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Iron oxide-impregnated filter paper (P_i test): II. A review of its application

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Abstract

The iron oxide impregnated filter paper test (P_i test) is a recently developed soil test for phosphorus (P) in which the FeO paper acts as an infinite sink for P mobilized in a soil solution. Several papers have been published evaluating the effectiveness of the test for predicting plant availability of P under different soil conditions. The use of FeO paper to predict algal availability of P in water bodies and runoffs has also been studied.

The purpose of this paper is to review studies on the use of the P_i test to evaluate plant availability of P in soils, and predict availability of P to algae in an aquatic environment. Phosphorus extracted by the FeO paper is primarily physically bound extractable (resin P) and correlates significantly with Bray I and Mehlich P in acid soils and Olsen P in calcareous soils. Dry-matter yield and P uptake by maize (*Zea mays* L), kidney beans (*Phaseolus vulgaris* L), and upland rice (*Oryza sativa* L) grown in acidic soils correlated well with P_i-P. Likewise, in calcareous soils, P_i-P was as good as Olsen-P in predicting crop response. Field trials have shown that the P_i test is a good predictor of plant yield in soils with wide ranging properties. Compared to the standard method to measure bioavailable P to algae in waters and agricultural runoffs involving lengthy algal essays culturing selenastrum capricornutum with sediment samples, the P_i method is a faster and easier method to estimate P that may be potentially available for uptake by algae.

Introduction

A good soil test for evaluating plant availability of nutrients is one that reflects response of a large variety of crops to nutrient application, works on different soils, and is accurate, reproducible, and simple. While the accuracy, simplicity and reproducibility of the test are evaluated in the laboratory, the efficiency of the test to reflect the nutrient uptake of crops is evaluated using potted plants under controlled conditions in the greenhouse. This is followed by field evaluations. A test which correlates well with plant response in the greenhouse is likely to do so in the field also.

The recently developed iron oxide (FeO) impregnated filter paper (P_i test) has the potential for use as a good soil test to assess P availability in soils. It is simple to use, is accurate, and is independent of the type of soil. The test makes use of paper strips impregnated with iron oxides (P_i strips) as a sink for P mobilized in a soil solution. The principles of the test and the methodology involved in the preparation and use of the strips are described in the article by Chardon et al. (1996). The purpose of this paper is to summarize data from published reports on the effectiveness of the test in evaluating extractable P from soils as compared to that by other soil tests and the ability of the test to predict P availability to various crops under different soil conditions. The use of the test in estimating P in water bodies and bioavailability of P in runoffs to algae are also discussed.

Evaluation of the P_i Test

It is customary to evaluate the efficacy of a new soil test by:

Correlating the quantity of nutrient measured by the test from a broad variety of soils with that estimated by proven soil tests;

Correlating the amount of nutrient measured by the test with crop yield and nutrient uptake by a number of crops grown on different soils under controlled conditions in the greenhouse; and

Correlating soil test values with crop response under field conditions.

Laboratory evaluations

A number of studies have been reported comparing the amount of P measured by the P_i test with that by other soil tests routinely used to measure bioavailability of P.

Menon et al. (1990) extracted P from 18 soils with widely ranging properties using P_i, Bray I and II (Bray and Kurtz, 1945), Mehlich I (Nelson et al., 1953) and Olsen (Olsen et al., 1954) tests. The amount of P measured by the P_i test was about the same as that by the Olsen test. Acid extractants on the other hand, extracted considerably larger amounts of P. Phosphorus extracted by the FeO paper correlated significantly with P extracted by other reagents. P_i-P correlated best with Olsen-P ($r = 0.95^{xx}$) and Bray I-P ($r = 0.89^{xx}$); correlation with Bray II-P, though significant, was less in magnitude. With Mehlich I-P correlation was not significant in these soils (Table 1). Both Bray II and Mehlich I reagents are strongly acidic and they can overestimate available P from soils having CaP minerals. Therefore, correlations between P_i-P and Bray II or Mehlich I-P are not as good as with other tests.

Similar results were reported by Sharpley (1991). Sharpley studied the relationship between P_i-P, Olsen-P, Bray I-P, resin-P (Sibbesen, 1978) and Mehlich III-P (Mehlich, 1984) on 203 surface soils from the United States, Indonesia, Malaysia, Papua New Guinea, The Philippines, and the Sudan. The soils were grouped into calcareous ($n = 56$), slightly weathered ($n = 80$) and high weathered, based on taxonomy and weathering. Amounts of P_i-P and Olsen-P in calcareous soils were closely related. Similar amounts of P were extracted by both methods, as indicated by the regression slope of 1.01. For the other two groups of soils, correlation was not as close. For both calcareous and noncalcareous soils, Bray I-P and P_i-P showed good correlation at >0.001 level. Greater amounts of P were extracted by Bray I than FeO strips with increase in the degree of weathering. The amount of P extracted by P_i and Mehlich III were closely correlated for noncalcareous soils, but not for calcareous soils (Table 2). As with the Bray I procedure, Mehlich III extracted more P from slightly weathered and highly weathered soils than the P_i procedure. P_i-P was closely correlated to resin P for each group of soils and similar amounts of P were extracted by each procedure. Sharpley correlated P_i-P with different P fractions in the soil and concluded that FeO strips dissolved primarily physically bound P (anion exchange resin P) with little extraction of amorphous Al, Fe, or Ca compounds. As the P_i test was very closely related to the different P tests on soils on which the use of the test is recommended, and with resin-P for the 203 soils used in the study, Sharpley suggested that the FeO paper may extract P closely related to plant availability of P for soils with widely ranging properties.

