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Accuracy Varies for Commercially Available Soil Test Kits Analyzing Nitrate–Nitrogen, Phosphorus, Potassium, and pH

Ben A. Faber¹, A. James Downer^{1,3}, Dirk Holstege², and Maren J. Mochizuki¹

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SUMMARY. Soil testing is an important component of a plant nutrient management program for farmers, home gardeners, and agricultural service personnel. Results from five commercially available colorimetric soil test kits were compared with standard laboratory analyses for pH, nitrate–nitrogen (NO_3), phosphorus (P_2O_5), and potassium (K_2O) content for Salinas clay loam soil with three cropping histories. The kits ranked in accuracy (frequency of match with analytical laboratory results) in the following sequence: La Motte Soil Test Kit, Rapitest, Quick Soilttest, Nitty-Gritty, and Soil Kit at 94%, 92%, 64%, 36%, and 33%. NO_3 was most accurately determined by Rapitest and Quick Soilttest, P_2O_5 by Rapitest, and pH by La Motte Soil Test Kit. K_2O was determined with equal accuracy by all but Soil Kit. The composition of the extractants may be an important factor affecting the accuracy of the test kit. For example, all kit extractants for K_2O were composed of the same chemical and matched analytical laboratory results 82% of the time. By contrast, kits using an acid-based extractant for NO_3 analysis more frequently matched the analytical laboratory results than kits using a zinc-based extractant ($P \leq 0.0001$). La Motte Soil Test Kit had the largest range of pH measures, whereas Rapitest was relatively easy to use and interpret and is a practical choice for home gardeners or landscapers; both were more than 90% accurate for this soil type. Although an important limitation of commercial test kits is the approximate or categorical value of nutrient content (i.e., low, medium, high), accurate test kits can yield results quickly and economically for improved nutrient management.

Soil testing is an important component of a plant nutrient management program and has been

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¹University of California Cooperative Extension, Ventura County, 669 County Square Drive, Suite 100, Ventura, CA 93003

²University of California, Davis, Agriculture and Natural Resources Analytical Laboratory, 207 Hoagland Hall, Davis, CA 95616

³Corresponding author. E-mail: ajdowner@ucdavis.edu.

standard practice for growers to aid in adjustment of fertilizer applications (Reisenauer, 1978). Soil testing is performed not only to improve plant

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
29.5735	fl oz	mL	0.0338
25.4000	inch(es)	mm	0.0394
1	ppm	$\text{mg}\cdot\text{kg}^{-1}$	1
4.9289	teaspoon(s)	cm^3	0.2029
$(^{\circ}\text{F} \div 1.8) + 255.37$	$^{\circ}\text{F}$	K	$(\text{K} - 255.37) \times 1.8$

growth, but also to reduce overapplication of fertilizers that may lead to nutrient toxicities, increased economic costs, and environmental pollution.

For maximum accuracy and benefit, soil testing must be conducted using reliable methods on correctly sampled soils [if the user is not trained in obtaining representative soil samples, test results, even from the same soil, can vary greatly (Voss, 1978)]. Test results must also be properly interpreted for a specific crop. Although interpretative guidelines are readily obtainable for many agronomic (Reisenauer, 1978) and horticultural crops and landscape trees (Bing et al., 1981), soil testing service is often available only through private laboratories in some states (in other states, the service is offered to private individuals by state cooperative extension offices). Cost for laboratory analysis for NO_3 , P_2O_5 , and K_2O was \$20 plus \$10 for pH per sample at the time of study (Agriculture and Natural Resources Analytical Laboratory, University of California, Davis) and results take ≈ 2 weeks. A local private laboratory charged \$20 per nutrient or pH test or \$68 per sample for a comprehensive test that included NO_3 , P_2O_5 , K_2O , and pH (Fruit Growers Laboratory, unpublished data).

By contrast, many retail garden centers offer commercial test kits ranging in cost from \$10 to \$50 for multiple tests (the range of prices paid in this study) so that the cost per test can be relatively low. Home testing kits are also advantageous because results can be obtained within 1 to 2 d. Commercial kits typically use a colorimetric method for indicating macro-nutrient and pH levels; soil is measured into a sample container, extractant is added, and after a specified time for the reaction, the user compares the color obtained with a color card corresponding to categorical nutrient and pH levels.

