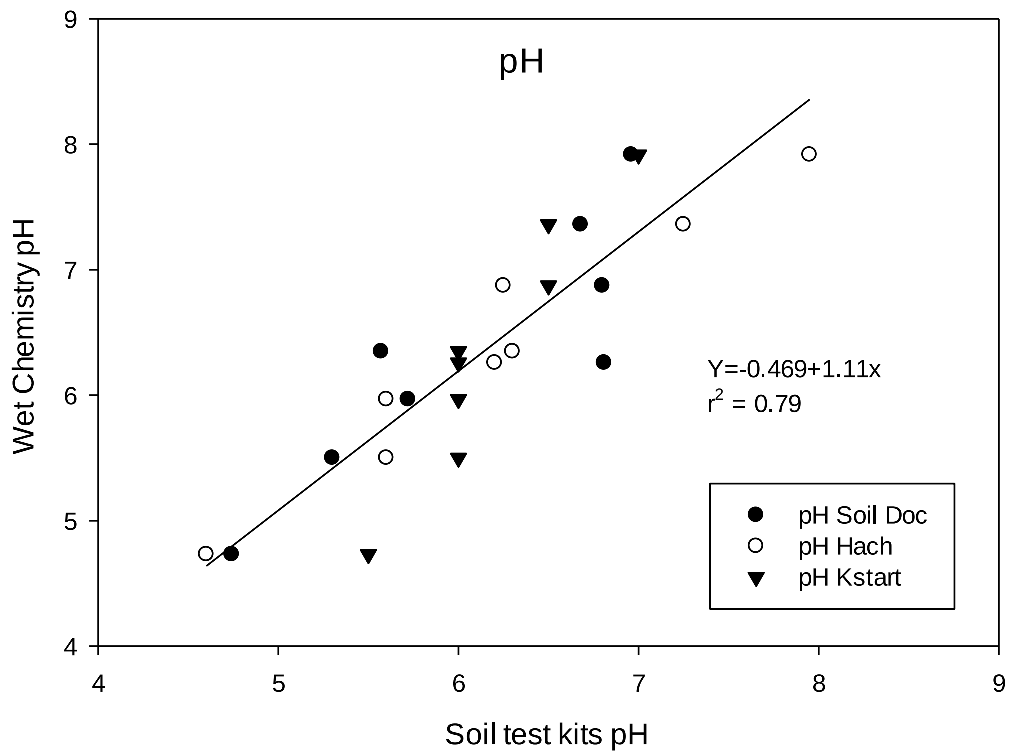


Figure 2. Results from the pH Analyses from the Portable Soil Test Kits as Compared with Values Obtained from Wet Chemistry

Soil Nitrate

The nitrate values obtained with the SoilDoc and the Hach soil test kits were within an acceptable range, as determined by the KCl method through the standard wet chemistry analysis (Figures 3 and 4). The only exceptions were values obtained from the Hartsell soil; all three soil test kits produced values that were complete outliers (Figures 3, 4, and 5). The Hartsell is very acidic in nature with a pH value of 4.7. The acidity of the soil possibly compromised the determination of the nitrate concentrations of the soil.

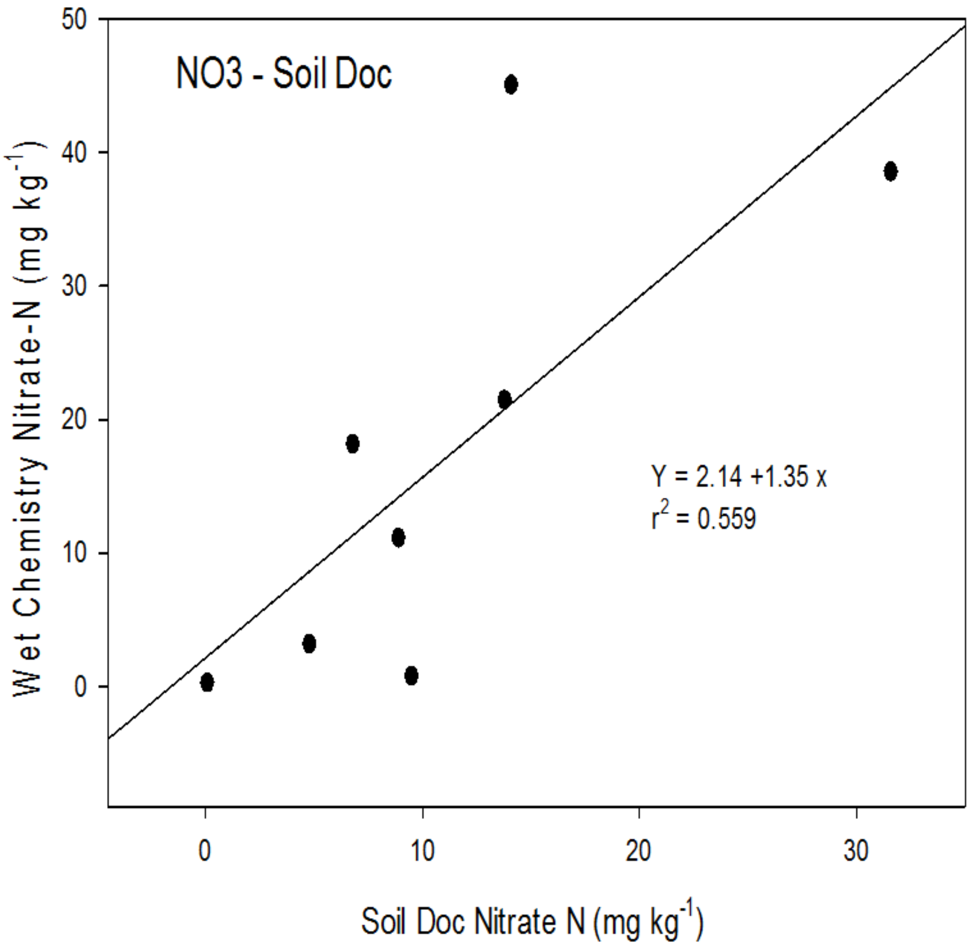


Figure 3. Results from the Nitrate Analyses from the SoilDoc Soil Test Kits as Compared with Values Obtained from Wet Chemistry

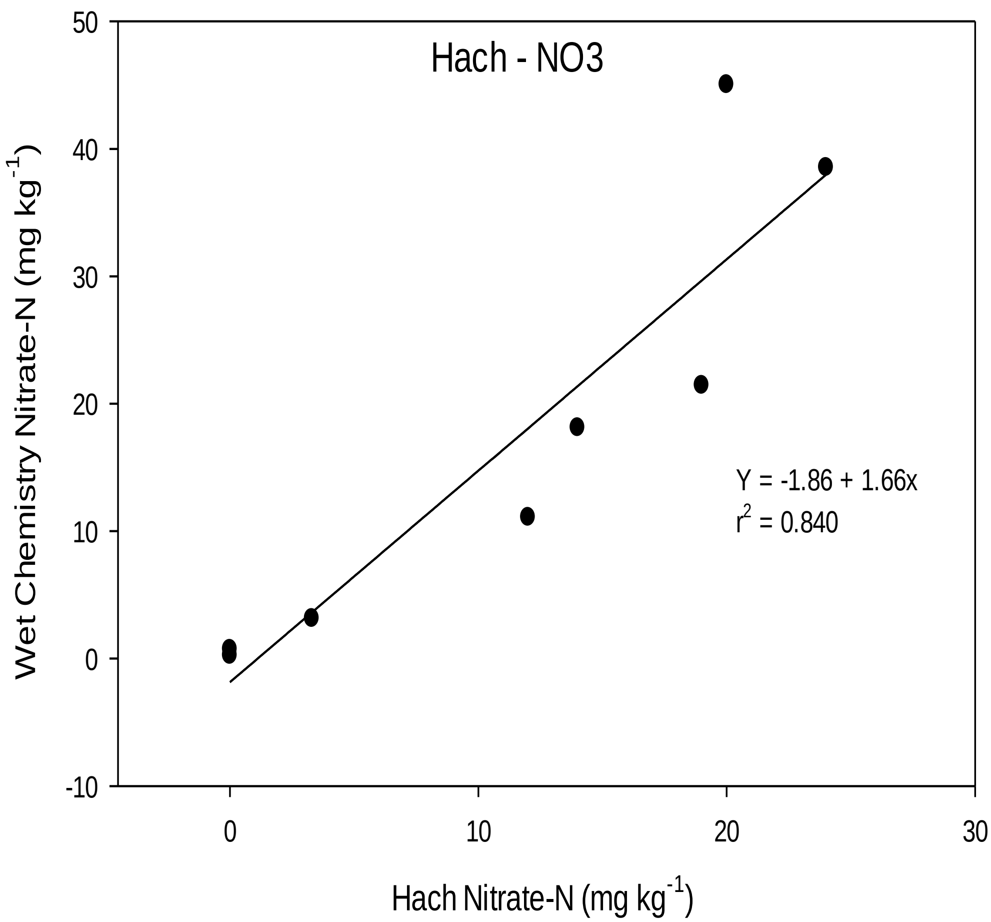


Figure 4. Results from the Nitrate Analyses from the Hach Soil Test Kits as Compared with Values Obtained from Wet Chemistry

The Kasetsart soil test kit, on the other hand, produced nitrate values that were within the acceptable range of the values obtained with the wet chemistry values for only three of the benchmark soils (Brownfield, Fayette, and Greenville). However, for the remaining five benchmark soils, the values obtained were outside the acceptable range of the values obtained through wet chemistry (Figure 5). These Brownfield, Fayette, and Greenville soils have pH values of near-neutral, whereas the others are either acidic or alkaline in nature. This suggests that in using the Kasetsart soil test kit for nitrate analysis, the pH of the soil must be taken into consideration.

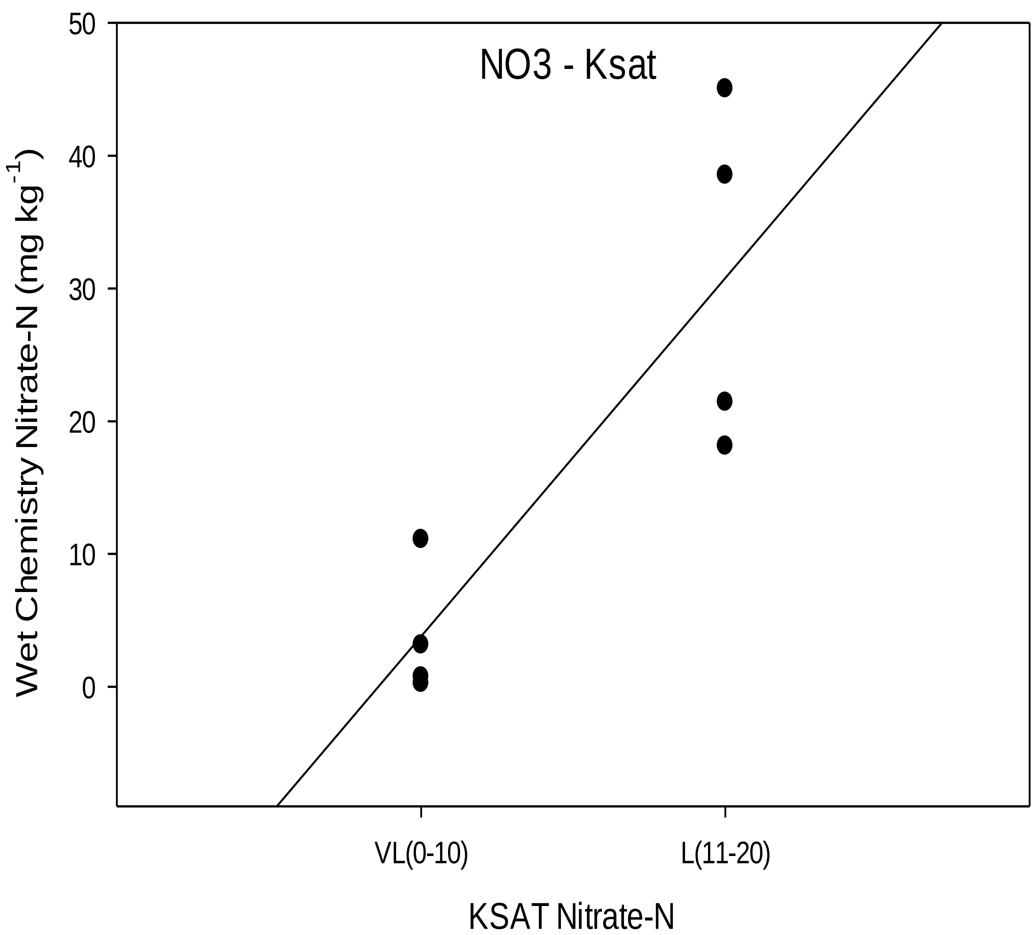


Figure 5. Results from the Nitrate Analyses from the Kasetsart Soil Test Kits as Compared with Values Obtained from Wet Chemistry

Soil "Available" Phosphate

Soil "available" P concentration values obtained with the SoilDoc test kit varied, with respect to the values obtained with the Pi method. The P concentration values of the soils with near-neutral pH were within acceptable values of those obtained with the Pi values (Figure 6). However, the acidic and alkaline soils produced P values that were outside the acceptable range of values obtained with the Pi procedure of wet chemistry analysis (Figure 6). Traditionally, soil "available" P concentrations are determined for acidic soils using the Bray-1 P method and for alkaline soils using the Olsen P determination procedures, whereas the Pi method is robust enough to determine "available" P in both acidic and alkaline soils. Due to differences in "available" P values obtained for the alkaline and acidic soils between the soil test kits and the Pi methods, the acidic soils will be reanalyzed using the Bray-1 P method, and the alkaline soils will be retested using the Olsen P procedures to validate the results.

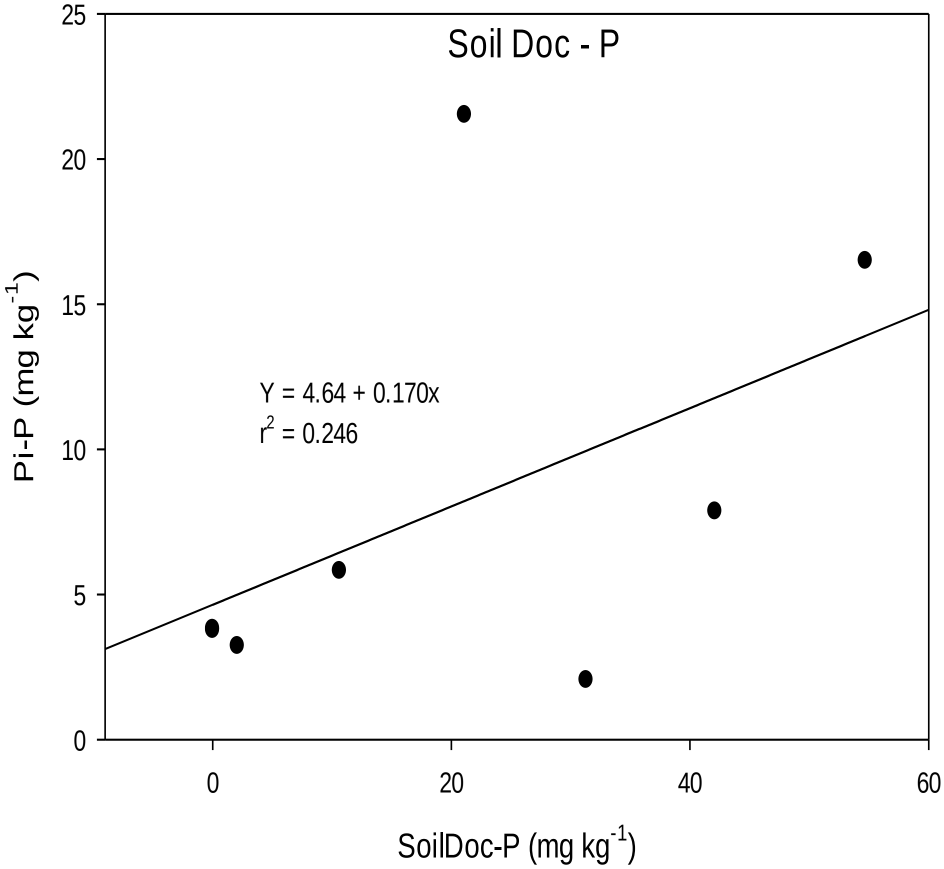


Figure 6. Results from the Phosphate Analyses from the SoilDoc Soil Test Kits as Compared with Values Obtained from Wet Chemistry

With the Hach soil test kit, only the values obtained with the Hartsell and Hiwassee soils (acidic soils) were outside the acceptable range of values obtained with the Pi method (Figure 7). Apart from these two soils, the values obtained from the remaining six benchmark soils were within the acceptable range of values as determine by the Pi method.