Ibrikci et al. (1992) analyzed soil samples from fields fertilized with increasing levels of superphosphates using Mehlich II, Mehlich III, resin, P_i, and water extraction methods. Phosphorus extracted by all the reagents increased with increase in the application of P fertilizer. Resin and P_i tests were the most sensitive, water least sensitive, and Mehlich I and III intermediate in sensitivity to reflect the increase in soil P resulting from fertilizer application. P_i-P correlated best with resin-P ($r^2 = 0.96^{xx}$). The next best correlation was with Mehlich III-P ($r^2 = 0.72^{xx}$) followed by Mehlich I-P ($r^2 = 0.65^{xx}$).

The close correlation between P_i-P and resin-P was also demonstrated by Leal et al. (1994) who evaluated available P from 32 Guatemalan soils which included Andasols with recent volcanic ash depositions. Though there was good correlation between all soil test methods on soils that did not have recent ash influence, in soils with ash depositions containing apatite, Bray I and Mehlich reagents dissolved Ca-P compounds and overestimated available P. The P_i and resin methods were more appropriate in estimating available P in soils, irrespective of their properties. The authors concluded that the P_i and resin tests can be adopted for fertilizer recommendations in Guatemala.

The close relationships between P measured by the P_i test and that by various other soil tests for soils on which the use of the test is recommended has also been reported by Van der Zee et al., 1987; Yli-Halla, 1991; Lin et al., 1991; Kumar et al., 1992; Bolland et al.,

Table 1. Correlation coefficient (r) for different methods of extracting P from 18 soils.

Method	P_i	Olsen	Bray I	Bray II	Mehlich I
P_i	-	0.95**	0.89**	0.56*	0.41 NS
Olsen	0.95**	-	0.89**	0.49*	0.31 NS
Bray I	0.89**	0.89**		0.41 NS	0.25 NS
Bray II	0.56*	0.49*	0.41 NS		0.98**
Mehlich I	0.41 NS	0.31 NS	0.25 NS	0.98**	-

* Significant at 0.05 probability level.
** Significant at 0.01 probability level.
NS = Not significant.
Source: Menon et al. (1990a).

Table 2. Correlation between P extracted by paper strips and P extracted by other soil test.

	Correlation coefficient (r^2)		
	Calcareous soils	Slightly weathered soils	Highly weathered soils
	n = 56	n = 80	n = 67
P_i-P versus:			
Olsen P	0.89***	0.38***	0.63***
Bray I P	0.87***	0.82***	0.89***
Mehlich III P	0.44**	0.84***	0.92***
Resin P	0.92***	0.90***	0.87***

Significant at 0.01 (**) and 0.001 (***) levels.
Source: Sharpley (1991).

1992; Menon, 1992; Monem and Gadalla, 1991; Kuo and Jellum, 1994; and others.

Greenhouse evaluations

Greenhouse studies have shown that phosphorus measured by the P_i test correlates well with dry-matter yield and P uptake by different crop species grown on soils fertilized with traditional water-soluble P fertilizers as well as phosphate rock (PR) based fertilizers.

Performance of the P_i test in soils fertilized with water-soluble fertilizers

Yli-Halla (1990) grew four successive crops of Italian rye grass (*Lolium multiforum, Lam*) on 32 cultivated soils in Finland and correlated P uptake with P extracted by water (Pw), ammonium acetate (0.5 m)-acetic acid (0.5 m) mixture (PAAAc), and the P_i test. Phosphorus extracted by all three methods predicted P uptake by rye grass accurately, the correlation coefficient (r) ranging from 0.88^{xxx} to 0.93^{xxx}. However, in soils with low P contents, P uptake by rye grass correlated more closely with P_i ($r = 0.87^{xxx}$) than Pw ($r = 0.57^{x}$) or PAAAc ($r = 0.64^{xx}$). The author suggested that Pw and PAAAc are measures of P intensity (i.e., P concentration in soil solution) and do not express the size of the capacity factor (i.e., absolute quantity of plant-available P). In contrast, P_i-P is supposed to be the actual amount of reversibly adsorbed P (Van der Zee et al., 1987) and is probably more closely related to the capacity factor.