In this study, five commercially available test kits were compared with standard laboratory analysis of NO_3 ,

P_2O_5 , K_2O , and pH from the same soil type with three distinct cropping histories. The objectives were to identify differences in accuracy, if any, among test kits and to suggest a kit that most closely corresponds to analytical laboratory results.

Materials and methods

SOILS TESTED. A Salinas clay loam (fine-loamy, mixed, superactive, thermic Pachic Haploxerolls) was sampled near Santa Paula, Calif., in Sept. 2005 from three cropping areas containing impatiens (*Impatiens holstii*), cucumber (*Cucumis sativus*), and petunia (*Petunia ×hybrida*), herein referred to as soils 1, 2, and 3, respectively. Cropping areas were fertilized according to current recommendations. Soil from each area was sampled in triplicate with a shovel, oven-dried, and passed through a 2-mm sieve. Part of each sample was reserved for kit testing and the remainder was sent to an analytical laboratory. Standard laboratory procedures (Agriculture and Natural Resources Analytical Laboratory, University of California, Davis) were conducted for NO_3 (Knepel, 2003), P_2O_5 (Olsen and Sommers, 1982), exchangeable K_2O (Thomas, 1982), and pH (U.S. Salinity Laboratory Staff, 1954).

SOIL TEST KITS. Four of the kits, La Motte Soil Test Kit (La Motte Co., Chesterton, Md.), Rapitest (Luster Leaf Products, Woodstock, Ill.), Quick Soiltest (Hanna, Woonsocket, R.I.), and NittyGritty (La Motte Co., Chesterton, Md.) measured NO_3 , P_2O_5 , K_2O , and pH. The Soil Kit (La Motte Co.) measured only NO_3 , P_2O_5 , and K_2O . Kit results for macronutrients were categorical (high, medium, and low); pH results were numeric, rounding to half pH units for the Rapitest and one pH unit for the other three kits.

The manufacturers' instructions for each kit were followed for soil testing. Briefly, for the Quick Soiltest and the Rapitest, field soil was mixed with distilled water (1:5) for 1 min and was left to settle for 1 d. For the Quick Soiltest, 2.5 mL of the supernatant extract was shaken for 30 s with respective reagents to test for NO_3 and P_2O_5 . For the K_2O test, 0.5 mL of extract was shaken for 30 s with its respective reagent. The color of each solution was matched with its

respective test card. For the NO_3 test, the color was allowed to develop for 30 s before comparison. pH was measured by combining one-half teaspoon of soil, 3.0 mL of distilled water, and its reagent, shaking for 30 s and allowing color to develop for 5 min before comparing with its color card. For the Rapitest, the supernatant extract was added to the "test" and "reference" chambers of the respective proprietary testing box followed by its reagent in the testing chamber only. Color was allowed to develop for 10 min and compared with the semitransparent color chart attached to the front of the reference chamber for which the background was the reference supernatant. pH was measured by shaking one-half teaspoon of soil, the pH reagent, and distilled water and comparing it with the color chart after 1 min.

The extraction method for NittyGritty and Soil Kit was similar with proprietary tablets composed of organic and inorganic salts dissolved in distilled water before the addition of field soil. Tests were conducted with the supernatant extract and the respective reagents; after 3 to 5 min of color development (depending on the test), the solutions were compared with their respective color cards. For pH (NittyGritty only), the reagent was dissolved in 10 mL of distilled water before adding one teaspoon of soil. After 30 s of shaking and 1 min of settling, the solution was compared with its color card.

The LaMotte Soil Test Kit used a separate extractant for each test. Generally, 1 to 2 g of soil (depending on the nutrient test) was added to the respective extractant, which was shaken and settled for 1 min each. The supernatant was added to a new test tube along with the respective nutrient indicator; this was mixed gently for 30 s after which color was allowed to develop for 5 min before comparing it with the chart. For pH, 1.5 g of soil was added to an indicator before allowing 10 min for color development and comparison.

Each soil was tested three times for each test and interpreted by two observers independently but simultaneously. For color interpretation, Rapitest recommends daylight, but not direct sunlight, to illuminate the solution, whereas La Motte Soil Test Kit and Quick Soiltest specify the

light source to be located behind the user. The comparison card and the sample solutions were occasionally exposed to both 4100-K clear metal halide fluorescent background lighting (the room contained 16 elements of 32 W each) and outdoor daylight and the color interpretation did not change. Therefore, to use a consistent, uniform light source that mimicked daylight, visual colorimetric comparisons for all tests were made with background 4100-K metal halide fluorescent lighting.