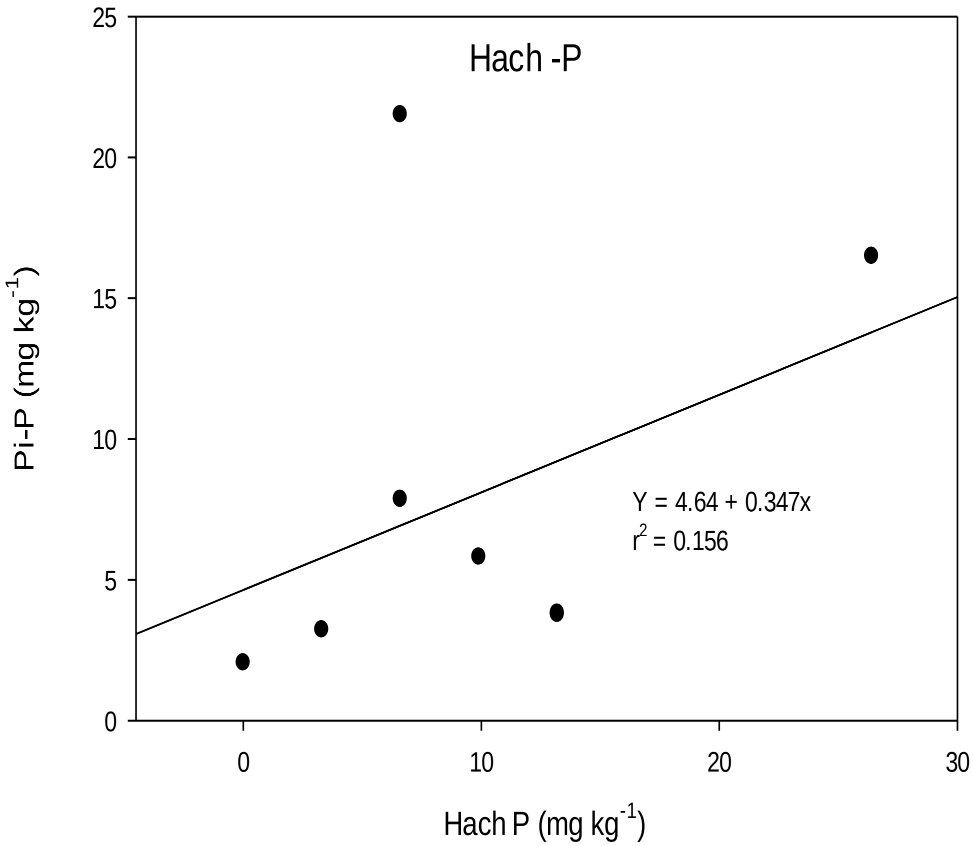


Figure 7. Results from the Phosphate Analyses from the Hach Soil Test Kits as Compared with Values Obtained from Wet Chemistry

Similarly to the soil "available" P concentration values obtained with the SoilDoc test kit, the values obtained with the Kasetsart soil test kits also varied, with respect to the values obtained with the Pi method. The "available" P concentration values of the soils with near-neutral pH were within acceptable values of those obtained with the Pi values (Figure 8), whereas the acidic and alkaline soils produced P values that were outside the acceptable range of values obtained with the Pi procedure of wet chemistry analysis (Figure 8). The combined "available" P results suggest that all three soil test kits can be used to analyze P for soils with near-neutral pH, and the Hach soil test kit can be used for alkaline soils. However, results obtained for acidic soils for all three portable soils test kits were outside the acceptable range of values as determined by wet chemistry, and both the SoilDoc and the Kasetsart soil test kits also did not perform well enough in alkaline soils.

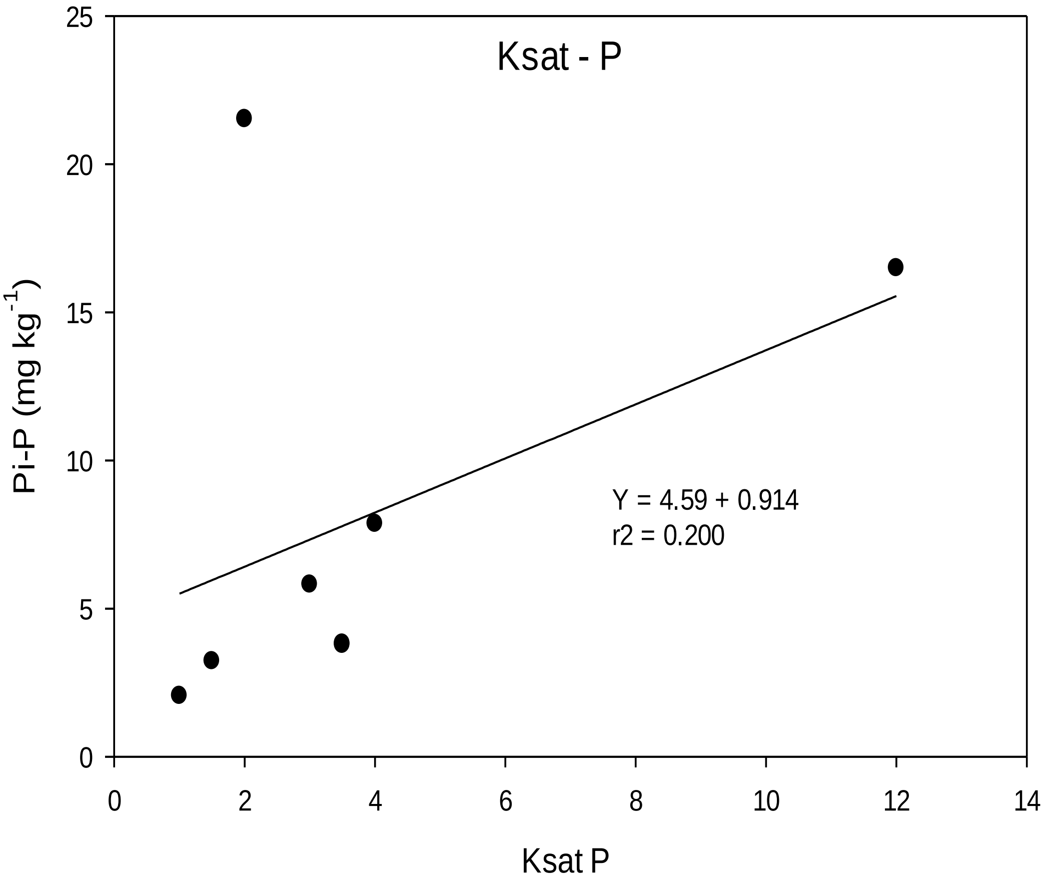


Figure 8. Results from the Phosphate Analyses from the Kasetsart Soil Test Kits as Compared with Values Obtained from Wet Chemistry

Soil Exchangeable Potassium

For exchangeable K, none of the three soil test kits were good enough to produce acceptable K values, compared with values obtained with the wet chemistry analysis (Figures 9, 10, and 11). Comparatively, the SoilDoc soil test kit performed better in terms of K determination relative to the other two soil test kits, predicting precisely the exchangeable K levels for two of the benchmark soils (soils with different texture, pH, and organic matter levels), as determined by the wet chemistry method.

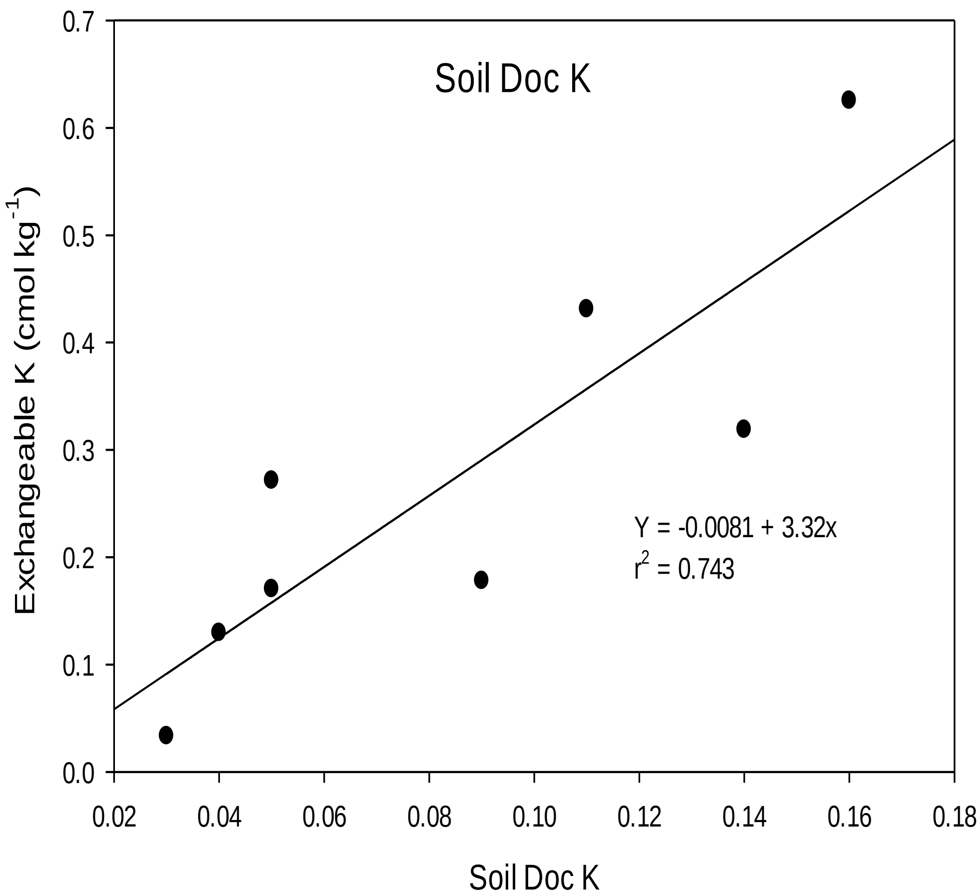


Figure 9. Results from the Exchangeable Potassium Analyses from the SoilDoc Soil Test Kits as Compared with Values Obtained from Wet Chemistry

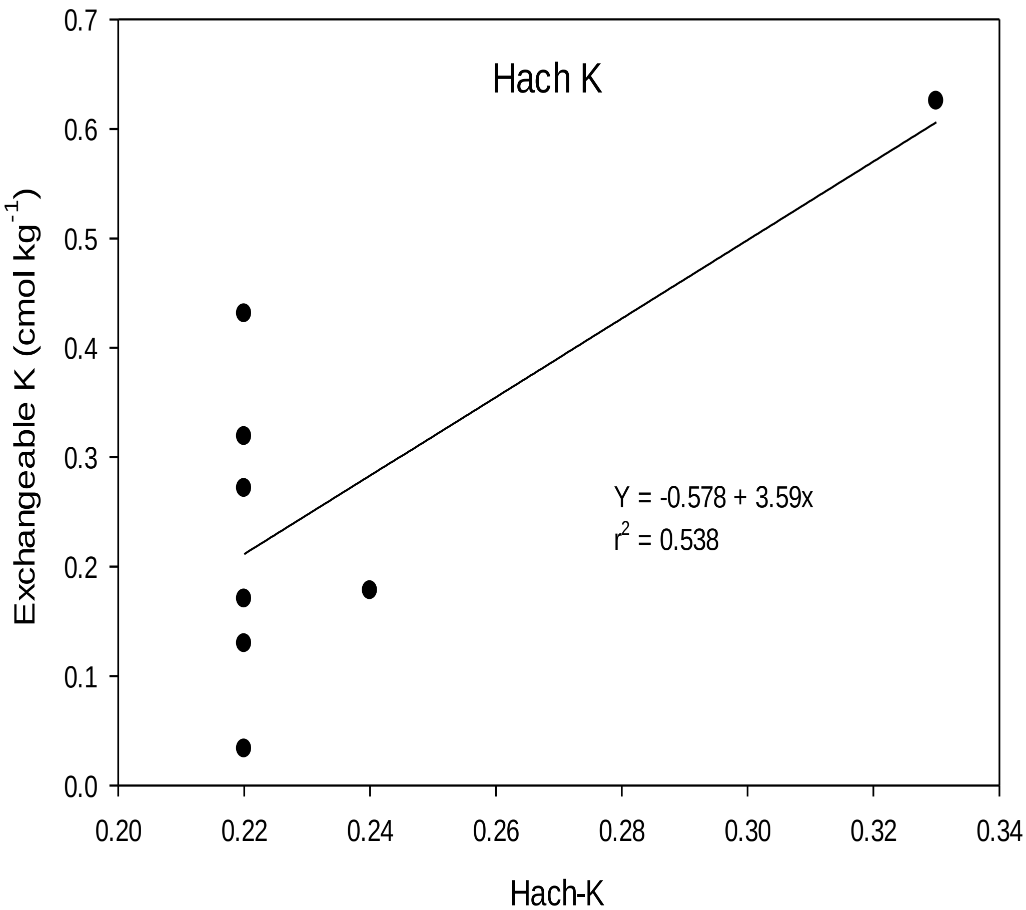


Figure 10. Results from the Exchangeable Potassium Analyses from the Hach Soil Test Kits as Compared with Values Obtained from Wet Chemistry

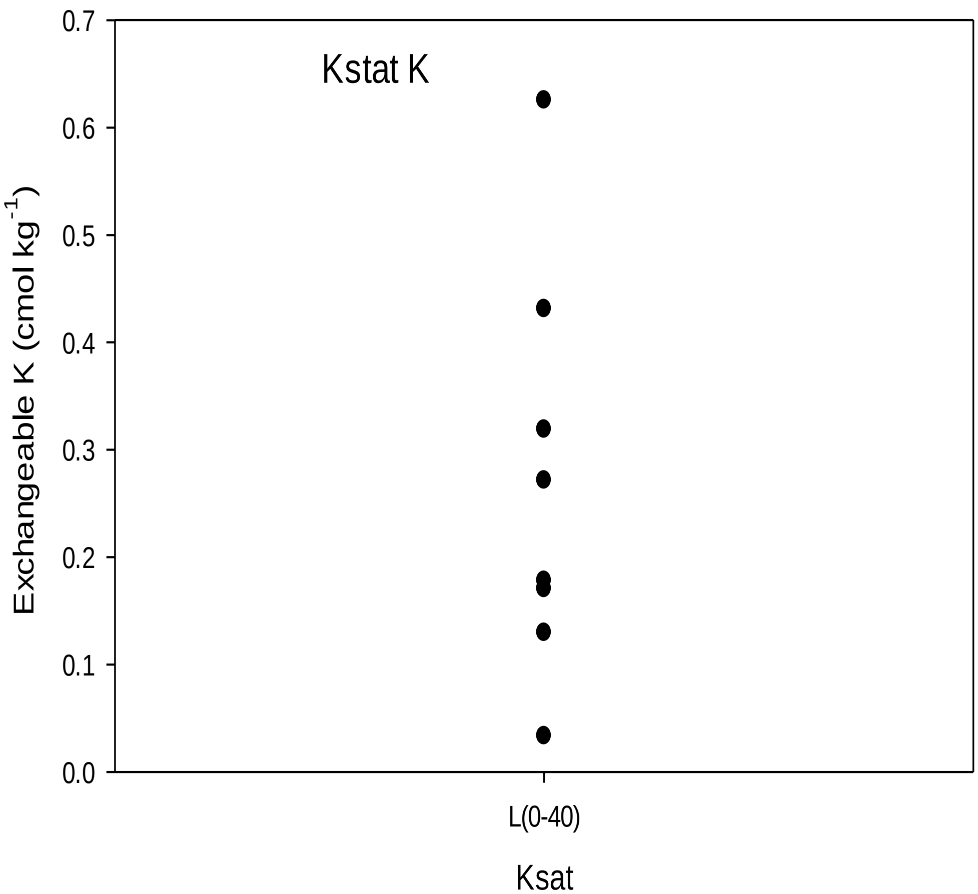


Figure 11. Results from the Exchangeable Potassium Analyses from the Kasetsart Soil Test Kits as Compared with Values Obtained from Wet Chemistry

Validation of Results of Soil Chemical Analyses Using Archived Soil Samples

a. ***Soil pH***

Consistent with the results obtained from the benchmark soils, the pH values of the respective soil samples determined by all three soil test kits were not significantly different from one another or from the values obtain through the standard laboratory procedures (Figure 12). Of practical significance, the soil test kits accurately differentiated among strongly acidic soils, acidic soils, near-neutral soils, and alkaline soils, which matched the native soil characteristics (Appendix Table 1).

