Phosphorus Fertilization through Drip Irrigation

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Although P fertilization through drip irrigation systems has not been widely recommended, a review of currently available literature indicates this fertilizer application technique can offer many advantages when performed properly. Using drip irrigation to apply P fertilizer allows nutrient placement directly into the plant root zone during critical periods of nutrient demand. Less P fertilizer is generally required to achieve sufficient tissue P concentrations and equivalent yields when it is drip-applied than with other application methods. The distribution of drip-applied P in soil depends on soil properties, the source of P fertilizer, the rate of application, and the amount of applied water. When irrigation water contains elevated concentrations of Ca^{2+} or Mg^{2+}, acidic P fertilizers are effective in drip systems for preventing precipitation of insoluble P salts. A variety of other soluble P fertilizers have been successfully used where the dissolved salt concentration of the irrigation water is low. A fertilizer compatibility test with the irrigation water should be conducted before injecting any soluble P fertilizer into a drip irrigation system.

The use of drip irrigation for providing water and nutrients to plants is increasing in many areas of the world. Although drip irrigation is not suited to every crop, site, or situation, this irrigation method can provide many potential benefits to growers. The use of drip irrigation has enabled high value crops to be produced in environments previously not considered conducive to agriculture (Kafkafi and Bar-Yosef, 1980), and has allowed expanded production in other areas. Some potential benefits of drip irrigation include increased water use efficiency (Singh et al., 1978), enhanced plant growth (Howell et al., 1981), reduced labor and energy requirements (Bucks et al., 1982), controlled salinity (Tscheschke et al., 1974), fewer weed problems (Marsh et al., 1975), and greater flexibility in applying plant nutrients (Rolston et al., 1981).

Fertilizers applied through drip irrigation systems must be water soluble, not react with the irrigation water, and not clog the irrigation equipment. Many N and K fertilizers are easily applied through drip irrigation systems. Other plant nutrients, such as P, are more difficult to apply and obtain proper distribution in the soil. Because P has limited mobility in soil and may form insoluble precipitates with Ca^{2+} and Mg^{2+} in irrigation water, the use of traditional P fertilizers has not generally been recommended for injection in drip irrigation systems (Haynes, 1985).

Considerable research has been done on P fertilization of crops because many soils are low in plant-available P (Engelstad and Terman, 1980). The availability of P fertilizers to plants in large part depends on soil-fertilizer reactions. Phosphorus reacts chemically in soil to form less-available compounds, therefore, P near the roots must be continually replenished or dissolved from these less-available P fractions in order to support plant growth. Phosphorus fertilizer is also relatively immobile in soil. When P fertilizer is broadcast on the soil surface, it will not usually move more than 1 to 2 in. into the soil (Hemwall, 1957), with the majority of the applied P remaining at the soil surface, inaccessible to plant roots. Under conditions where the soil surface is subject to drying, roots cannot grow near the surface and use surface-applied P. Limitations caused by P reactivity and immobility are partially overcome by banding the fertilizer in a concentrated zone beneath the soil surface. This