COMPARING ANALYTICAL LABORATORY RESULTS WITH SOIL TEST KIT RESULTS. Analysis of variance was performed on the analytical laboratory results using the SAS GLM procedure (version 9.1; SAS Institute, Cary, N.C.) to verify the difference in nutrient content and pH of the soils tested. These numeric analytical laboratory results were converted to categories of low, medium, and high for comparison with the commercial test kit values (Table 1) based on the interpretive guide of Reisenauer (1978). The pH values from the analytical laboratory were rounded to the closest pH unit to compare with the test kit values.

χ^2 analysis was conducted by hand to compare the frequency of correspondence between the soil kit and analytical laboratory results for pH and each nutrient. Each statistical test compared the number of successes (a match between soil kit and laboratory results) and the number of nonmatches with the expected frequencies of each. In some cases, the nature of the commercial kits suggested further χ^2 tests based on the formulation of their extractants or the number of color choices on the

Table 1. The association of the categorical rating scale of commercial soil test kits (low, medium, high) to the quantitative amount of macronutrients measured by an analytical laboratory (Reisenauer, 1978).

Analysis ^z	Low	Medium	High
$NO_3\text{-}N$ ($\text{mg}\cdot\text{kg}^{-1}$) ^y	<25	25–60	>60
P_2O_5 ($\text{mg}\cdot\text{kg}^{-1}$)	<6	6–10	>10
K_2O ($\text{mg}\cdot\text{kg}^{-1}$)	<50	50–80	>80

^y $NO_3\text{-}N$, P_2O_5 , and K_2O are nitrate-nitrogen, Olsen-phosphorus, and exchangeable potassium, respectively.

^z1 $\text{mg}\cdot\text{kg}^{-1}$ = 1 ppm.

interpretative cards. According to the commercial kits, the soils were generally similar; frequencies for all soils were therefore pooled for these statistical tests (NO_3 for soil 2 was the exception but yielded similar statistical results when analyzed on its own compared with being pooled with the other soils; the results for NO_3 are therefore still presented as pooled soils). χ^2 tests also determined whether the differences in correspondence for a single commercial kit among the three soil types were the result of chance.

Results and discussion

The nutrient content and pH at the three soil locations were statistically distinct ($P \leq 0.001$; Table 2) based on the laboratory analysis, except the P_2O_5 content of soil 3, which was similar to soils 1 and 2 (Table 2). Once categorical values were assigned to the analytical laboratory results and pH was rounded to the nearest whole number for comparison with soil test kits results, however, the three soils were very similar (Table 2). Generally, the soils rated high (Table 1) for all nutrients, which probably resulted from prior cropping. Soil 2 had low to medium levels of NO_3 (Tables 1 and 2), probably because the nitrogen demands of cucumber were high after 3 months of growth. Additionally, NO_3 is the most active pool of soil nitrogen and changes constantly and relatively quickly; the static result may not accurately represent the soil NO_3 content.

pH results from LaMotte Soil Test Kit and Rapitest generally matched laboratory results, although Rapitest measured pH 6.5 for all tests regardless of the soil (Table 3). Soils 1 and 3 proved to be in the pH 6.5 range, but the pH of soil 2 was 7.8, technically beyond the capacity of Rapitest (pH 4.5 to 7.5). NittyGritty did not match laboratory results at all; the correspondence of Quick Soiltest results was intermediate (Table 3). Thus, the frequency of matching analytical laboratory results for pH depended on the soil kit used for all soils ($P \leq 0.05$; Table 4). The kits generally indicated lower pH values than the analytical laboratory.

Results from LaMotte Soil Test Kit, Rapitest, and Quick Soiltest generally matched the analytical laboratory results for NO_3 and P_2O_5 ,

Table 2. Macronutrient content and pH of Salinas clay loam with three crops measured by the Agriculture and Natural Resources Analytical Laboratory, University of California, Davis^a.