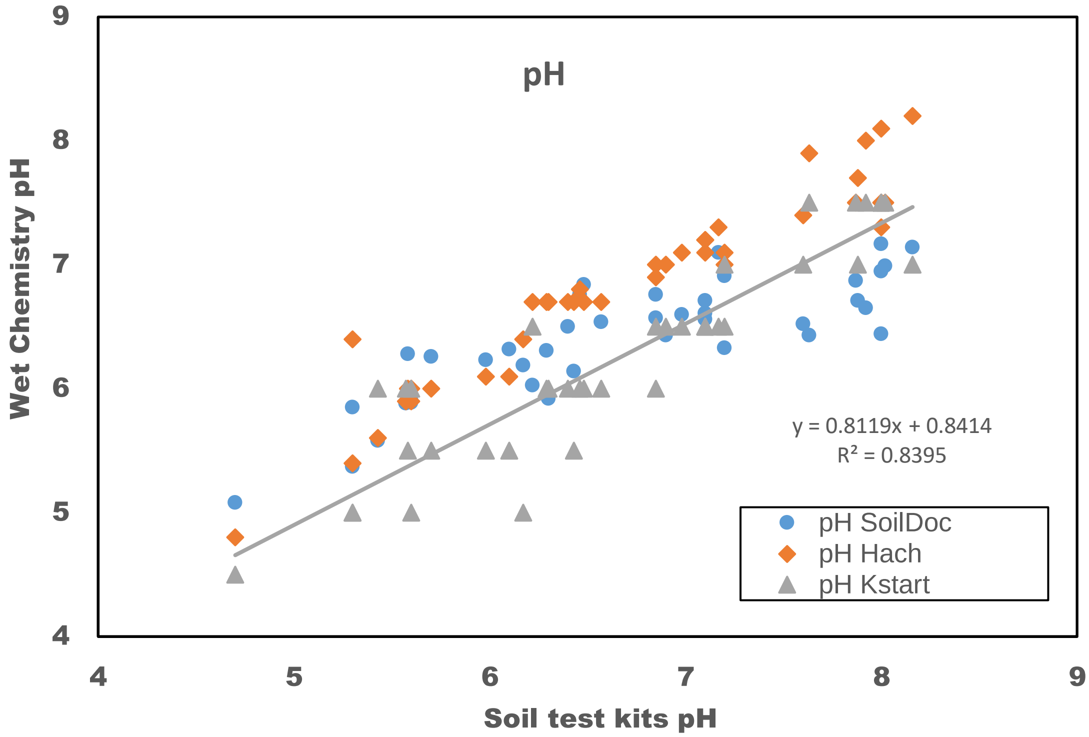


Figure 12. Results from the pH Analyses of 40 Archived Soil Samples Determined with the Portable Soil Test Kits as Compared with Values Obtained from Wet Chemistry

b. ***Soil Nitrate Concentration of Archived Soil Samples***

Although there was a very high correlation of the results obtained from the SoilDoc soil test kit with those of the standard soil chemistry procedure, with a coefficient of determination (R_2) value of greater than 0.96 (Figure 13), the actual values obtained from the SoilDoc soil test kits were consistently orders of magnitude greater than those obtained from the standard wet chemistry procedure (Figure 13, Appendix Table 2). Using the recommended procedure of the SoilDoc kit with the tablet provided in the kit by the manufacturers, the soil nitrate concentration values obtained with the SoilDoc kit were, on average, more than 10 times greater than those obtained with the standard wet chemistry procedure (actual values ranged from five to 50 times greater) (Appendix Table 2). This prompted a manual calculation of the values obtained with the SoilDoc kit. The values obtained through manual calculations were consistently about one-half (50%) of the values obtained using the tablet provided in the kit by the manufacturers (Appendix

Table 2). This notwithstanding, the values obtained through the manual calculations were also, on average, about five times greater than the values obtained with the standard wet chemistry procedure (with values ranging from three times to 26 times greater). While there was a very high correlation between the values obtained from the SoilDoc test kits and those from the standard wet chemistry procedure, the magnitude of the differences between the actual values obtained using the two procedures were rather too high and warrant a critical look into the extraction procedures used for nitrate analysis for the SoilDoc soil test kits.

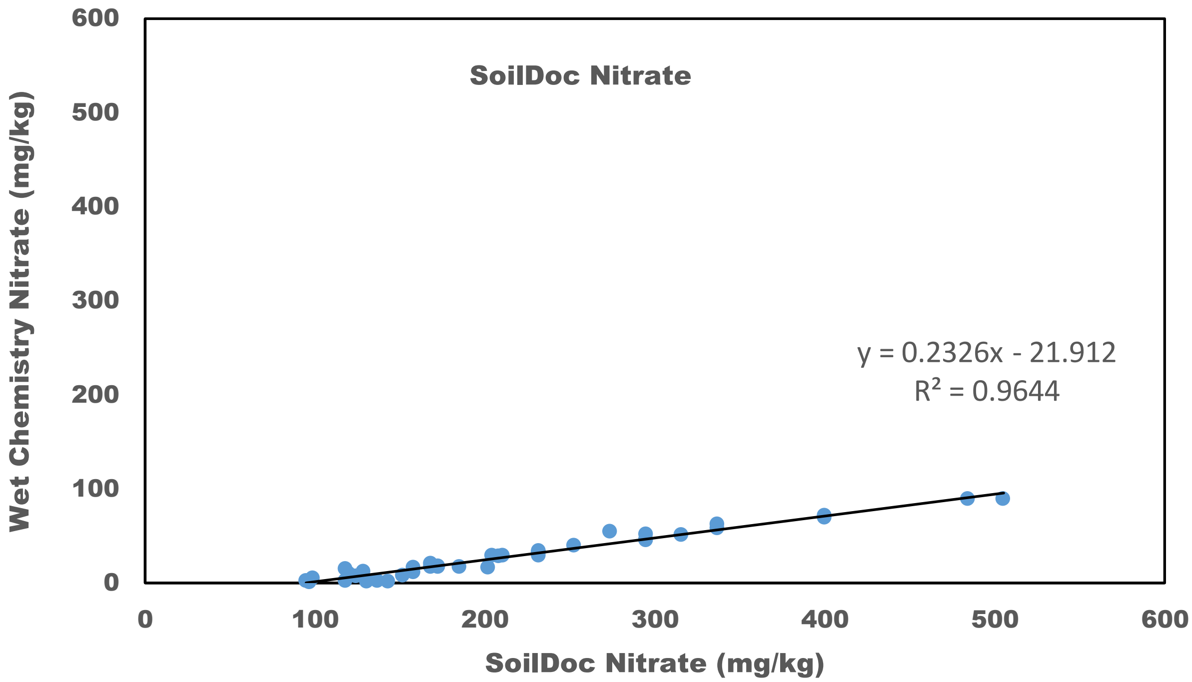


Figure 13. Results of the Nitrate Analysis of 40 Archived Soil Samples Determined with the SoilDoc Soil Test Kit as Compared with Values Obtained from Wet Chemistry

As observed with the benchmark soils, the pH of the soils had a significant effect on the nitrate analysis using the Hach soil test kits. With the exception of the soils having strongly acidic pH (which produced values that were clearly outliers), there was a very high correlation between the values obtained with the Hach soil test kits and those of the standard wet chemistry procedure (Figure 14). However, the actual soil nitrate concentration values from the Hach soil test kits were relatively smaller than those obtained with the standard wet chemistry procedure (Figure

14, Appendix Table 2). The actual values from the Hach soil test kits were 1.1 to 5.4 times lower than those obtained with the standard wet chemistry procedure (Appendix Table 2).

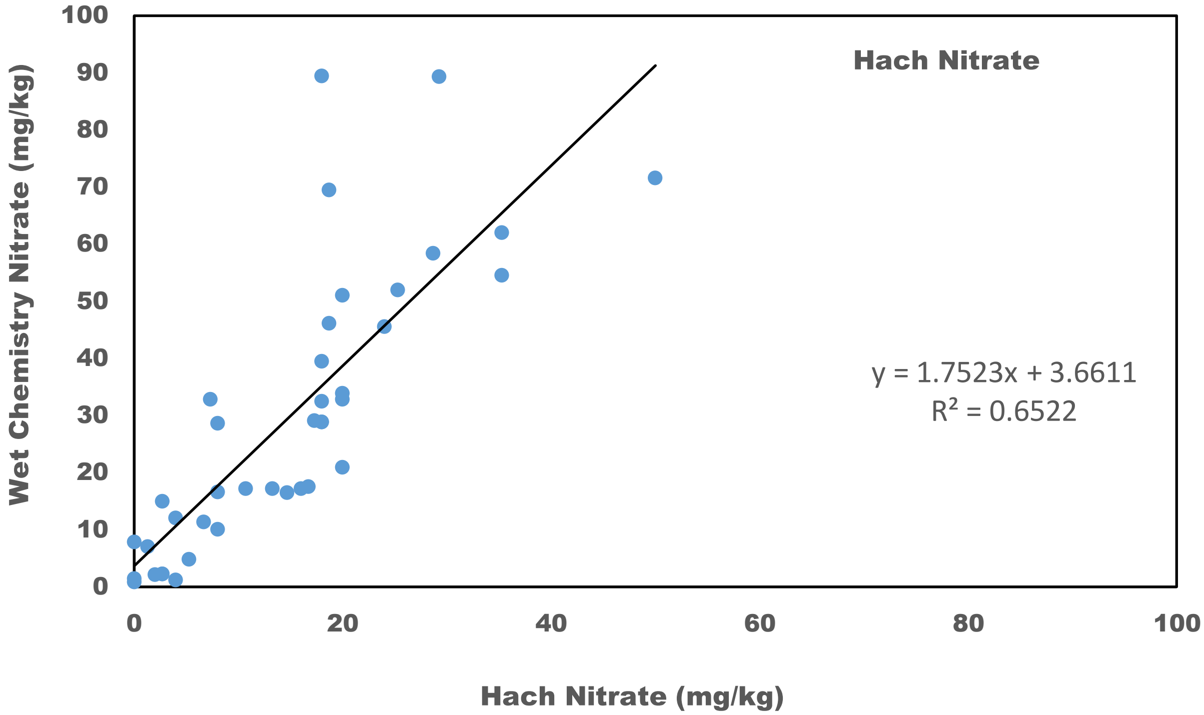


Figure 14. Results of the Nitrate Analysis of 40 Archived Soil Samples Determined with the Hach Soil Test Kit as Compared with Values Obtained from Wet Chemistry

The results obtained with the Kasetsart soil test kit were rather inconsistent. For soil with medium to high nitrate concentrations, there was a partial match with the results of the standard wet chemistry procedure (Figure 15). However, there were several soil samples that were classified by the Kasetsart soil test kits as having very low to low nitrate concentrations that were contrary to the values obtained with the standard wet chemistry procedure (Figure 15, Appendix Table 2). This anomaly could be attributed to the soil pH and the organic matter content of the soil. The acidity of the soil likely affected the chemical extraction of the nutrients from the soil, but since the procedure used by the Kasetsart test for nitrate determination is entirely colorimetric, the organic matter content of the soil likely compromised the color of the soil extract, which affected the reading of the extract to determine nitrate concentration. Thus, the ranges of pH and organic matter content of the soil within which the Kasetsart soil test kits produce accurate and acceptable values of soil nitrate concentration must be evaluated and specified in the user's manual.

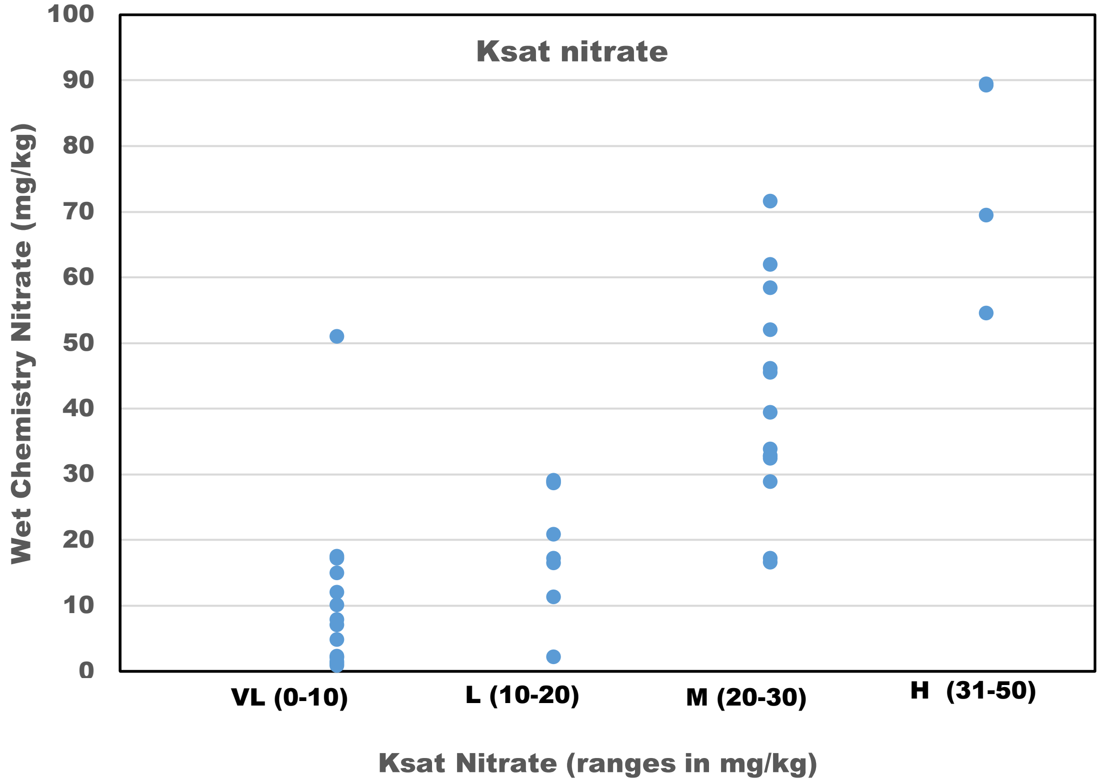


Figure 15. Results of the Nitrate Analysis of 40 Archived Soil Samples Determined with the Kasetsart Soil Test Kit as Compared with Values Obtained from Wet Chemistry

c. *Soil "Available" Phosphorus Concentration of Archived Soil Samples*

Similarly to the observation of the benchmark soils, the "available" P concentrations determined by all three soil test kits were highly pH dependent. For the SoilDoc soil test kits, there was a poor correlation of the P concentration values with the standard laboratory Pi procedure (Figure 16). However, for the soil samples with near-neutral pH, there was a rather strong correlation of the "available" P values between the SoilDoc results and those of the standard laboratory procedure (Appendix Table 3). Similarly to the soil nitrate determination with the SoilDoc soil test procedure, when the tablet provided by the manufacturers was used to determine the P concentrations in the soil samples, the values obtained were orders of magnitude (an average of six times) greater than those obtained from the standard wet chemistry procedure (Appendix Table 3). When the values were manually calculated, as was done for the nitrate concentrations, the values of the “available” P concentrations decreased by an average of 50%. This confirms that a second look needs to be given to the algorithms being used for the calculations with the SoilDoc software.

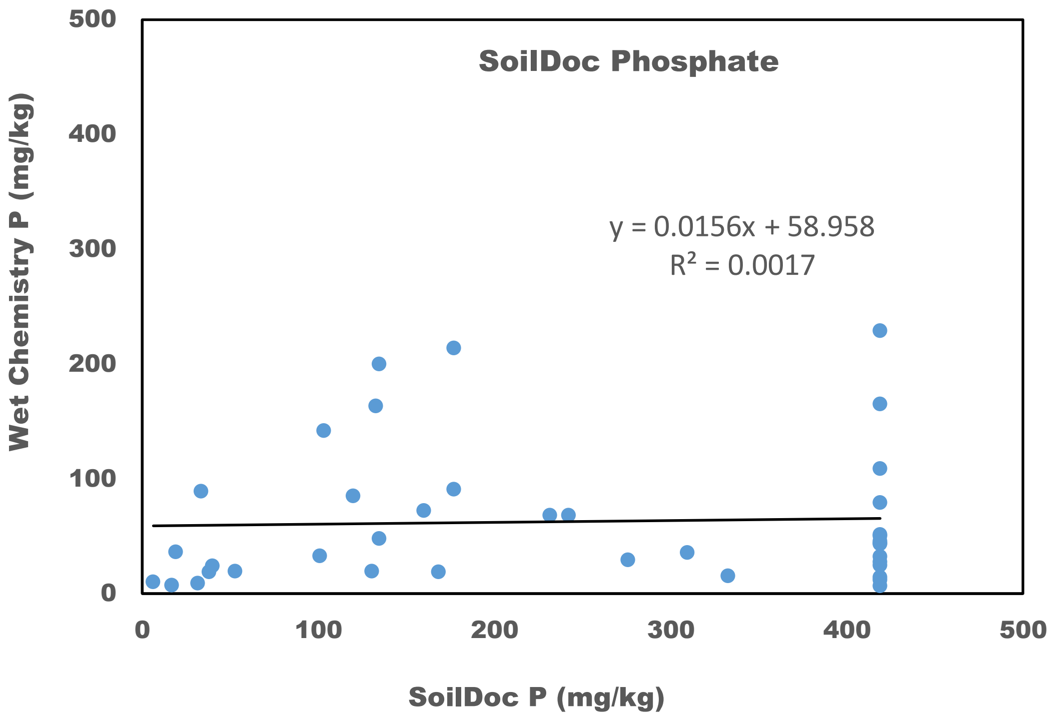


Figure 16. Results of the Available Phosphorus Analysis of 40 Archived Soil Samples Determined with the SoilDoc Soil Test Kit as Compared with Values Obtained from Wet Chemistry

Consistent with the observation of the benchmark soils, the “available” P determination conducted with the Hach soil test kits produced better results than the other two soil test kits being evaluated. With the exception of the strongly acidic soil samples that produced values that were clearly outliers, the test on most of the weakly acidic, near-neutral, and weakly alkaline soils produced values that were within the limits of those observed with the standard wet chemistry procedure (Figure 17, Appendix Table 3). Again, the actual values generated with the Hach soil test kits were not statistically different from the values obtained with the standard wet chemistry procedure (Appendix Table 3).