These results were confirmed in another experiment in which Yli-Halla (1991) compared the suitability of different soil tests in evaluating the residual effects of repeated applications of P fertilizers. Soil samples were collected from an 11 year field experiment in which 0, 154, 309, 541, or 686 kg P/ha had been applied in annual doses. Half of the field had been limed twice with 10 tonnes/ha $CaCO_3$. In a pot experiment, six yields of Italian rye grass were grown in soils taken from each plot. In the unlimed soils (pH 5.8 to 6.1), the quantities of P extracted by Pw, PAAAc, and P_i correlated closely with P uptake by plants throughout

Table 3. Linear regressions for soil P extracted by different methods vs. dry-matter yield and P uptake of maize.

Phosphorus extracted (X)	Dry-matter yield (Y)	r	P uptake (Y)	r
Pi	Y = 0.52 + 0.26X	0.88**	Y = 2.41 + 0.61X	0.94**
Olsen	Y = 1.52 + 0.24X	0.78**	Y = 0.88 + 0.60X	0.90**
Bray I	Y = 2.52 + 0.10X	0.68**	Y = 0.89 + 0.29X	0.86**
Bray II	Y = 3.92 + 0.02X	0.40 NS	Y = 5.22 + 0.06X	0.46*
Mehlich I	Y = 4.70 + 0.02X	0.26 NS	Y = 7.19 + 0.05X	0.31 NS

* Significant at 0.05 probability level.
** Significant at 0.01 probability level.
NS = Not significant.
Source: Menon et al. (1990a).

the experiment. In the limed soils (pH 6.4 to 7.1), Pw and PAAAc methods did not predict P uptake as accurately as P_i did. When the data for limed and unlimed soils were pooled, the P_i method was more closely (P = 1%) correlated (R = 0.95^{xxx}) with P uptake than were those of Pw (r = 0.78^{xxx}) and PAAAc (r = 0.78^{xxx}). The authors concluded that the P_i method appeared to be well suited for assessment of potentially available P reserves in both limed and unlimed soils in Finland.

Similar results were reported by Lin et al. (1991) in Taiwanese soils. Phosphorus uptake by wheat seedlings grown on 39 soils collected from major agricultural areas of Taiwan correlated equally well with P measured by the P_i test (r = 0.842^{xxx}), resin test (r = 0.828^{xxx}), Olsen test (r = 0.829^{xxx}) and water (r = 0.818^{xxx}) at 1% level. Correlation with Bray I-P and Mehlich I-P were less in magnitude. The authors concluded that for Taiwan, soils containing moderate amounts of P, Bray I, and Mehlich I, tests are not suitable, but the P_i method was applicable and the results are comparable with those obtained by Olsen and anion exchange resin methods.

The use of the P_i test in evaluating P availability in soils with widely differing properties was further demonstrated by several others. Menon et al. (1990a) found that biomass yield of maize grown on 18 soils widely differing in properties correlated significantly with P_i-P, Olsen-P, and Bray I-P, but not with Bray II-P or Mehlich I-P (Table 3). In another study involving a large number of soils, Menon (1992) reported that in soils with pH less than 7.0, correlation between dry-matter yield or P uptake of maize was highest with P measured by the P_i test followed by that with the Olsen test, Bray I test, and Mehlich I test. In soils with pH over 7.0, both the P_i test and Olsen test worked equally well (Table 4).

Table 4. Correlation between P extracted by P_i strips and P extracted by other tests.

	Correlation Coefficient, (r)	
	Soils with pH <7.0	Soils with pH >7.0
P_i-P versus Olsen-P	0.97**	0.95**
P_i-P versus Bray I-P	0.94**	0.87**
P_i-P versus Mehlich I-P	0.89**	0.74**

** Significant at 0.01 level.
Source: Menon (1992).

In the highly calcareous soils of Egypt, the P_i test was as good or better than the Olsen test in predicting plant response. Monem and Gadalla (1992) reported that dry-matter yield of maize grown on 10 Egyptian soils with $CaCO_3$ content ranging from 2.9% to 50.0% correlated equally well with the P_i test and Olsen-P test. The authors concluded that the P_i test is a reliable test for plant- available P in Egyptian soils, and for maize, 6 μg P/strip is the critical level when the P_i test was used.

Though the P_i test and Olsen test correlated well with maize yields, tissue P concentration, and P uptake, Kuo and Jellum (1994) did not see much advantage of the P_i test over the Olsen test in describing maize response to increasing P availability in some acid soils with different P sorption capacities.