Analysis ^b	Soil 1: Impatiens		Soil 2: Cucumber		Soil 3: Petunia	
	Mean \pm SE	CV	Mean \pm SE	CV	Mean \pm SE	CV
pH	6.9 \pm 0	7	7.8 \pm 0	8	7.2 \pm 0	7
$\text{NO}_3\text{-N}$ ($\text{mg}\cdot\text{kg}^{-1}$) ^c	365 \pm 9	H ^w	24 \pm 2	L-M	188 \pm 19	H
P_2O_5 ($\text{mg}\cdot\text{kg}^{-1}$)	103 \pm 2	H	83 \pm 5	H	94 \pm 1	H
K_2O ($\text{mg}\cdot\text{kg}^{-1}$)	1310 \pm 11	H	632 \pm 16	H	1080 \pm 30	H

^aMean values of three samples. The categorical value (CV) was assigned for comparison with commercial test kit values (pH was rounded to the nearest whole number).

^b $\text{NO}_3\text{-N}$, P_2O_5 , and K_2O are nitrate-nitrogen, Olsen-extractable phosphorus, and exchangeable potassium, respectively.

^c1 $\text{mg}\cdot\text{kg}^{-1}$ = 1 ppm.

^wH, M, and L are high, medium, and low, respectively, derived from Reisenauer, 1978 (Table 1).

SE = standard error.

Table 3. Commercial soil test kit results for Salinas clay loam soil with three crops.

Kit ^a	Analysis ^b	Soil 1: Impatiens		Soil 2: Cucumber		Soil 3: Petunia		
		Kit results ^x	F _m ^w	Kit results	F _m	Kit results	F _m	
Rapitest	pH	6.5, 6.5, 6.5	3	6.5, 6.5, 6.5	0	6.5, 6.5, 6.5	3	
	NO_3	H, H, H	3	M, M, M	3	H, H, H	3	
	P_2O_5	H, H, H	3	H, H, H	3	H, H, H	3	
	K_2O	H, H, H	3	H, H, H	3	H, H, H	3	
Quick Soiltest	pH	5.0, 5.0, 7.0	1	6.5, 6.5 ^{v, u}	0	6.5, 6.5 ^{v, u}	2	
	NO_3	H, H, L	2	L, L, L	3	H, H, L	2	
	P_2O_5	H, H, H	3	H, H, H ^v	3	H, H, H	3	
	K_2O	H, L, L	1	M, M, M	0	H, H, H	3	
La Motte	Soil Test Kit	pH	7.0, 7.0, 7.0	3	8.0, 8.0, 8.0	3	6.5, 7, 7	3
		NO_3	H, H, H	3	L, L, L	3	H, H, H	3
		P_2O_5	H, M, L	1	H, H, H	3	H, H, H	3
		K_2O	H, H, H	3	H, H, H	3	H, H, H	3
Soil Kit ^t	NO_3	L, L, L	0	L, L, L	3	M, M, L	0	
	P_2O_5	M, M, M	0	M, M, M ^v	0	M, M, M	0	
	K_2O	M, M, M	0	H, H, H	3	H, H, H	3	
NittyGritty	pH	5.0, 6.0, 6.0	0	5.0, 6.0, 6.0	0	5.0, 6.0, 6.0	0	
	NO_3	M, L, M	0	L, L, L	3	H, M, L	1	
	P_2O_5	M, M, M	0	M, M, M	0	M, M, M	0	
	K_2O	H, H, H	3	H, H, H	3	H, H, H	3	

^aRapitest (Luster Leaf Products, Woodstock, Ill.), Quick Soiltest (Hanna, Woonsocket, R.I.), La Motte Soil Test Kit, Soil Kit, and NittyGritty (La Motte Co., Chesterton, Md.).

^b $\text{NO}_3\text{-N}$, P_2O_5 , and K_2O are nitrate-nitrogen, phosphorus, and potassium, respectively.

^xH, M, and L are high, medium, and low, respectively, derived from Reisenauer, 1978 (Table 1).

^wThree tests for each soil and nutrient/pH were conducted. The frequency that the soil test kits results matched analytical laboratory results (F_m), ranging from 0 (no test soil kit results matched laboratory results) to 3 (all soil kit results matched laboratory results), is presented in a separate column.

^vOccasionally a test yielded no interpretable result.

^uObservers independently interpreted results differently in at least two of the three tests; the higher categorical value was used.