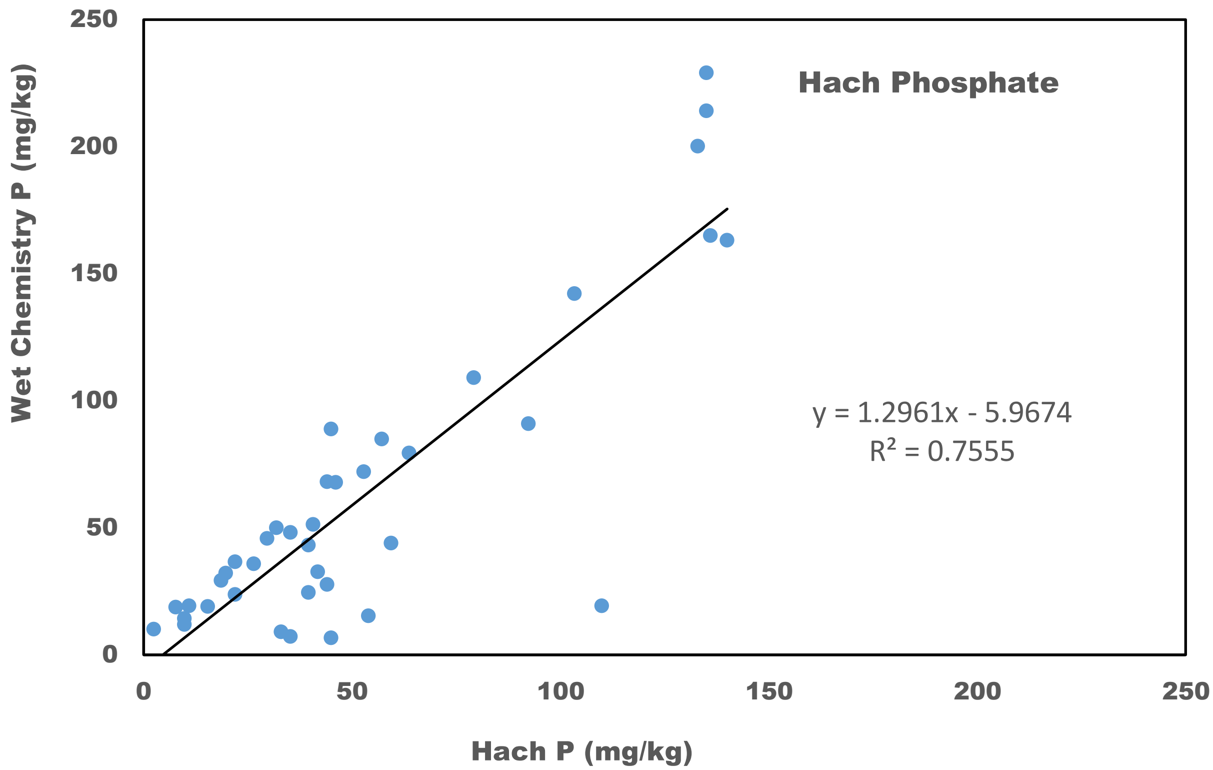


Figure 17. Results of the Available Phosphorus Analysis of 40 Archived Soil Samples Determined with the Hach Soil Test Kit as Compared with Values Obtained from Wet Chemistry

Determination of the soil "available" P content by the Kasetsart soil test kit was better for the soils with high to very high P concentrations than soils with low to medium P concentrations. For the soils with high to very high P concentrations, most of the results were consistent with those of the standard wet chemistry procedure. However, there were few samples with inherent native low P concentrations that were designated as having high to very high P concentrations when the Kasetsart soil test kits were used to test them (Figure 18, Appendix Table 3). This could be attributed to the limits of delineations used to categorize soils based on the soil P concentrations by the manufacturers of the Kasetsart soil test kits. Several studies have shown that "available" P concentration values between 11 and 31 mg P kg^{-1}, depending on the extractant used, could be the critical value for most soil, below which P could be deficient in those soils. However, with the Kasetsart soil test kits, soils with "available" P concentration values of 7 to 9 mg P kg^{-1} are considered as having high P levels, and values of 10 mg P kg^{-1} and above are considered very high P levels. As a result of this classification, it was not surprising that more than 90% of the soils analyzed were designated as high to very high P soils by the Kasetsart soil test kits, although some such soils had native "available" P concentrations of less than 11 mg P kg^{-1}. In this regard, it will be necessary to match the "available" P level designations by the Kasetsart soil test kits with the range of "available" P concentration values assigned by researchers for most soils.

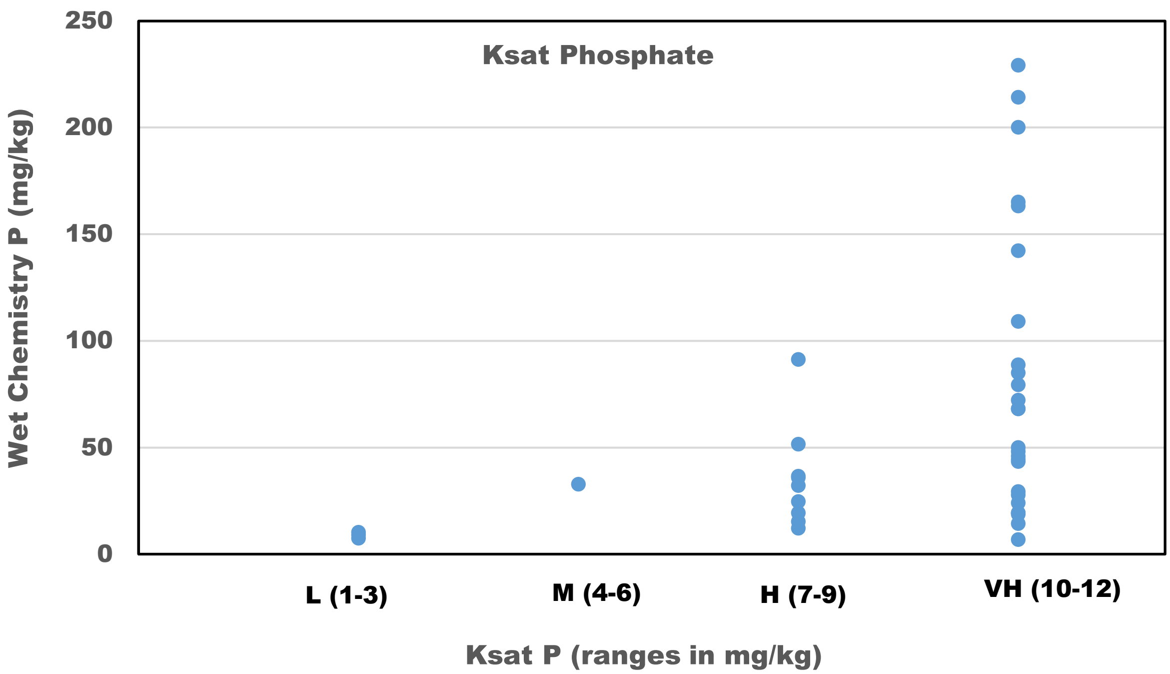


Figure 18. Results of the Available Phosphorus Analysis of 40 Archived Soil Samples Determined with the Kasetsart Soil Test Kit as Compared with Values Obtained from Wet Chemistry

d. *Soil Exchangeable Potassium Concentration of Archived Soil Samples*

The SoilDoc test kit produced better results in terms of K determination relative to the other two soil test kits, determining precisely the exchangeable K levels for most of the soil samples as determined by the standard wet chemistry procedure. There was a high correlation of the results obtained from the SoilDoc soil test kit with those of the standard soil chemistry procedure, with a coefficient of determination (R^2) value of 0.81 (Figure 19). However, contrary to the results observed for the nitrate and phosphorus determination using the tablet, the actual values obtained from the SoilDoc soil test kits were consistently smaller than those obtained from the standard wet chemistry procedure (Figure 19, Appendix Table 4). Using the recommended procedure of the SoilDoc kit with the tablet provided in the kit by the manufacturers, the soil potassium concentration values obtained with the SoilDoc kit were about one-half of those obtained with the standard wet chemistry procedure (Appendix Table 4).

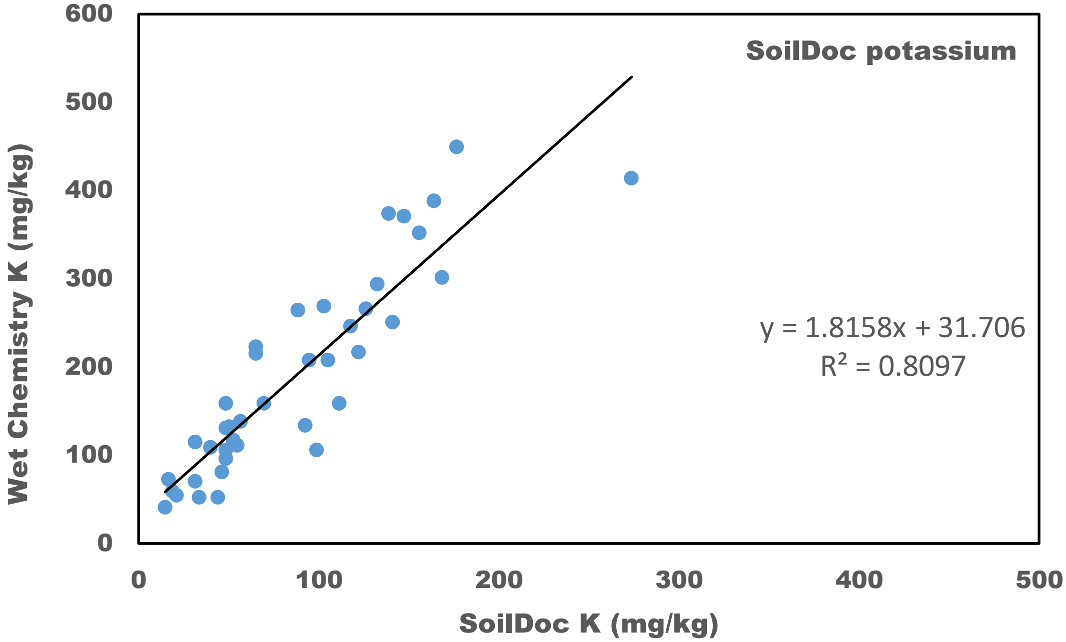


Figure 19. Results of the Exchangeable Potassium Analysis of 40 Archived Soil Samples Determined with the SoilDoc Soil Test Kit as Compared with Values Obtained from Wet Chemistry

As observed with the benchmark soils for exchangeable K, the other two soil test kits were not good enough to produce acceptable K values, compared with values obtained with the wet chemistry analysis (Figures 20 and 21). As has been the case for the results obtained with the Kasetsart soil test kit for nitrate and phosphorus, the potassium values were also inconsistent (Figure 21). There were several soil samples that were classified by the Kasetsart soil test kits as having low potassium concentrations that were contrary to the values obtained with the standard wet chemistry procedure and vice versa (Figure 21, Appendix Table 4). Again, this anomaly could be attributed to the organic matter content of the soil. Since the procedure used by the Kasetsart for potassium determination is also entirely colorimetric, the organic matter content of the soil likely compromised the color of the soil extract, which affected the reading of the extract to determine nitrate concentration. Therefore, the ranges of organic matter content of the soil within which the Kasetsart soil test kits produce accurate and acceptable values of soil potassium concentrations must also be evaluated and specified in the user's manual.

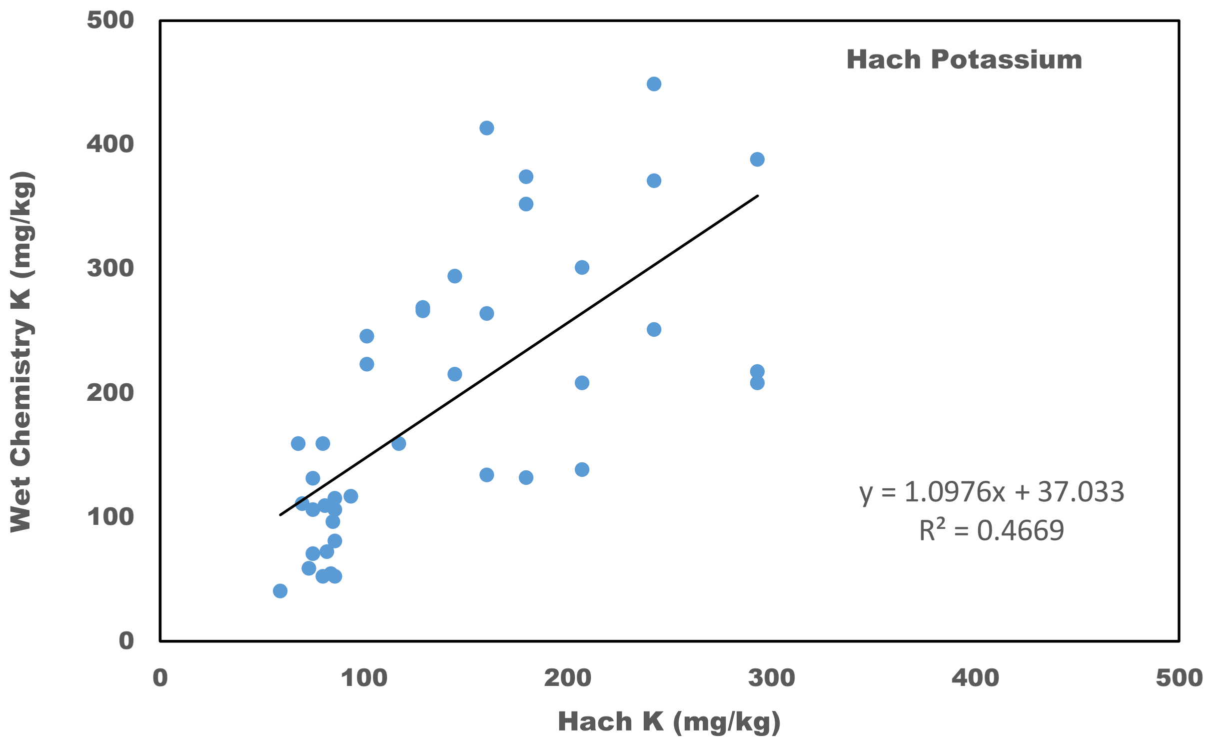


Figure 20. Results of the Exchangeable Potassium Analysis of 40 Archived Soil Samples Determined with the Hach Soil Test Kit as Compared with Values Obtained from Wet Chemistry

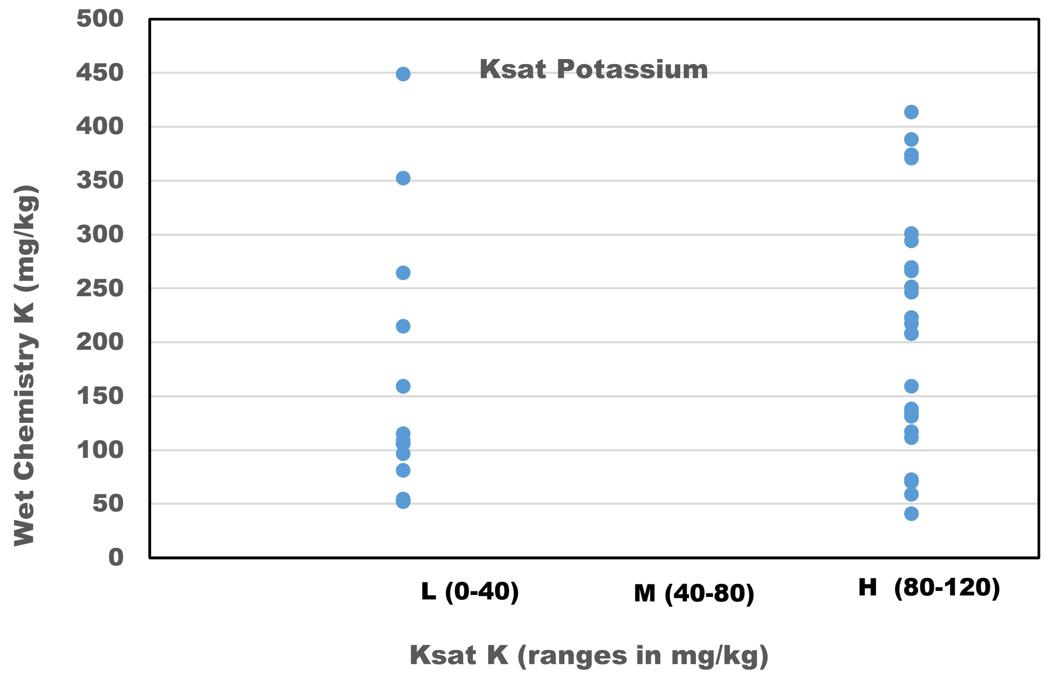


Figure 21. Results of the Exchangeable Potassium Analysis of 40 Archived Soil Samples Determined with the Kasetsart Soil Test Kit as Compared with Values Obtained from Wet Chemistry

Plant Nutrient Uptake and Dry Matter Yield

A greenhouse experiment was set up to validate the results of the soil chemical analysis by determining the correlation between the soil chemical analysis and the plant nutrient uptake and dry matter yield. Thus, the dry matter yield and N, P, and K content of the plant tissues were identified in order to determine nutrient uptake on maize in response to different nutrient applications and from the unamended soil. The results of the plant nutrient uptake did not consistently correlate with the results of soil chemical analyses done with all three soil test kits and with the standard laboratory procedures. With the exception of potassium uptake, which weakly correlated with the exchangeable K determined by the standard laboratory procedure (Figure 22) and the SoilDoc soil test kit (Figure 23), K uptake by the plants did not correlate with soil K values determined by the Hach and the Kasetsart soil test kits (Appendix Figure 1).