Performance of the P_i test in soils where phosphate rock based fertilizers are used

Traditional soil tests may not be suitable for evaluating bioavailability of P in soils fertilized with phosphate rock (PR) based fertilizers because they involve the use of extracting solutions which react with the soil and extract part of the P which under natural conditions may not be available for plant use. Furthermore, the dissolution of the PR in the soil is greatly influenced by soil properties, especially soil acidity. In comparing the effectiveness of various soil tests, Yost et al. (1982) found that Mehlich I extractant overestimated available P in soils fertilized with PR while Bray I and Olsen tests gave a better measure of P availability. Barnes and Kamprath (1975), however, reported that maize yield obtained with a given level of Bray I-P with PR was higher than that with superphosphates indicating that Bray I underestimated available P from PR with respect to TSP. On the other hand, Chien (1978) and Bolland et al. (1994) reported that the Bray I test overestimated P availability from soils fertilized with PR, and Mackay et al. (1984) found that the Olsen reagent did not perform well in PR treated soils. Several others have reported that conventional soil tests are not suitable for evaluating P availability in soils fertilized with PR and modified PR products (Conforth et al., 1983; Gregg et al., 1981; Rajan, 1982).

The P_i test has a potential for use in soils fertilized with PR and modified PR products such as partially acidulated PR (PAPR), and compacted mixtures of PR and soluble phosphates. Menon et al. (1989a) found that on three acidic and one calcareous soils preincubated with TSP or Central Florida PR, P extracted by the various soil tests was significantly affected by the type of fertilizer used. Both dry-matter yield and P uptake by two successive crops of maize correlated significantly with P measured by all the tests used. Though the correlation coefficient (r) between yield, P uptake, and P measured by the P_i test differed from soil to soil, the r value for the P_i was not lower than that for the Olsen or Bray I tests. Across all soils, crops, and fertilizers used, correlation between dry-matter yield or P uptake was best with P_i-P and was in the order P_i > Olsen > Bray I > resin > Bray II > Mehlich I (Table 5)

Table 5. Correlation coefficient (r) between dry matter and P uptake, and P extracted by soil tests with two P fertilizers.

Soil test	Dry-matter yield	P uptake
P_i	0.837***	0.870***
Bray I	0.666**	0.737***
Bray II	0.412**	0.491***
Mehlich I	0.354**	0.410**
Olsen	0.781***	0.814***
Resin	0.648***	0.623***

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
Source: Menon et al. (1989a).

Kumar et al. (1992) however, noted that in West Australian soils fertilized with PRs, the effectiveness of the P_i test in predicting yields of crops was not consistent. They evaluated the effectiveness of various soil tests in predicting the yield of maize, wheat (*Triticum aestivum*), and lettuce (*Laetuca sativa*) grown on two acid, sandy soils fertilized 6 years previously with superphosphate and three PRs. The P_i and ammonium oxalate tests were the most predictive tests in the more acid soil (pH 4.6) where as Bray I and Colwell (1963) tests were the most predictive for the less acid soil (pH 6.5). Bray II, Truog, and anion exchange resins were very poor predictors of yield in both soils.

The effectiveness of various soil tests in predicting crop response in soils fertilized with PAPR will be different from that from soils fertilized with PR, as PAPR contains both water- soluble P from the monocalcium phosphate (MCP) formed from the acidulation of PR, and the unacidulated PR. Menon et al. (1989b) have shown that the P_i test is a good predictor of plant availability of P in soils fertilized with PAPR. In an acid soil (pH 4.8) fertilized with PAPR prepared from PR from seven locations in Africa and Latin America, both dry-matter yield and P uptake of maize correlated better with P_i-P than with Bray I-P (Figure 1) indicating that

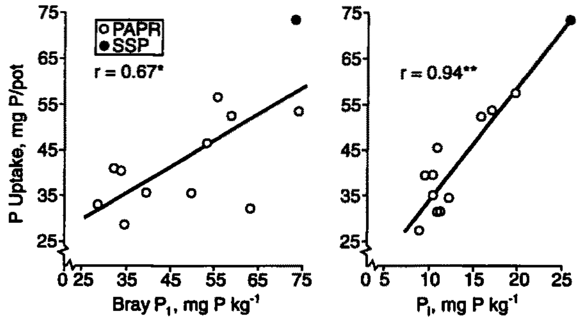

Figure 1. Phosphorus uptake by maize as related to P extracted by Bray I and FeO-paper (P_i) from soils treated with PAPR and SSP (Menon et al., 1989b).

Table 6. Correlation coefficient (r) between total P uptake by bean and rice and P extracted by the Bray P-I and P_i soil tests from soils treated with different P sources.

Fertilizer	Bean		Rice	
	P_i	Bray I	P_i	Bray I
Capinota phosphate rock (PR)	0.82**	0.59*	0.65*	0.73**
Compacted Capinota PR plus triple superphosphate TSP	0.91**	0.94**	0.84**	0.83**
Capinota partially acidulated PR (PAPR)	0.57**	0.69*	0.89**	0.94**
Huila PR	0.75**	0.88**	0.97**	0.83**
Compacted Huila PR plus TSP	0.91**	0.97**	0.84**	0.89**
Huila PAPR	0.93**	0.95**	0.86**	0.91**
TSP	0.88**	0.87**	0.78**	0.85**
All P sources	0.77**	0.79**	0.76**	0.77**

* ** Significant at P = 0.05 and 0.01, respectively.
Source: Menon et al. (1991b).