^tSoil Kit did not test pH.

whereas Soil Kit and NittyGritty did not (Table 3). The frequency of correspondence between the laboratory and commercial test kits depended on the kit used in most cases ($P \leq 0.05$; Table 4). Test kits did not account for differences in correspondence for NO_3 in soil 3 ($P \geq 0.05$; Table 4), probably because NittyGritty and Soil Kit had few matches with

analytical laboratory readings (Table 3). The frequency of matching may have depended on the use of an acid-based extractant for NO_3 (LaMotte Soil Test Kit, Rapitest, and Quick Soiltest) rather than a zinc-based one (Soil Kit and NittyGritty) ($P \leq 0.0001$; Table 5). There was no statistical difference in frequency of matching among kits using an

Table 4. Probability values and test statistics (TS) for χ^2 analysis derived from the observed frequency of matching between commercial test kits [Rapitest (Luster Leaf Products, Woodstock, Ill.), Quick Soiltest (Hanna, Woonsocket, R.I.), La Motte Soil Test Kit, Soil Kit, and NittyGritty (La Motte Co., Chesteron, Md.)] and analytical laboratory results compared with the expected frequency of a match on Salinas clay loam soil with three crops.

Analysis ^z	Soil 1: Impatiens		Soil 2: Cucumber		Soil 3: Petunia	
	P ≤	TS ^y	P ≤	TS	P ≤	TS
pH	0.05	9	0.01	12	0.05	10
NO ₃	0.0001	17	0.0001	17	NS	9
P ₂ O ₅	0.001	12	0.0001	15	0.0001, 0.0001 ^x	24, 18
K ₂ O	0.001	12	0.0001	15	N/A ^w	

^zNO₃-N, P₂O₅, and K₂O are nitrate-nitrogen, phosphorus, and potassium, respectively.

^yTest statistics are included for each test to illustrate how each P-value was derived. The df for each test = 4, except for pH tests = 3.

^xP₂O₅ content in soil 3 was found to be equal to soil 1 and 2; results are pooled tests of soils 1 and 3 and soils 2 and 3, respectively.

^wN/A, not applicable for soil 3, 100% of the commercial kit results matched those of the analytical laboratory for K₂O.

^{NS}Nonsignificant at P ≤ 0.05.

Table 5. Probability values, test statistics (TS) and df for χ^2 analysis derived from the observed frequency of matching between commercial test kits [Rapitest (Luster Leaf Products, Woodstock, Ill.), Quick Soiltest (Hanna, Woonsocket, R.I.), La Motte Soil Test Kit, Soil Kit, and NittyGritty (La Motte Co., Chesteron, Md.)] and analytical laboratory results for Salinas clay loam soil.

Analysis ^z	P ≥	TS ^y	df
pH (four commercial kits) ^x	0.0001	20	4
NO ₃ (all commercial kits)	0.0001	27	4
Kits using acid-based extraction ^w versus zinc-based ^v	0.0001	27	1 ^u
Kits with four or more colorimetric chart choices ^w versus three ^v	0.0001	27	1 ^u
Acid-based kits only ^w	NS	6	2
P ₂ O ₅ (all commercial kits)	0.0001	29	4
Kits without isoascorbic acid extractant ^w versus with ^v	0.0001	24	1 ^u
Kits with four or more colorimetric chart choices ^w versus three ^v	0.0001	24	1 ^u
Kits without isoascorbic acid only ^w	NS	4	2
K ₂ O (all commercial kits)	0.01	11	4
Kits with three or more extractant components ^w versus two or less ^v	NS	2	1

^zNO₃-N, P₂O₅, and K₂O are nitrate-nitrogen, phosphorus, and potassium, respectively.

^yTest statistics are included for each test to illustrate how each P value was derived. In some cases, single df χ^2 tests were suggested by the formulation of the respective extractants of the commercial kits.

^xRapitest, Quick Soiltest, La Motte Soil Test Kit, and NittyGritty.

^wRapitest, Quick Soiltest, and La Motte Soil Test Kit.

^vNittyGritty and Soil Kit.

^uThese comparisons grouped the same test kits and therefore resulted in the same P value and TS.

acid-based extractant for NO₃ ($P \geq 0.10$; Table 5), indicating that regardless of the acid type, these extractants were equally effective.

For P₂O₅, the commercial kits with results that least matched the analytical laboratory used extractants with isoascorbic acid (Soil Kit and NittyGritty) ($P \leq 0.0001$; Tables 3 and 5). This ingredient may have reduced the P₂O₅ extractant potential compared with the other ingredients found in kits with a higher frequency of matches. For example, the P₂O₅ extractants for LaMotte Soil Test Kit, Rapitest, and Quick Soiltest were composed of multiple ingredients but

did not contain isoascorbic acid; there was no difference in the frequency of matching among these three kits ($P \geq 0.10$; Table 5).