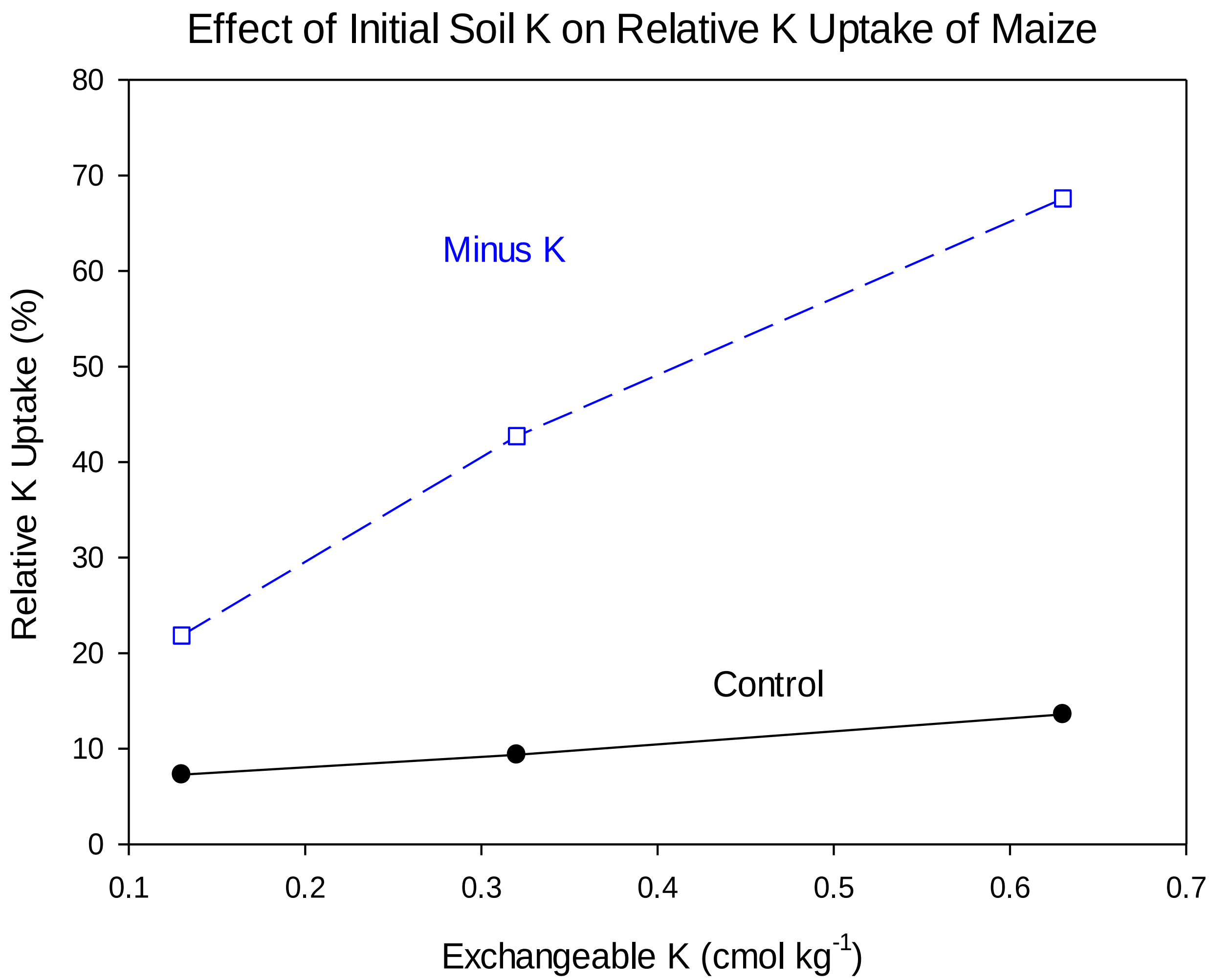


Figure 22 Effect of Initial Soil Exchangeable K as Determined by the Ammonium Acetate (Wet Chemistry) Method on Relative P Uptake of Maize

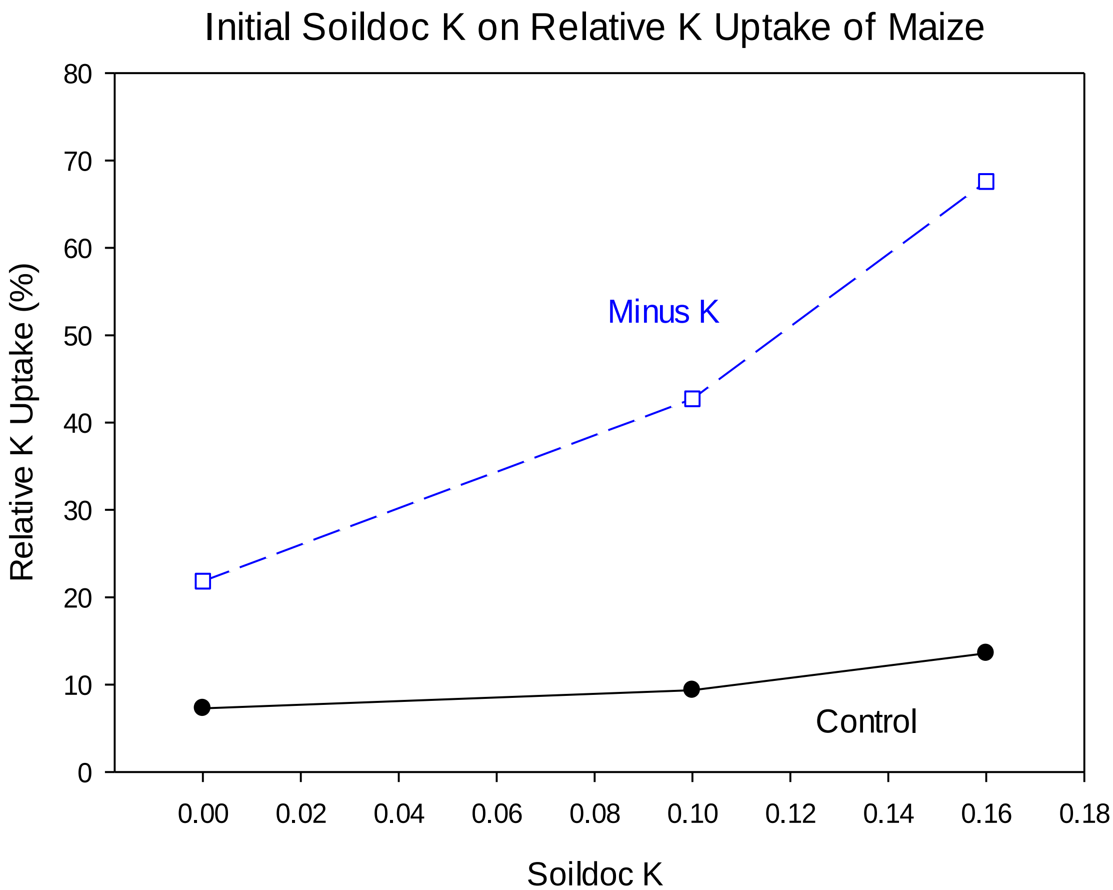


Figure 23. Effect of Initial Soil Exchangeable K as Determined by the SoilDoc Soil Test Kit on Relative K Uptake of Maize

For N and P, plant uptake did not correlate with the results of the soil chemical analyses, irrespective of the soil test kit used to analyze the soil, or with the standard laboratory procedures (Appendix Figures 2-5). For dry matter yield, the results obtained did not correlate with soil nutrients determined using all three soil test kits or the wet chemistry analysis (Appendix Figures 6-12). With these inconsistent results, the greenhouse experiment will be repeated to validate observations and conclusions.

Conclusions and Recommendations

The study confirmed that the Kasetsart soil test kit is very easy to use and could be conveniently used by most smallholder farmers for analysis. On the other hand, the SoilDoc kit is very complicated to use and the user manual is not easy to follow; therefore, the kit must be handled by personnel trained in soil analysis. The combined results obtained from the benchmark soils and the archived soil samples showed good correlation for pH for all three kits tested with standard wet chemistry analysis.

For nitrate analysis, the Hach soil test kits produced reasonably good results for all samples, except for the strongly acidic soil. The values obtained from the SoilDoc kits for both soil nitrate and “available” P levels were orders of magnitude greater than those observed from the standard laboratory wet chemistry procedures. This suggests the need for a critical look into the extraction procedures for the various elements and the algorithms being used for the calculations within the SoilDoc software. For “available” P determination, the Hach soil test kit was the only one that produced good results. With the exception of the strongly acidic soil, determinations on most of the weakly acidic, near-neutral, and weakly alkaline soils produced values that were within the limits of those observed with the standard wet chemistry procedure. For potassium determination, the SoilDoc was the only test kit that produced relatively good results.

The results obtained with the Kasetsart soil test kit were rather inconsistent, with some soil samples classified as having low nutrient concentrations contrary to the values obtained with the standard wet chemistry procedure. This anomaly could be attributed to the soil pH and the organic matter content of the soil. The acidity of the soil likely affected the chemical extraction of the nutrients from the soil, but since the procedure used by the Kasetsart kit for analysis is entirely colorimetric, the organic matter content of the soil likely compromised the color of the soil extract, which affected the reading of the extract to determine nitrate concentration. Thus, the ranges of pH and organic matter content of the soil within which the Kasetsart soil test kits produce accurate and acceptable values must be evaluated and specified in the user’s manual. Also, it is important to align the “available” P level designations by the Kasetsart soil test kits with the range of “available” P concentration values assigned by researchers for most soils.

For the plant nutrient uptake study, only potassium uptake correlated (weakly) with the exchangeable K determined by the SoilDoc soil test kit, but not with those of the Hach and the

Kasetsart soil test kits. For N and P, plant uptake did not correlate with the results of the soil chemical analyses, irrespective of the soil test kit used to analyze the soil.

The combined results suggest that, for now, accurate soil fertility recommendations for major nutrients using these portable soil test kits across a range of soil pH values are not realistic. While their use could provide basic soil information, including pH, nitrate, and "available" P and K, for soils with a near-neutral pH, such soils are not common in areas where smallholder farmers are concentrated. Use on soils with lower or higher pH values resulted in erratic performance across all three kits. However, use of the low-cost kits by farmers who have no access to soil testing would, at least, help identify the limiting macronutrients within a field. Even if a consistently well-performing kit is eventually identified, before it can be widely used, field validation should be required based on a soil test kit approach that includes the blanket recommended fertilizer as a control to which the soil test kit recommendation would be compared in terms of yield-enhancing efficiency and economic profitability. The economic feasibility of such an approach is questionable, particularly in light of the recent focus on spectral analysis as a replacement for standard wet chemistry. Regardless, laboratory wet chemistry will remain the standard for identifying soils' fertility and for improving fertilizer recommendations for the immediate future.

Appendices

Appendix Table 1. Results of pH Analyses of Soil Samples Obtained from the NAPT Laboratories Using Standard Laboratory Procedure Versus Those Obtained with the Portable Soil Test Kits

	Soil	Wet Chemistry	SoilDoc	Hach	Kasetsart
1	Soil 2009-114	6.3	5.9	6.7	6.0
2	Soil 2009-115	7.9	6.9	7.5	7.5
3	Soil 2009-116	6.4	6.5	6.7	6.0
4	Soil 2009-118	6.3	6.3	6.7	6.0
5	Soil 2009-119	8.0	7.0	7.5	7.5
6	Soil 2010-111	6.1	6.3	6.1	5.5
7	Soil 2010-112	8.0	6.4	8.1	7.5
8	Soil 2010-113	7.1	6.6	7.2	6.5
9	Soil 2010-114	4.7	5.1	4.8	4.5
10	Soil 2010-115	5.3	5.4	5.4	5.0
11	Soil 2011-106	7.6	6.4	7.9	7.5
12	Soil 2011-107	7.9	6.7	8.0	7.5
13	Soil 2011-108	5.4	5.6	5.6	6.0
14	Soil 2011-109	7.1	6.6	7.2	6.5
15	Soil 2011-110	6.0	6.2	6.1	5.5
16	Soil 2012-116	7.0	6.6	7.1	6.5
17	Soil 2012-117	6.5	6.8	6.7	6.0
18	Soil 2012-118	5.6	5.9	6.0	6.0
19	Soil 2012-119	6.9	6.4	7.0	6.5
20	Soil 2012-120	5.6	5.9	5.9	6.0
21	Soil 2013-101	6.2	6.0	6.7	6.5
22	Soil 2013-102	7.6	6.5	7.4	7.0
23	Soil 2013-103	6.6	6.5	6.7	6.0
24	Soil 2013-104	7.1	6.7	7.1	6.5
25	Soil 2013-105	8.0	7.0	7.5	7.5
26	Soil 2014-111	7.9	6.7	7.7	7.0
27	Soil 2014-112	5.7	6.3	6.0	5.5
28	Soil 2014-113	6.9	6.6	6.9	6.5
29	Soil 2014-114	5.6	6.3	6.0	5.5
30	Soil 2014-115	7.2	7.1	7.3	6.5
31	Soil 2015-106	8.2	7.1	8.2	7.0
32	Soil 2015-107	5.6	5.9	5.9	5.0
33	Soil 2015-108	6.4	6.1	6.7	5.5
34	Soil 2015-109	6.2	6.2	6.4	5.0
35	Soil 2015-110	6.9	6.8	7.0	6.0
36	Soil 2016-101	6.5	6.8	6.8	6.0
37	Soil 2016-102	7.2	6.9	7.0	7.0
38	Soil 2016-103	8.0	7.2	7.3	7.5
39	Soil 2016-104	5.3	5.9	6.4	5.0
40	Soil 2016-105	7.2	6.3	7.1	6.5

Appendix Table 2. Results of Nitrate Analyses of Soil Samples Obtained from the NAPT Laboratories Using Standard Laboratory Procedure Versus Those Obtained with the Portable Soil Test Kits