Table 7. Correlation between dry-matter yield and P uptake of maize and P extracted by different soils tests from 58 soils.

Soil Test	Correlation coefficient, (r)			
	Soils with pH <7.0		Soils with pH >7.0	
	Dry-matter yield	P uptake	Dry-matter yield	P uptake
P_i	0.72**	0.75**	0.86**	0.93**
Olsen	0.69**	0.73**	0.73**	0.80**
Bray I	0.65**	0.68**	–	–
Mehlich	0.49**	0.55**	–	–

** Significant at 0.01 level.
Source: Menon (1992).

the Bray I test was less effective than the P_i test in evaluating P availability from PAPR.

However, in another study evaluating the agronomic effectiveness of PAPR versus compacted mixtures of PR and TSP for kidney beans (*Phaseolus vulgaris*) and upland rice (*Oryza sativa*) grown in an acid silt loam, both P_i-P and Bray I-P correlated equally well with P uptake by rice as well as beans when all the data were pooled (Menon et al., 1991b).

Butegwa et al. (1996a, b) on the other hand found that when PR from Sukulu Hills of Uganda was applied as PR, PAPR, or compacted mixtures of PR and TSP to an acidic soil with high sorption capacity, the P_i test was the best in predicting yield of maize. The Mehlich 1 test was least correlated with dry-matter yield and P uptake of maize.

In calcareous soils fertilized with PAPR or mixtures of PR and soluble phosphates, the ability of various tests to predict crop response will be different than that in acid soils. Menon et al. (1991a) applied PR from Togo, Togo PAPR, and superphosphates to calcareous Vernon clay preincubated with KH_2PO_4 to vary extractable P to different levels. In these soils, P_i-P showed very high correlation with Olsen-P (Figure 2). In soils fertilized with PAPR or superphosphates, dry-matter yield of maize and P uptake correlated equally well with P_i-P and Olsen-P (Figure 3). This is because PRs are ineffective in calcareous soils and when PAPR or compacted mixtures of PR and soluble P are applied to calcareous soils, availability of P is governed by the soluble P content of the fertilizer used. In such cases, both the P_i and Olsen tests should be equally effective in predicting crop response.

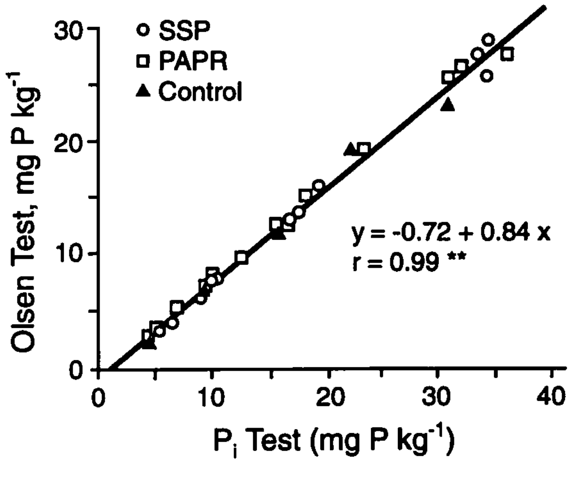

Figure 2. Correlation between P extracted by FeO-paper (P_i) and Olsen test from soils treated with SSP or PAPR (Menon et al., 1991a).

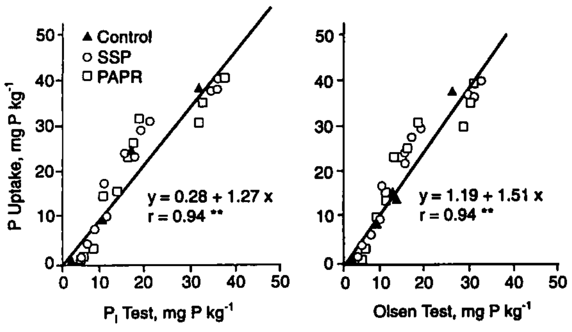

Figure 3. Correlation between P extracted by FeO-paper (P_i) and Olsen tests and P uptake by maize (Menon et al., 1991a).

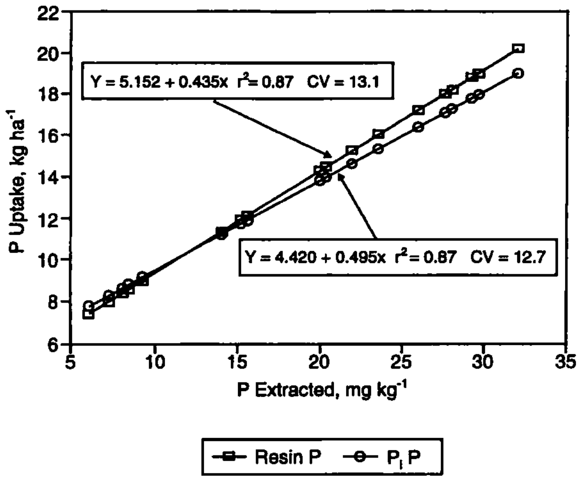

Figure 4. Relation of values of soil extractable P, using resin and FeO-paper (P_i) extractants, and P uptake by bahiagrass (Ibrikci et al., 1992).