Although these differences may be related to the methods of extraction rather than the composition of the extractants, Soil Kit, NittyGritty, and LaMotte Soil Test Kit had similar extraction methods with the La Motte Soil test kit yielding results most frequently matching analytical laboratory testing. Another factor affecting correspondence (i.e., matching) to laboratory results may be the result of the degree of color gradation on the colorimetric cards used for

interpreting results. The tests with minimal correspondence had only three color choices for NO₃ and P₂O₅ content (whereas the others had four or more ($P \leq 0.0001$; Table 5)). This level of precision may also relate to the use of more effective extractants for LaMotte Soil Test Kit, Rapitest, and Quick Soiltest.

Soil Kit and NittyGritty analyzed K₂O content with greater accuracy than for the other nutrients; the commercial tests in total corresponded with the analytical laboratory 82% of the time for this test. For soil 3, 100% of the commercial test results matched those of the analytical laboratory results (Table 3). For soils 1 and 2, Quick Soiltest and Soil Kit varied, whereas the other tests consistently matched the analytical laboratory (Table 3). In fact, the differences in correspondence for Quick Soiltest among all three soils was the result of chance (test statistic = 6 with 2 df, $P \geq 0.05$). Furthermore, there was no difference between test extractants using multiple ingredients compared with two ingredients ($P \geq 0.10$; Table 5) probably because all were based on sodium tetraphenyl boron or sodium tetraphenyl borate; this uniformity in extractant composition, in contrast to the variety of ingredients used in tests for other nutrients, probably resulted in better correspondence among the test kits and with the analytical laboratory results.

Precautionary measures for these commercial kits may increase their accuracy. For Soil Kit and NittyGritty, the extracting powders that came with the kits dissolved poorly; these kits generally yielded inaccurate results, but pulverizing the tablets or powders may increase extraction potential. Interpretation of color development should be made only within the time specified by the kit instructions because color intensity could vary within minutes. The source of light could potentially influence color interpretation, which is briefly mentioned in the instructions for Rapitest, La Motte Soil Test Kit, and Quick Soiltest, but not for Soil Kit and NittyGritty. In this investigation, the comparison card and the sample solution varied similarly when exposed to 4100-K clear metal halide fluorescent lighting and occasionally to outdoor daylight; the color interpretation did not change. However,

when the solutions were occasionally compared with 6200-K "daylight" fluorescent backlight, the color of both the solution and card was different from the color under 4100-K fluorescent lighting and natural daylight. These differences stress the importance of using a uniform light source when interpreting reaction color. Interpretation can occasionally vary depending on the user. In this study, the observers independently interpreted the same result for 91% of the tests; this would probably be an acceptable proportion for a home gardener or farmer individually conducting tests, but occasional independent interpretation by another source may change the result. Finally, these results were obtained using one soil type; variation in accuracy may occur when testing other soils.

La Motte Soil Test Kit results corresponded to those from the analytical laboratory for pH and all nutrients (94% of the tests matched). This kit is suitable for growers, cooperative extension personnel, and university-level laboratory classes because it proved to be accurate over a wide pH range. The individual extractants and indicators for each test, although accurate, may be cumbersome for the home gardener, however. Rapitest yielded accurate results 92% of the time for all nutrients and pH less than 7.5 and was comparatively

easy to use and interpret with color-coded extractants and test boxes and instructions in large print on stiff paperboard; this kit would be a good choice for the home gardener. Quick Soiltest matched the analytical laboratory results 64% of the time because K₂O and pH results did not match those obtained from the laboratory analysis. Soil Kit and NittyGritty were unable to reproduce laboratory analysis findings for P₂O₅ in any soil. Because some kits underestimate nutrient concentrations, overapplications of fertilizer could result from their use.

An important limitation of all commercial test kits is the approximate or categorical value of nutrient levels into broad categories of low, medium, or high. Analytical laboratories must be used when precise nutrient levels or interpretation are required. Nevertheless, commercially available kits such as Rapitest and La Motte Soil Test Kit were 92% and 94% accurate, respectively, for the soils tested and are a fast and economic means by which farmers, home gardeners, and agricultural service personnel can improve nutrient management for crop production and environmental protection.

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