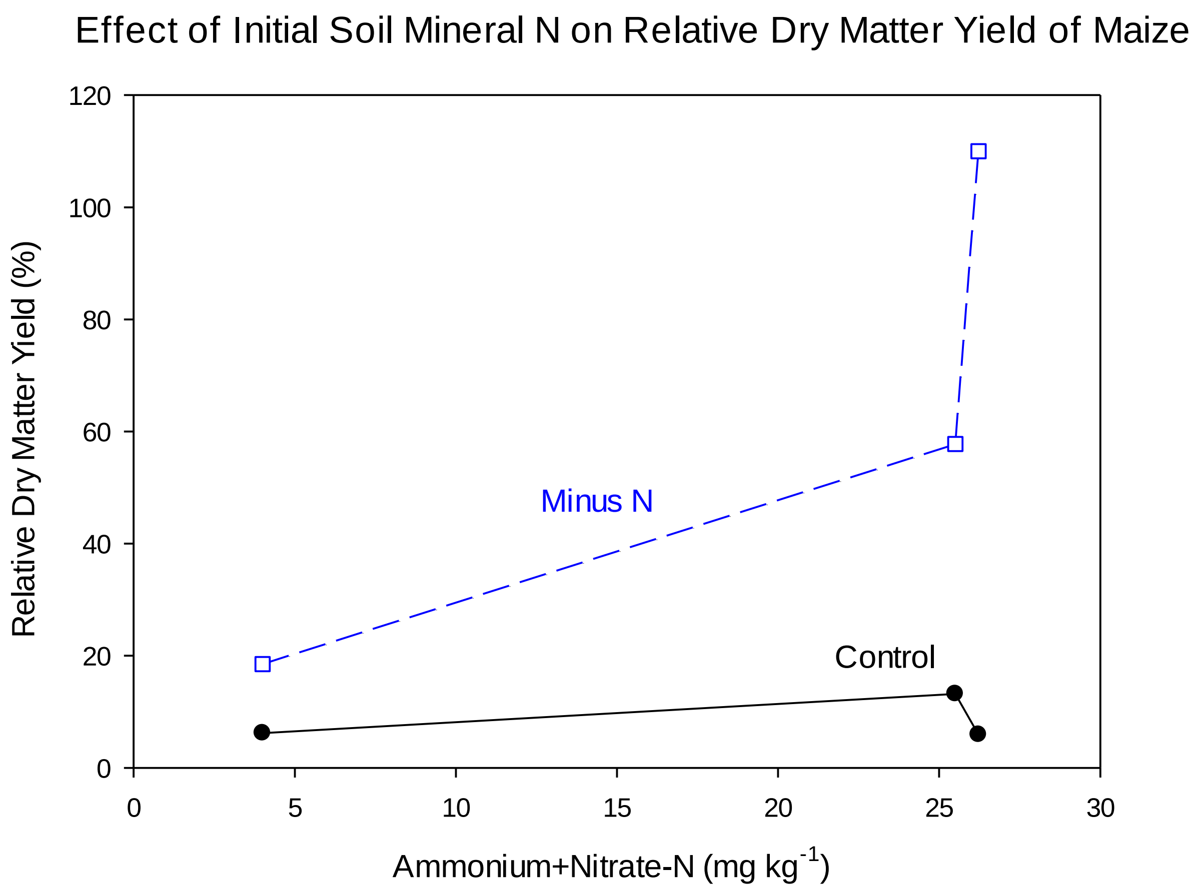
	Soil	**Wet Chemistry** mg kg-1	**SoilDoc Calc.** mg kg-1	**SoilDoc Tablet** mg kg-1	**Hach** mg kg-1	**Kasetsart** Level
1	Soil 2009-114	1.4	62	130.52	<1.0	VL
2	Soil 2009-115	16.5	96.0	202.1	8.0	M
3	Soil 2009-116	7.0	59.0	124.2	1.3	VL
4	Soil 2009-118	1.1	68.0	143.2	4.0	VL
5	Soil 2009-119	2.2	65.0	136.8	2.7	L
6	Soil 2010-111	7.8	72.0	151.6	<1.0	VL
7	Soil 2010-112	28.8	100.0	210.5	18.0	M
8	Soil 2010-113	28.6	99.0	208.4	8.0	L
9	Soil 2010-114	28.8	97.0	204.2	18.0	L
10	Soil 2010-115	45.5	140.0	294.7	24.0	M
11	Soil 2011-106	32.7	110.0	231.6	7.3	M
12	Soil 2011-107	89.4	230.0	484.2	18.0	H
13	Soil 2011-108	14.9	56.0	117.9	2.7	VL
14	Soil 2011-109	12.0	61.0	128.4	4.0	VL
15	Soil 2011-110	54.5	130.0	273.7	35.3	H
16	Soil 2012-116	17.1	80.0	168.4	13.3	L
17	Soil 2012-117	2.0	45.0	94.7	2.0	VL
18	Soil 2012-118	61.9	160.0	336.8	35.3	M
19	Soil 2012-119	20.8	80.0	168.4	20.0	L
20	Soil 2012-120	71.5	190.0	400.0	50.0	M
21	Soil 2013-101	39.4	120.0	252.6	18.0	M
22	Soil 2013-102	69.4	190.0	400.0	18.7	H
23	Soil 2013-103	33.8	110.0	231.6	20.0	M
24	Soil 2013-104	11.3	75.0	157.9	6.7	L
25	Soil 2013-105	29.0	110.0	231.6	17.3	L
26	Soil 2014-111	32.4	110.0	231.6	18.0	M
27	Soil 2014-112	32.8	110.0	231.6	20.0	M
28	Soil 2014-113	89.2	240.0	505.3	29.3	H
29	Soil 2014-114	50.9	150.0	315.8	20.0	VL
30	Soil 2014-115	17.4	82.0	172.6	16.7	VL
31	Soil 2015-106	4.8	47.0	98.9	5.3	VL
32	Soil 2015-107	16.4	75.0	157.9	14.7	L
33	Soil 2015-108	51.9	140.0	294.7	25.3	M
34	Soil 2015-109	10.0	57.0	120.0	8.0	VL
35	Soil 2015-110	58.3	160.0	336.8	28.7	M
36	Soil 2016-101	17.1	88.0	185.3	10.7	VL
37	Soil 2016-102	46.1	140.0	294.7	18.7	M
38	Soil 2016-103	2.2	56.0	117.9	2.7	VL
39	Soil 2016-104	0.8	46.0	96.8	<1.0	VL
40	Soil 2016-105	17.1	82.0	172.6	16.0	M

Appendix Table 3. Results of "Available P" Analyses of Soil Samples Obtained from the NAPT Laboratories Using Standard Laboratory Procedure Versus Those Obtained with the Portable Soil Test Kits

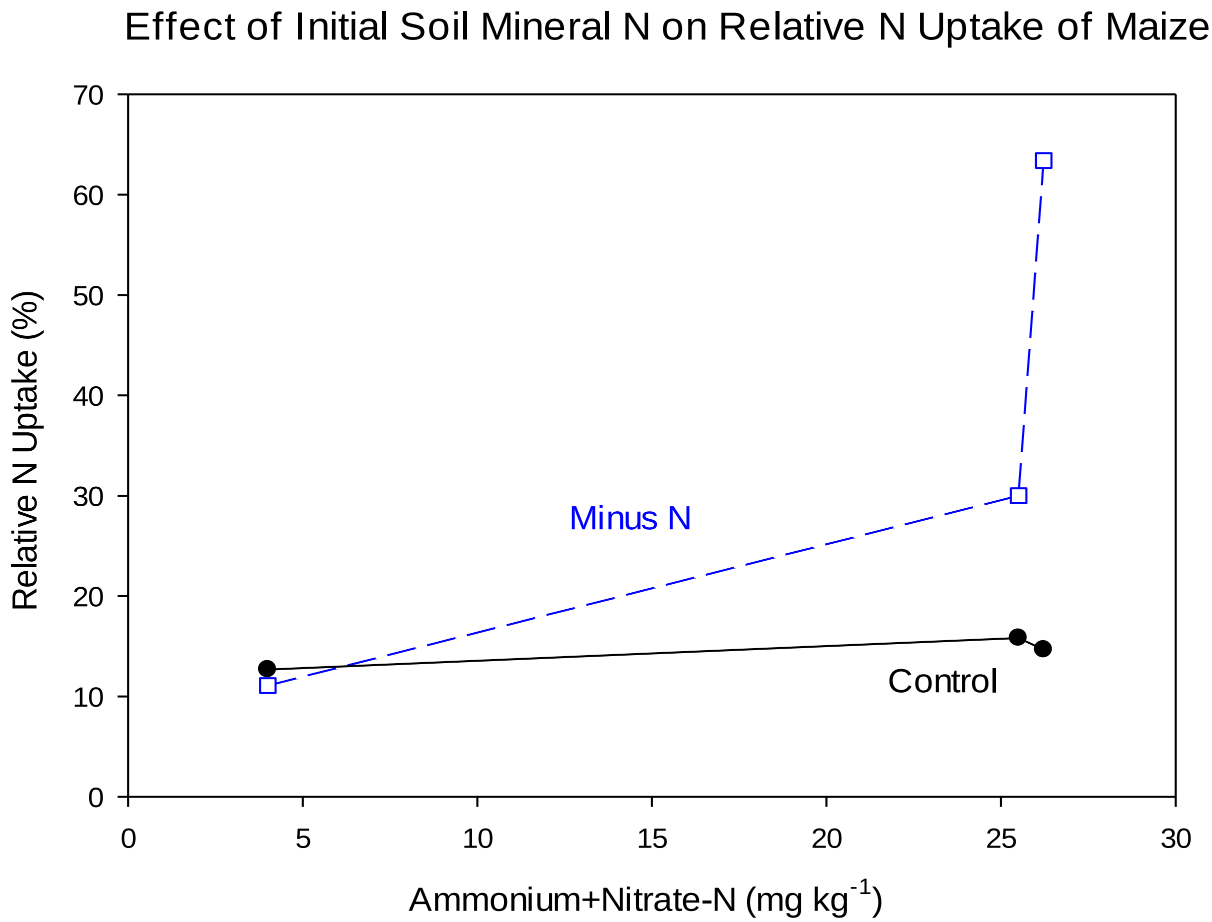
	Soil	Wet Chemistry	SoilDoc Calculated	SoilDoc tablet	Hach	Kasetsart
		mg kg-1	mg kg-1	mg kg-1	mg kg-1	Level
1	Soil 2009-114	68.0	115.0	242.1	44.0	VH
2	Soil 2009-115	23.7	19	40	22.0	VH
3	Soil 2009-116	48.0	64	134.73	35.2	VH
4	Soil 2009-118	67.9	110	231.57	46.2	VH
5	Soil 2009-119	8.9	15	31.57	33.0	L
6	Soil 2010-111	35.7	147	309.47	26.4	H
7	Soil 2010-112	24.5	199	418.94	39.6	H
8	Soil 2010-113	43.1	199	418.94	39.6	VH
9	Soil 2010-114	200.0	64	134.73	> 132.0	VH
10	Soil 2010-115	163.0	63	132.63	> 132.0	VH
11	Soil 2011-106	6.5	199	418.94	45.1	VH
12	Soil 2011-107	44.0	199	418.94	59.4	VH
13	Soil 2011-108	32.0	199	418.94	19.8	H
14	Soil 2011-109	79.2	199	418.94	63.8	VH
15	Soil 2011-110	49.9	199	418.94	31.9	VH
16	Soil 2012-116	19.0	80	168.42	15.4	H
17	Soil 2012-117	14.1	199	418.94	9.9	VH
18	Soil 2012-118	51.2	199	418.94	40.7	H
19	Soil 2012-119	91.0	84	176.84	92.4	H
20	Soil 2012-120	72.0	76	160	52.8	VH
21	Soil 2013-101	309.0	199	418.94	> 132.0	VH
22	Soil 2013-102	19.1	62	130.52	110.0	VH
23	Soil 2013-103	36.4	9	18.94	22.0	H
24	Soil 2013-104	84.9	57	120	57.2	VH
25	Soil 2013-105	32.5	48	101.05	41.8	M
26	Soil 2014-111	15.2	158	332.63	53.9	H
27	Soil 2014-112	29.1	131	275.78	18.7	VH
28	Soil 2014-113	45.7	199	418.94	29.7	VH
29	Soil 2014-114	214.0	84	176.84	> 132.0	VH
30	Soil 2014-115	19.2	25	52.63	11.0	VH
31	Soil 2015-106	27.7	199	418.94	44.0	VH
32	Soil 2015-107	109.0	199	418.94	79.2	VH
33	Soil 2015-108	11.8	199	418.94	9.9	H
34	Soil 2015-109	229.0	199	418.94	> 132.0	VH
35	Soil 2015-110	165.0	199	418.94	> 132.0	VH
36	Soil 2016-101	88.7	16	33.68	45.1	VH
37	Soil 2016-102	142.0	49	103.15	103.4	VH
38	Soil 2016-103	7.25	8	16.84	35.2	L
39	Soil 2016-104	10.1	3	6.31	<1.0	L
40	Soil 2016-105	18.6	18	37.89	7.7	VH

Appendix Table 4. Results of Exchangeable Potassium Analyses of Soil Samples Obtained from the NAPT Laboratories Using Standard Laboratory Procedure Versus Those Obtained with the Portable Soil Test Kits

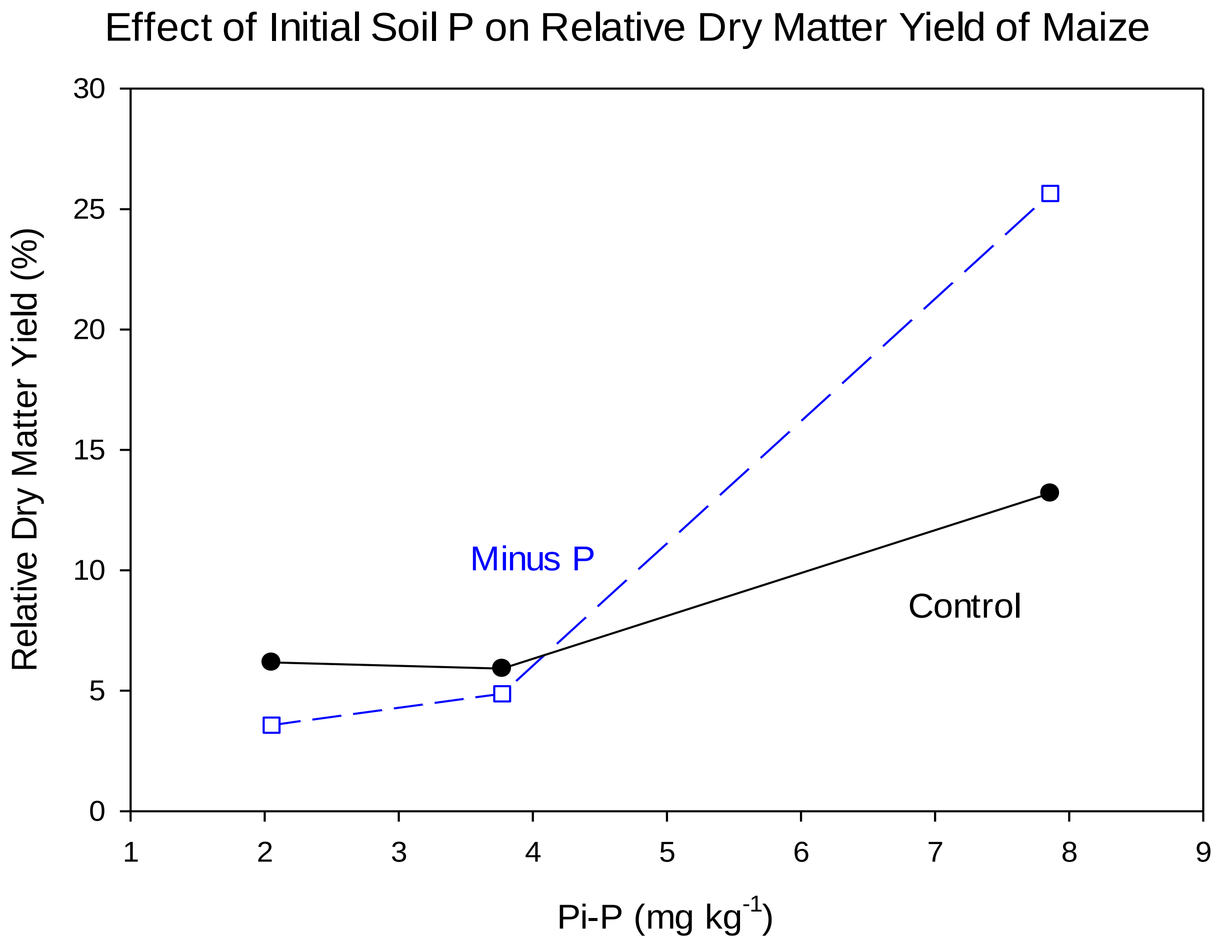
		Wet Chemistry	SoilDoc Tablet	Hach	Kasetsart
		mg kg^{-1}	mg kg^{-1}	mg kg^{-1}	Level
1	Soil 2009-114	266.0	126.3	129.0	H
2	Soil 2009-115	106.0	48.42	< 86.0	L
3	Soil 2009-116	109.0	40.00	< 86.0	L
4	Soil 2009-118	269.0	103.15	129.0	H
5	Soil 2009-119	132.0	50.52	179.9	H
6	Soil 2010-111	413.5	273.68	160.3	H
7	Soil 2010-112	208.0	94.73	207.2	H
8	Soil 2010-113	159.0	48.42	117.3	H
9	Soil 2010-114	81.0	46.31	< 86.0	L
10	Soil 2010-115	96.3	48.42	< 86.0	L
11	Soil 2011-106	117.0	52.63	93.8	H
12	Soil 2011-107	388.0	164.21	293.2	H
13	Soil 2011-108	115.0	31.57	< 86.0	L
14	Soil 2011-109	374.0	138.94	179.9	H
15	Soil 2011-110	264.0	88.42	160.3	L
16	Soil 2012-116	58.6	18.94	< 86.0	H
17	Soil 2012-117	72.4	16.84	< 86.0	H
18	Soil 2012-118	131.0	48.42	< 86.0	H
19	Soil 2012-119	111.0	54.73	< 86.0	H
20	Soil 2012-120	449.0	176.84	242.4	L
21	Soil 2013-101	294.0	132.63	144.7	H
22	Soil 2013-102	70.5	31.57	< 86.0	H
23	Soil 2013-103	159.0	69.47	< 86.0	L
24	Soil 2013-104	352.0	155.78	179.9	L
25	Soil 2013-105	208.0	105.26	293.2	H
26	Soil 2014-111	217.0	122.1	293.2	H
27	Soil 2014-112	251.0	141.05	242.4	H
28	Soil 2014-113	106.0	98.94	< 86.0	L
29	Soil 2014-114	159.0	111.57	< 86.0	L
30	Soil 2014-115	215.0	65.26	144.7	L
31	Soil 2015-106	134.0	92.63	160.3	H
32	Soil 2015-107	301.0	168.42	207.2	H
33	Soil 2015-108	54.4	21.05	< 86.0	L
34	Soil 2015-109	52.5	33.68	< 86.0	L
35	Soil 2015-110	246.0	117.89	101.7	H
36	Soil 2016-101	40.7	14.73	< 86.0	H
37	Soil 2016-102	371.0	147.36	242.4	H
38	Soil 2016-103	138.0	56.84	207.2	H
39	Soil 2016-104	52.1	44.21	< 86.0	L
40	Soil 2016-105	223.0	65.26	101.7	H