Field studies

Most of the published work on the P_i test relates to investigations carried out in the laboratory and greenhouse. Information about the relationship between P_i-P and crop response in the field is very scarce. Ibrikci et al. (1992) studied the effectiveness of the P_i and other soil P tests in predicting the yield of bahia grass (*Paspalum notanum L*) in fields which did not respond to P applications though the preplant Mehlich I test indicated very low extractable P. Analysis of the soil samples revealed that the P_i and resin tests gave higher extractable P values than Mehlich I, Mehlich III, and water extraction methods. There was a high correlation between P_i-P and resin-P (r^2 = 0.96). Uptake of P by bahia grass increased linearly with increasing P rates and calibrated better with P_i-P (r^2 = 0.87) and resin-P (r^2 = 0.87) (Figure 4). The authors concluded that P_i extractant was the most sensitive to P applications.

Kumar et al. (1994) evaluated the P_i test in three field experiments on lateritic soils in Southwest Australia fertilized with TSP and two PRs. They correlated the yield of triticale (*Trilicosecale*), oats (*Avena sativa*), barley (*Hordeum vulgare*), or subterranean clover (*Trifolium subterraneum*) with P measured by P_i, Colwell, Bray I, calcium lactate (CAL), and Truog soil tests. For each soil test and plant species, the relationship between yield and soil test P differed with fertilizer type and year. Though the P_i test provided the best prediction of plant yield in one soil in 1 year, for combined data for all the sites, the CAL soil test was a better predictor of plant yield. Next best were the P_i and Colwell tests which were almost equally predictive of plant yield.

Bolland et al. (1994) also reported similar results for lupins (*Lupinus angustifolius*) and rape seed (*Brassica napus*), barely, oats, and triticale in two field experiments conducted in the same area in Southwest Australia.

Use of FeO-paper in other applications

The FeO-paper method has been used as a tool to study P kinetics in soil minerals and bioavailable P in soil surface runoff in relation to potential eutrophication problems. Monitoring of P concentration in soil solution and aquatic environments, e.g., rivers, lakes, etc., may also be achieved by using the FeO-paper. Although the principle of using the FeO strip is the same, the performance often differs from the P_i test in soils.

P Kinetic studies

Van der Zee et al. (1987) first introduced the use of FeO-paper to study the P desorption kinetics from soil minerals. Because FeO-paper serves as an "infinite" sink for P in bulk solution, the P concentration can be reduced to negligible level that prohibits the possible readsorption of desorbed P. Thus, FeO-paper can be used to study the "true" desorption kinetics of reversibly adsorbed P in soil minerals. A similar study on P adsorption and desorption kinetics with FeO-paper was also reported by Huffman and Cole (1993) and Chardon and Blaauw (1994).

Using nine noncalcareous sandy soils, Van der Zee et al. (1987) fitted their desorption data obtained with four FeO-papers, assuming first-order kinetics. Their final equation, rewritten after Van der Zee et al. (1988, 1989), is

$$P_i(t) = P_{i,max}[1 - \exp(-k_d t)] \quad (1)$$

where $P_i(t)$ is the amount of P desorbed at time t, and $P_{i,max}$ is the amount of P desorbed at infinite time. For k_d, values were found between 0.079 and 0.353 h^{-1} (average 0.20 ± 0.08). For these values of k_d the equation predicts a nearly complete desorption of P within 24 h. Equation (1) was also used by Pierzynski et al. (1994a,b) who used a nearly equivalent surface area of FeO-paper. They concluded that the P_i test may be used on a routine basis to compare total desorbable P contents of different soils and is an alternative to conventional dilution methods at low native P contents. Van der Zee et al. (1988) used FeO-paper to desorb P from soil samples collected in the field and watershed. They found that the quantity of P desorbed, which approximated the adsorption maximum, was proportional to the oxalate-extractable Fe + Al. Thus, it is possible to estimate the adsorption maximum of P from the routinely measurable value of oxalate-extractable Fe + Al. Yli-Halla (1989) also used FeO-paper to estimate the quantities of reversible adsorbed P in 39 mineral soils in Finland. He found that P extracted with FeO-paper correlated well ($r = 0.84$) with Al-P that was extractable with NH_4F. He concluded that the P_i method can be a useful tool in assessing the residual effect of P fertilization and the P status of soils very low in P.