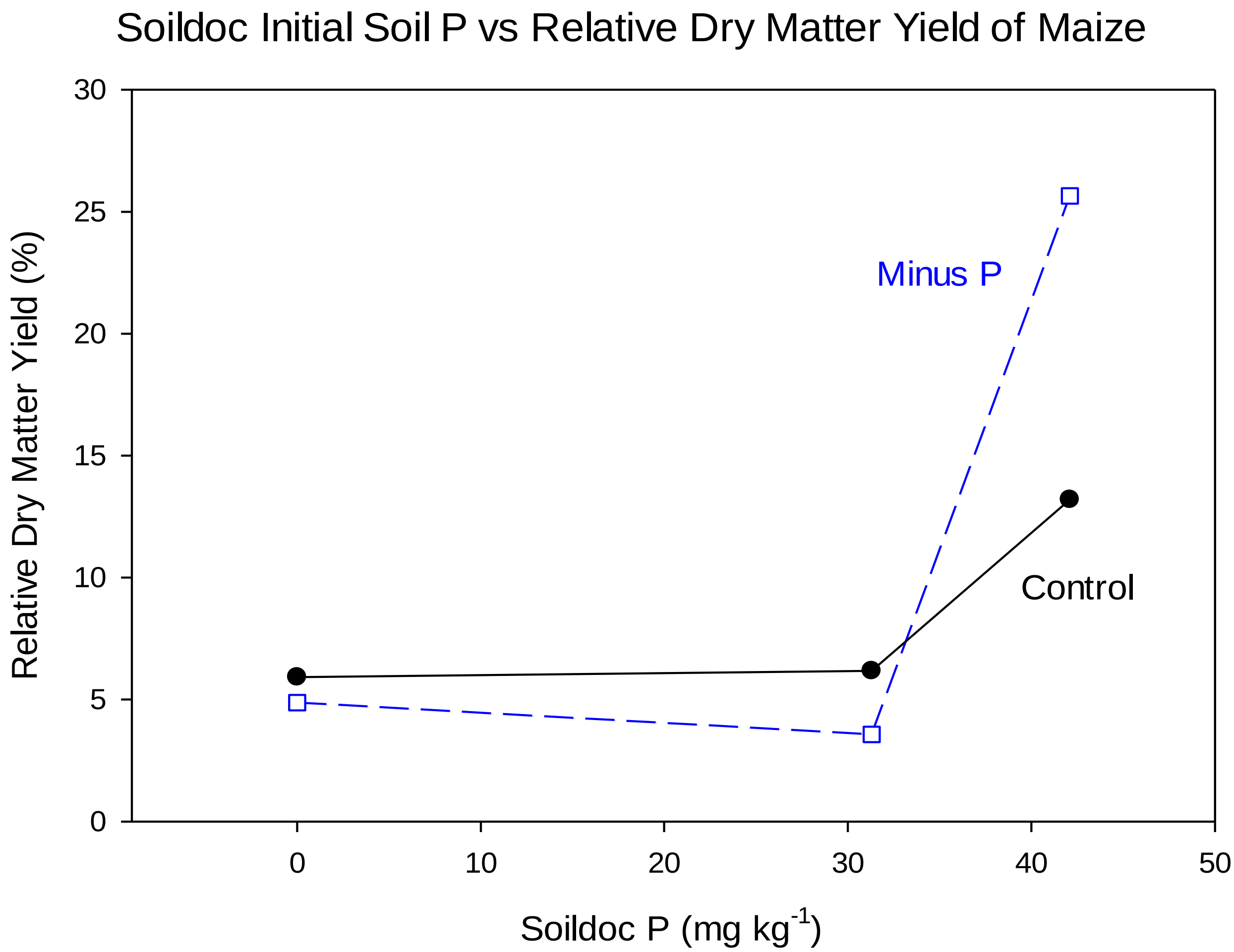
Appendix Figure 1. Effect of Initial Soil Mineral N on Relative Dry Matter Yield of Maize



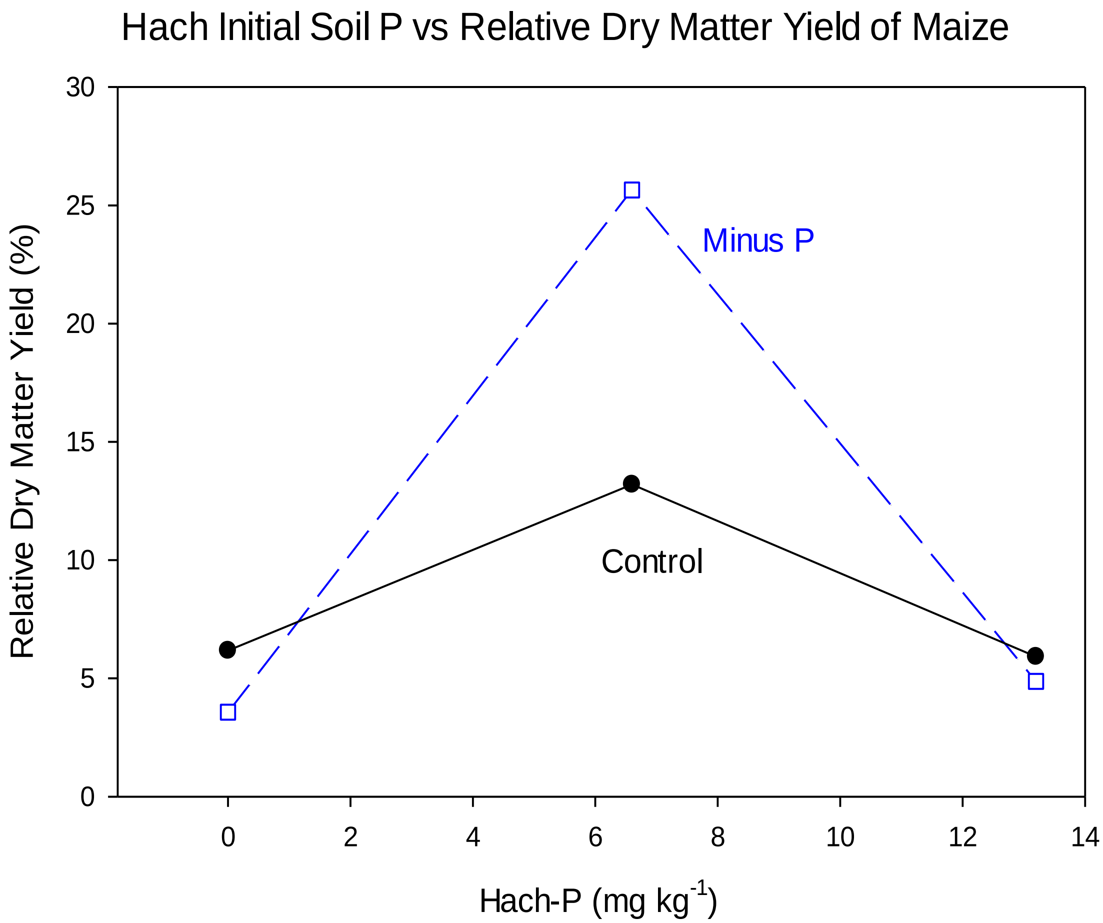
Appendix Figure 2. Effect of Initial Soil Mineral N on Relative N Uptake of Maize



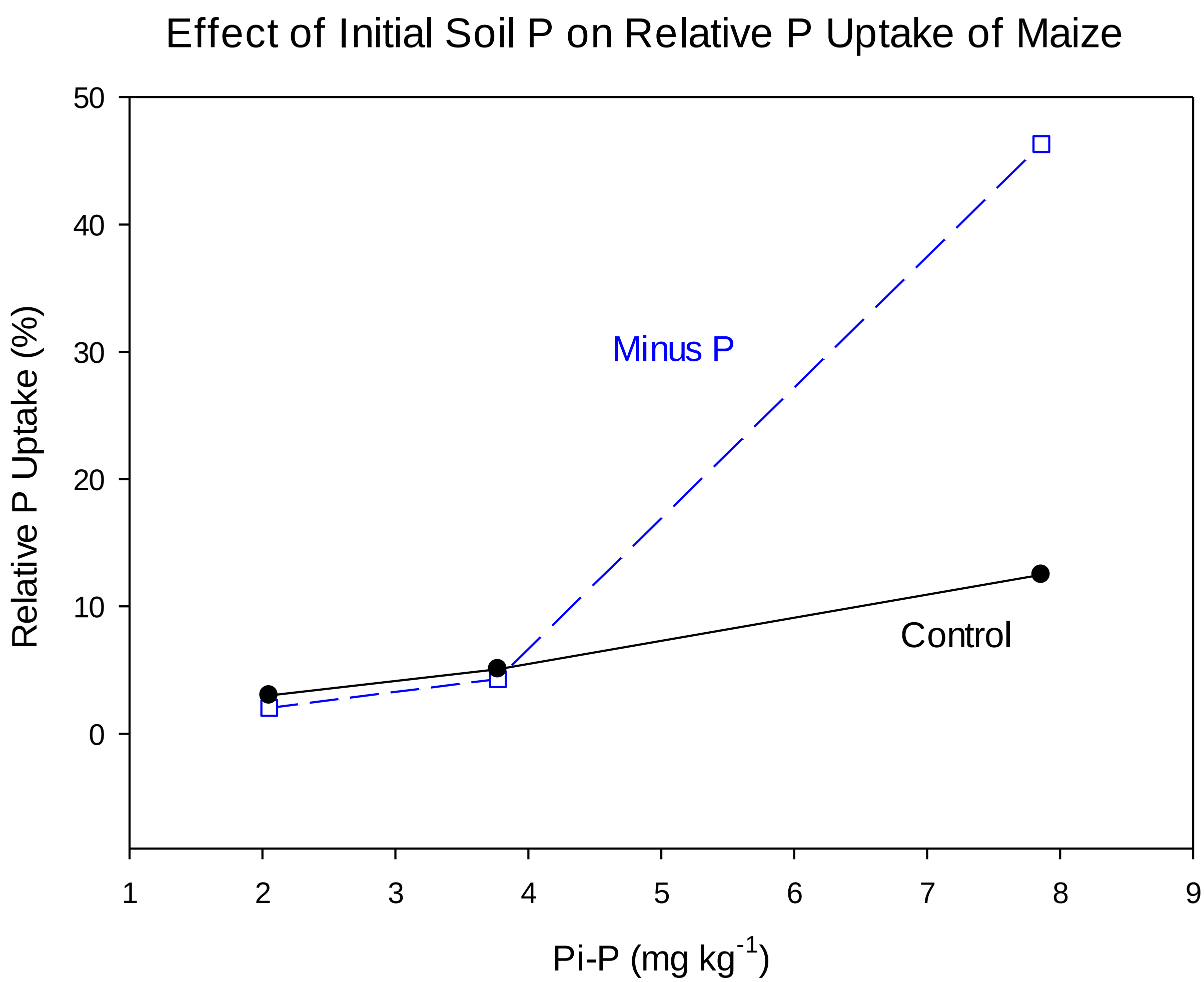
Appendix Figure 3. Effect of Initial Soil "Available" P as Determined by the Pi (Wet Chemistry) Method on Relative Dry Matter Yield of Maize



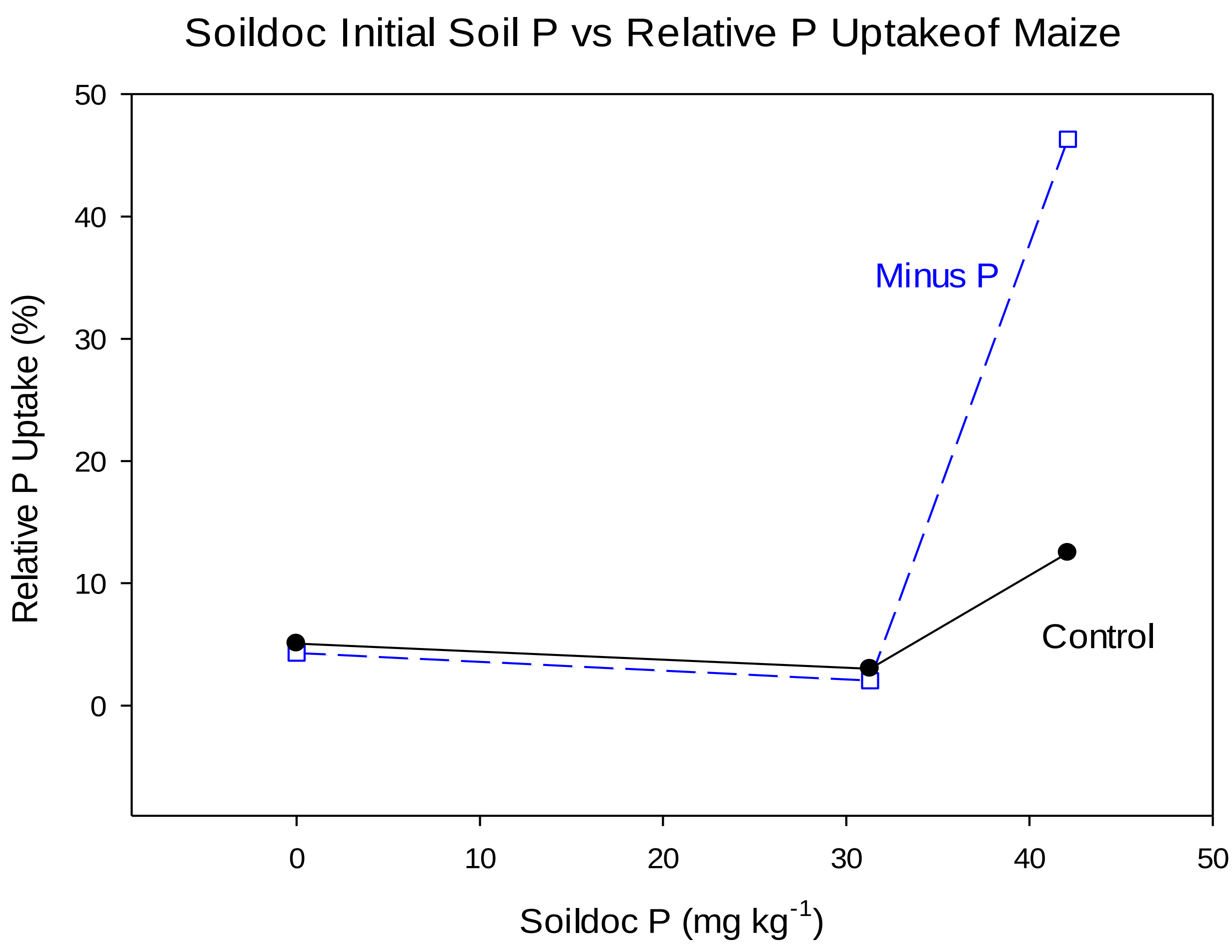
Appendix Figure 4. Effect of Initial Soil "Available" P as Determined by the SoilDoc Soil Test Kit on Relative Dry Matter Yield of Maize