Menon et al. (1990b) embedded FeO-paper in soils to desorb soil P. Under flooded conditions, the amount of P extracted by the FeO-paper increased with the period of submergence and embedding time of the FeO-paper. Under unsaturated conditions, the FeO-paper was found to extract P from soils over a wide range in moisture conditions. The maximal sorption of P by the FeO-paper was found at moisture level between saturation and field capacity (Figure 5).

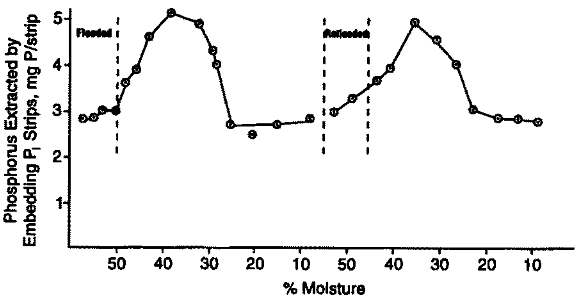

Figure 5. Effect of soil moisture on the amount of P extracted by FeO-paper (Pi) embedded in Vernon clay (Menon et al., 1990). The FeO paper was withdrawn after every 8 hrs. and 16 hrs. embedding and replaced by new strips until the soil became dry.

Saarela (1992) used the FeO-paper as a simple diffusion test for soil P availability. Close linear correlations were found between the initial (18 or 42 h) P diffusion rate and water-extractable P contents. The amounts of P obtained by the P_i method were small when the diffusion time was short, but after prolonged diffusion (1 week) the test values were close to the amounts of P taken up by plants (barley followed by oats).

Bramley et al (1992) added P to soil and incubated the soil during 110 days after drying. The rate of the continuing reaction between soil and P was measured using FeO-paper. Kpomblekou and Tabatabai (1993) incubated soil with phosphate rocks and organic acids during 30 days, and used FeO-paper to follow the release of P from phosphate rock during the incubation time. Thien et al. (1994) treated soil samples with hexanol in order to lyse microbial cells. The increase in P, extractable with FeO- paper, was used as a measure of microbial P. Pierzynski et al. (1994b) used FeO-paper to follow the decrease in available P after successive croppings of sorghum-sudan grass.

P in aquatic environments

Yli-Halla (1989) and Menon (1992) suggested that FeO-paper may be used in environmental studies to assess the P released into surface waters from soil sur-

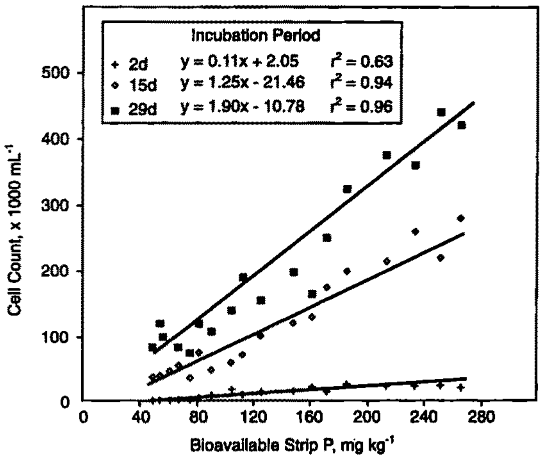

Figure 6. Relationship between the bioavailable P extracted by FeO-paper (strip P) from runoff sediment and P-starved *S. capricornutum* growth during 2-, 15-, and 29-d incubations (Sharpley, 1993a).

face runoff that may accelerate the eutrophication of receiving water bodies.

Sharpley (1993a) first used FeO-paper to estimate bioavailable P content of runoff from 20 agricultural watersheds. A good correlation was found between the bioavailable P as measured by FeO- paper and the growth of algae (*S. capricornutum*) (Figure 6). Bioavailable P as estimated by the proposed P_i method and more widely used NaOH extraction method closely followed a 1:1 relationship. Since the FeO-paper acts as a P-sink, Sharpley (1993a) argued that the FeO-paper simulates P removal from sediment-water samples by algae. Therefore, the P_i method may have a stronger theoretical justification for its use over chemical extractants in estimating bioavailable P.

Subsequently, Sharpley (1993b,c) used FeO-paper to estimate bioavailability of P in runoff to several fresh-water algae. The algal growth was found to correlate significantly to the amount of P extracted from runoff sediment by FeO-paper. The FeO-paper was also able to distinguish the response of algal cell growth to bioavailable P among various algal types. For a given bioavailable P as extracted by FeO- paper, algal cell count increased in the order *Anabaena, englena, selenastrum,* and *Ankistrodesmus*. Pote et al. (1994) correlated dissolved P concentrations in surface runoff with P availability in soils, extracted either with Mehlich III, distilled water or FeO-paper. The best correlation was found with both distilled water and FeO-paper.

One advantage of using FeO-paper to estimate bioavailable P from agricultural runoff as related to potential eutrophication of receiving water bodies is that the storage of FeO-paper for a long period of time has no effect on the amount of P released (Sharpley et al., 1994). Thus the Pi method can be used as a convenient, reproducible, and interference-free method to estimate the bioavailable P content of runoff in remote locations or where laboratory facilities are minimal.