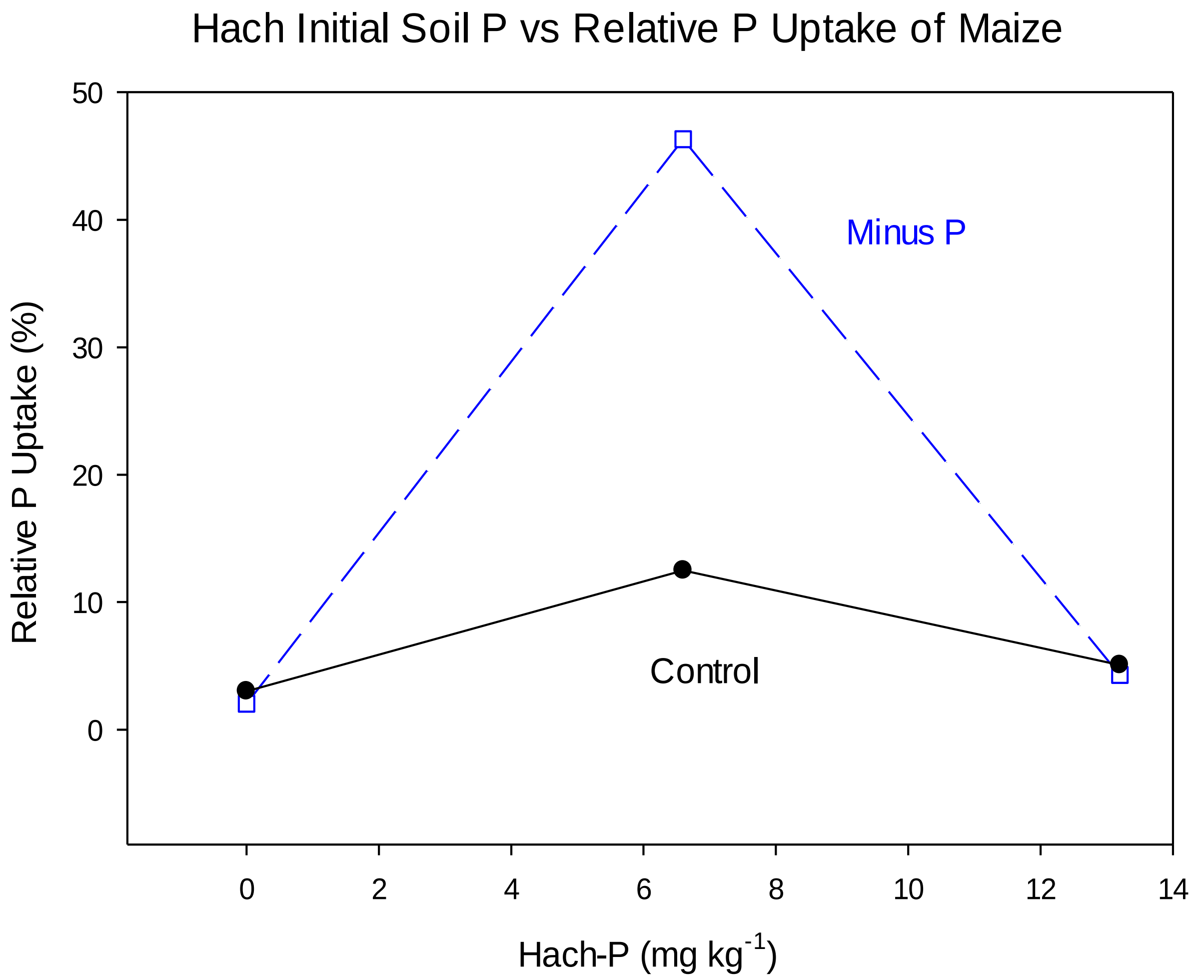
Appendix Figure 5. Effect of Initial Soil "Available" P as Determined by the Hach Soil Test on Relative Dry Matter Yield of Maize



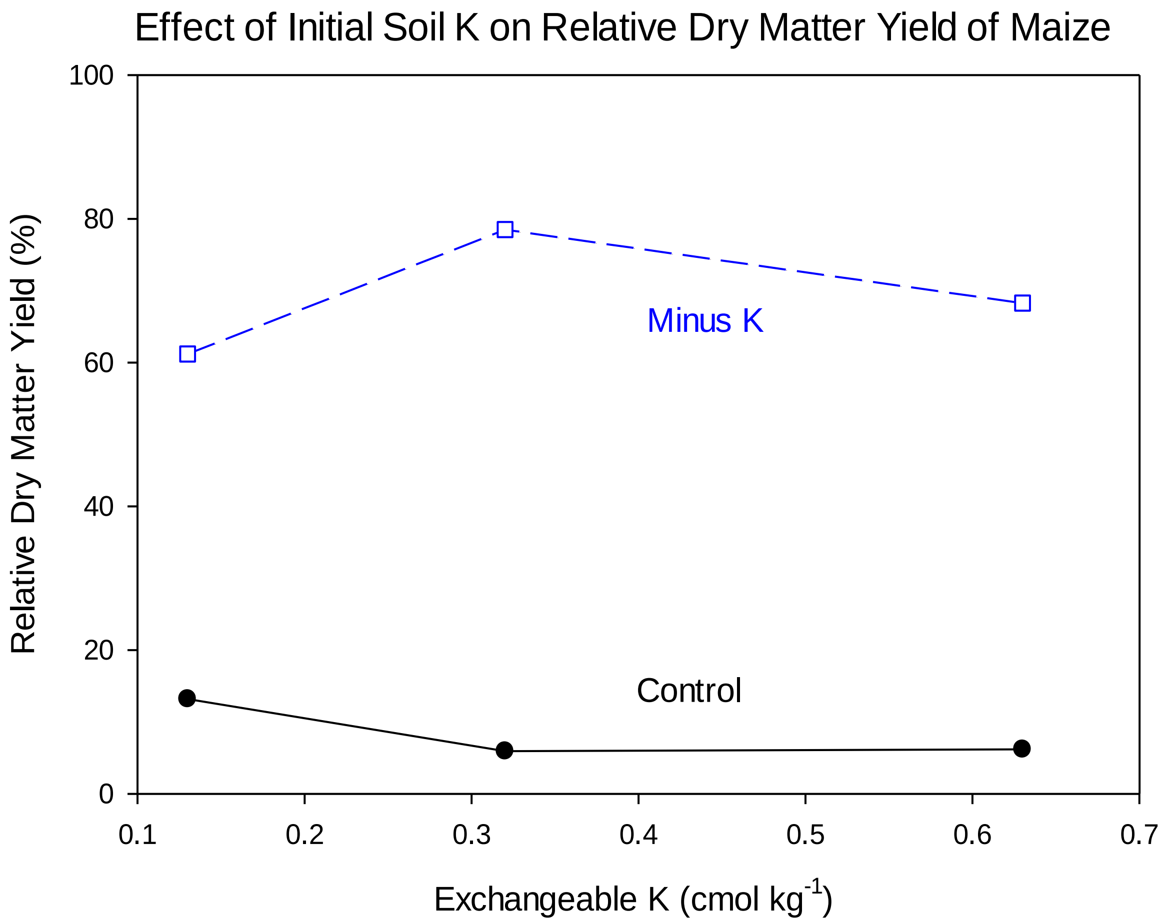
Appendix Figure 6. Effect of Initial Soil "Available" P as Determined by the Pi (Wet Chemistry) Method on Relative P Uptake of Maize



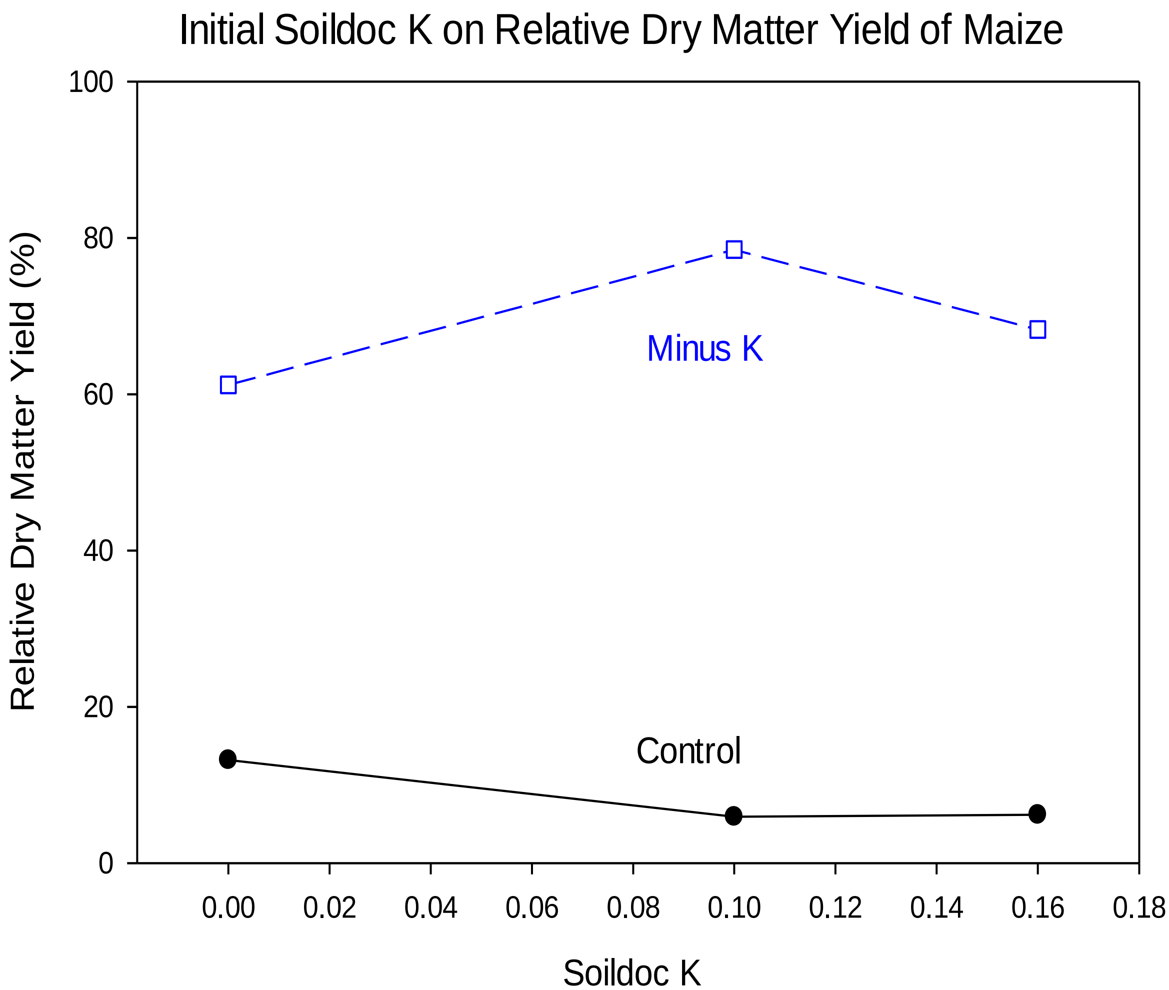
Appendix Figure 7. Effect of Initial Soil "Available" P as Determined by the SoilDoc Soil Test Kit on Relative P Uptake of Maize



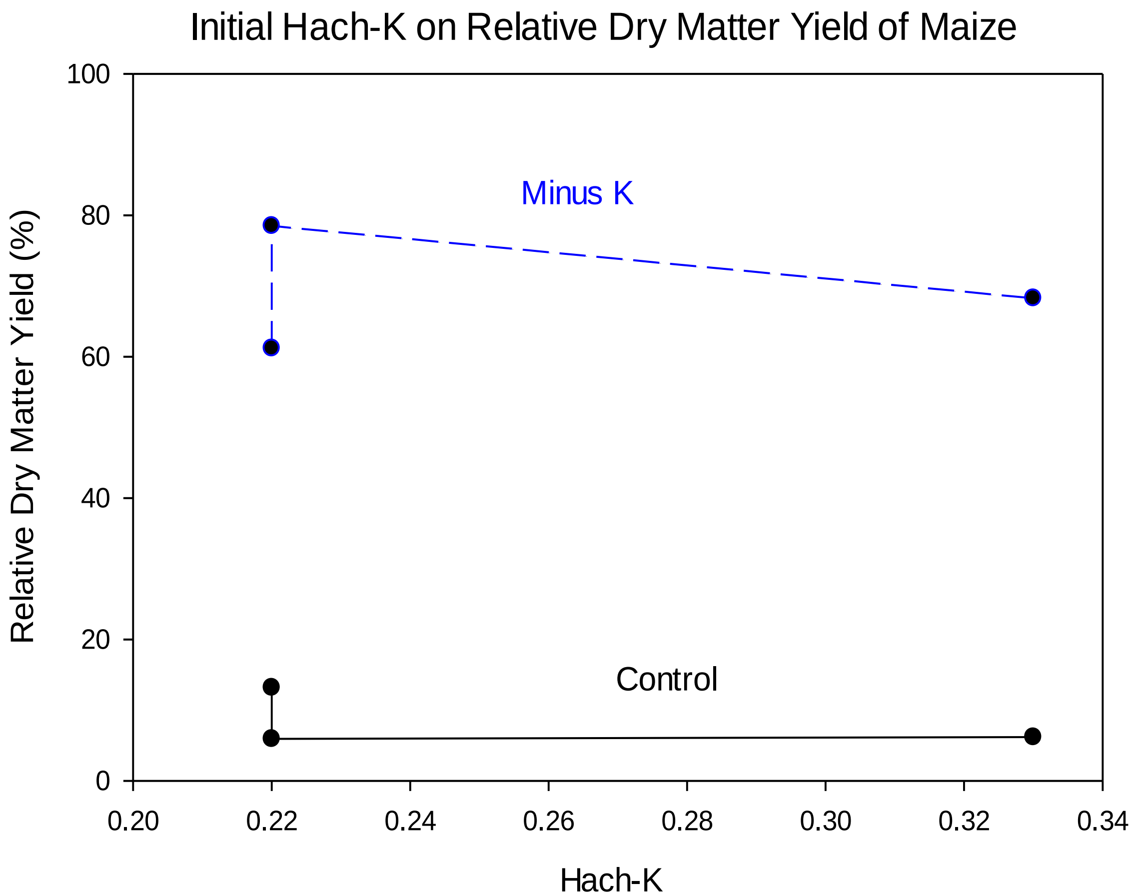
Appendix Figure 8. Effect of Initial Soil "Available" P as Determined by the Hach Soil Test Kit on Relative P Uptake of Maize



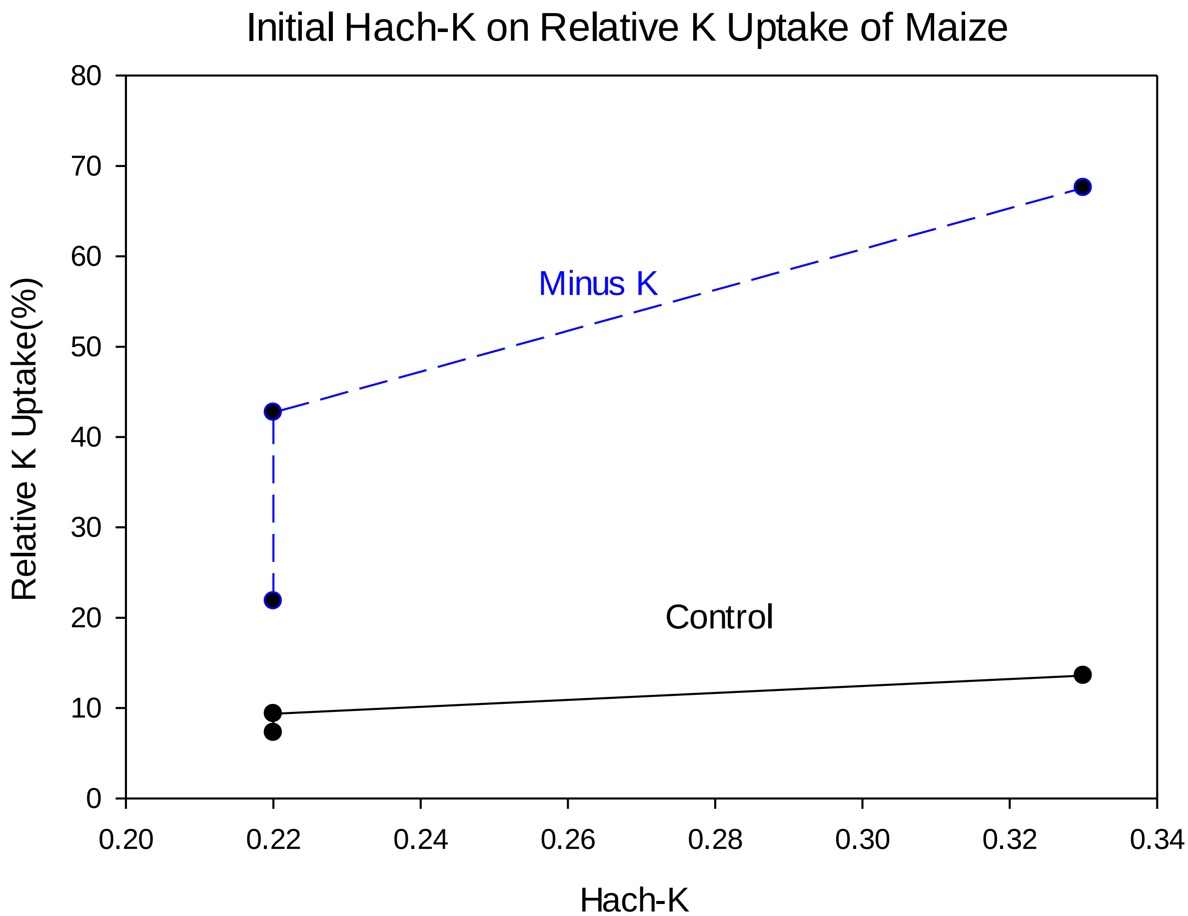
Appendix Figure 9. Effect of Initial Soil Exchangeable K as Determined by the Ammonium Acetate (Wet Chemistry) Method on Relative Dry Matter Yield of Maize



***Appendix Figure 10.** Effect of Initial Soil Exchangeable K as Determined by the SoilDoc Soil Test Kit on Relative Dry Matter Yield of Maize*



Appendix Figure 11. Effect of Initial Soil Exchangeable K as Determined by the Hach Soil Test Kit on Relative Dry Matter Yield of Maize



Appendix Figure 12. Effect of Initial Soil Exchangeable K as Determined by the Hach Soil Test Kit on Relative K Uptake of Maize

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