Concluding remarks

The soil tests which are routinely used in soil testing laboratories have certain limitations. Their ability to predict bioavailability of P in soils with widely differing properties is somewhat limited. Furthermore, these tests were developed for evaluating P availability in soils fertilized with soluble P fertilizers and may not work in soils where PR and PR based fertilizers are used. Because PR is a slow release fertilizer, its effectiveness depends on PR reactivity, soil properties, climatic conditions, and crop species.

The P_i test appears promising for use with soils fertilized with soluble P fertilizers as well as PR based fertilizers. Greenhouse evaluations carried out in several countries have shown that in soils with widely differing properties fertilized with soluble P fertilizers, the P_i test was as good a predictor of crop response as the soil test recommended for the particular soil. One of the advantages of the P_i test is that unlike the extractants which react with the soil and dissolve specific P fractions, the FeO paper acts as an infinite sink to sorb and retain the P mobilized in the soil solution. The P_i test therefore, is independent of the type of soil and can be used in acidic, alkaline, or calcareous soils.

The P_i test has a potential for use in soils fertilized with PR and PR based fertilizers. Traditional soil tests are not appropriate for such soils because acid extractants such as Bray, Truog, and Mehlich extractants dissolve some of the PR and overestimate P availability where as alkaline reagents such as Olsen extractant underestimates P availability. Limited greenhouse studies have shown that the P_i test is a good predictor of P availability in such soils.

When PR fertilizers are used, residual PR may be present in the soil unlike in soils where only soluble P fertilizers are used. Furthermore, the reaction products of PR in the soil may be different from those with soluble P fertilizers. Hence, calibrations based on soluble P fertilizers may not be suitable when PR fertilizers are used. One approach to solve this problem is to derive separate calibrations for PR and soluble P fertilized soils and to use as appropriate. This, however, requires information about fertilizer use history which may not always be available. Although Menon et al. (1989a) have shown that the P_i test was able to measure available P in soil fertilized with PR as well as TSP, the range in P_i-P in soil treated with TSP was much wider than that in soil treated with PR as both PR and TSP were applied at the same rate. To evaluate whether PR and TSP follow the same curve when crop response is plotted against P_i- P in the soil, the ranges in P_i-P with TSP and PR should be the same. Research is continuing at the International Fertilizer Development Center (IFDC) to arrive at a solution to this problem.

There are certain factors, however, which may influence the widespread use of the P_i test in routine soil testing. Whenever a new soil test is introduced there is bound to be resistance from soil laboratories to change the current soil tests used. Soil testing laboratories usually have a lot of time and experience invested in their current testing procedures. Soil tests such as Bray and Olsen tests were tested and calibrated under local conditions for decades before they were accepted in routine soil testing. The P_i test is new and for it to be adopted as a tool for fertilizer recommendations, extensive experience in its performance will be needed.

Though the P_i test appears to be suitable for both soluble and PR based fertilizers, this may not be considered an advantage in areas where only soluble P fertilizers are used. Likewise, the applicability of the P_i test to all types of soils may not sound attractive to laboratories which deal only with soils of similar properties, i.e., acidic or calcareous soils.

In soil testing laboratories where a large number of samples are received during certain seasons and are expected to be analyzed and fertilizer recommendations sent to the farmer promptly, time is an important factor. Many of the laboratories may favor an analysis that can be completed in 1 day. The P_i test on the other hand, takes 2 days to complete. Likewise, some laboratories prefer multinutrient tests using an extractant such as Mehlich III reagent to estimate several elements. The P_i test can be used only to determine available P content of soils.

Despite these limitations, the use of the P_i test should be encouraged in soil testing. It is a simple test and has a good potential as a general soil test for P, especially in the P deficient soils of the tropics and in soils fertilized with PR based fertilizers.

The P_i test has several other possible applications in addition to routine soil testing. It has a potential as a research tool for in situ evaluation of P in the field by embedding the FeO strips in saturated soil, and for monitoring P availability during different stages of plant growth without destructive sampling. The possibility of using the test to evaluate P in flooded soils is promising. Furthermore, the P_i test can serve as an important tool for monitoring P concentration in runoffs and in aquatic ecosystems.

Future research

Most of the P_i test-crop response data presented in literature are based on experiments conducted in the greenhouse. Extensive trials need to be conducted in the field to study the response of different crops to increasing levels of P_i-P in the soil, and increasing rates of P application under different soils, climatic conditions, and management practices to enable the P_i test to be used as a tool to assist in fertilizer recommendations. Evaluations should be made in fields with varied fertilizer histories so that the effect of different PRs, PR based fertilizers, and soluble P fertilizers can be calibrated.

It is possible that the FeO strips could be used to extract sulfates. Preliminary studies at IFDC have indicated that the strips extract sulfates from standard solutions (unpublished data). This needs further investigation.

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