<table>
<thead>
<tr>
<th>P source (pH)†</th>
<th>Application rate</th>
<th>Soil</th>
<th>Crop†</th>
<th>Depth of movement</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>K₂HPO₄ (10.1)</td>
<td>115-475 lbs/acre</td>
<td>Sand</td>
<td>Tomato</td>
<td>12-16</td>
<td>Bar-Yosef, 1977</td>
</tr>
<tr>
<td></td>
<td>150-300</td>
<td>CaCO₃</td>
<td>Tomato</td>
<td>12</td>
<td>Kafkasi and Bar-Yosef, 1980</td>
</tr>
<tr>
<td></td>
<td>620 ppm</td>
<td>Sand</td>
<td>Tomato</td>
<td>&lt;4</td>
<td>Fujitama and Nagai, 1986</td>
</tr>
<tr>
<td>H₃PO₄</td>
<td>17</td>
<td>Clay loam</td>
<td>Cotton</td>
<td>NR§</td>
<td>Janat and Streehein, 1986</td>
</tr>
<tr>
<td></td>
<td>0-100</td>
<td>Sand</td>
<td>None</td>
<td>&gt;24</td>
<td>O’Neill et al., 1979</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>Loam</td>
<td>None</td>
<td>8</td>
<td>Rauchkolb et al., 1976</td>
</tr>
<tr>
<td></td>
<td>1-40 ppm</td>
<td>Clay loam</td>
<td>Apple</td>
<td>&gt;24</td>
<td>Klein and Spiller, 1987</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>Loam</td>
<td>Tomato</td>
<td>NR</td>
<td>Haas et al., 1987</td>
</tr>
<tr>
<td></td>
<td>44</td>
<td>Sandy loam</td>
<td>Tomato</td>
<td>NR</td>
<td>TVA, 1985</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>Loam</td>
<td>Squash, cabbage</td>
<td>8</td>
<td>Rubeiz, 1984</td>
</tr>
<tr>
<td></td>
<td>0-1070</td>
<td>Medial</td>
<td>Lettertuce</td>
<td>5</td>
<td>Chase, 1985</td>
</tr>
<tr>
<td>Glycerophosphate</td>
<td>12</td>
<td>Loam</td>
<td>None</td>
<td>10</td>
<td>Rauchkolb et al., 1976</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>Clay loam</td>
<td>Tomato</td>
<td>12</td>
<td>Rauchkolb et al., 1976</td>
</tr>
<tr>
<td></td>
<td>59</td>
<td>Clay loam</td>
<td>None</td>
<td>5</td>
<td>Rolston et al., 1975</td>
</tr>
<tr>
<td>DAP (8.0)</td>
<td>620 ppm</td>
<td>Clay</td>
<td>None</td>
<td>6</td>
<td>Keng et al., 1982</td>
</tr>
<tr>
<td></td>
<td>620 ppm</td>
<td>Sandy loam</td>
<td>None</td>
<td>12</td>
<td>Keng et al., 1982</td>
</tr>
<tr>
<td>MAP (3.5)</td>
<td>60 ppm</td>
<td>Clay</td>
<td>Tomato</td>
<td>NR</td>
<td>Papadopoulos, 1985</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Loamy sand</td>
<td>Carnation</td>
<td>8</td>
<td>Goldberg et al., 1971</td>
</tr>
<tr>
<td></td>
<td>4-18</td>
<td>NR</td>
<td>Tomato</td>
<td>NR</td>
<td>Paterson, 1980</td>
</tr>
<tr>
<td>APP (6.2)</td>
<td>30-50</td>
<td>NR</td>
<td>Cotton</td>
<td>NR</td>
<td>Meron and Levin, 1985</td>
</tr>
<tr>
<td></td>
<td>165</td>
<td>Sandy clay</td>
<td>Apple</td>
<td>36</td>
<td>Klein and Spiller, 1987</td>
</tr>
</tbody>
</table>

† pH data from Sample et al., 1980.
† Apple = Malus pumila Mill.; carnation = Dianthus caryophyllus L.; cotton = Gossypium hirsutum L.; pepper = Capsicum annuum L.
§ NR = not reported.

method of application reduces soil-fertilizer contact and generally results in greater P availability to plants than surface applications or mixing P with the soil (Randall and Hoefi, 1988).

An advantage of drip irrigation is that plant nutrients can be applied directly to the root zone. Nutrient application through drip irrigation could be compared to an adjustable fertilizer band where the nutrient applications can be exactly timed to meet critical plant growth stages. Since the majority of roots in root-irrigated crops are located within the wetting zone (Earl and Jury, 1977), drip-applied P will be placed in the soil region containing the highest root density. Therefore, drip-applied P generally is used more efficiently than plants if the same amount of P was surface- or spot-applied (O’Neill et al., 1979; Chase, 1985; Mikkelsen and Jarrell, 1987). Like band-applied P, the primary benefit derived from drip-applied P probably results from placement of P fertilizer directly in the zone of active roots, rather than from increased availability resulting from decreased soil-fertilizer contact (Sleight et al., 1984).

Due to the limited mobility of P in soil, it has been suggested that the localized accumulation of P surrounding a drip emitter may be detrimental to plant growth (Goldberg et al., 1976). Since only a portion of the soil volume around each plant is fertilized and irrigated, the P uptake rate by roots in the fertilized zone must be high enough to compensate for the roots in the unfertilized soil. However, roots have the compensatory capacity to adjust physiologically and exploit favorable growth conditions. Roots are commonly found to proliferate in zones with high P concentrations and a small portion of the root system can adequately meet the nutrient demand of the entire plant (Drew, 1975). The plant response to an uneven spatial distribution of nutrients probably is not significant when adequate levels of nutrients are present in the root zone.

Using traditional methods of P fertilization, midseason P applications have not been feasible due to the difficulty in entering the field with the equipment required to obtain proper fertilizer placement. By applying P through drip irrigation, it is possible to fertilize crops according to the exact demand of the plant while placing the fertilizer directly in the root zone, resulting in more efficient fertilizer use.

Phosphorus fertilization through drip irrigation may provide a residual benefit similar to a band or a spot placement of P fertilizer. With permanent and subsurface drip lines, annual crops can be planted each year in this high-P soil zone to use carry-over P from previous applications. These P-rich zones can be identified by noting the wetted soil near or above each emitter after an irrigation cycle begins. In view of the potential advantages obtained from supplying P through drip irrigation, there is a need for P fertilizers suitable for injection into drip irrigation systems.

**PHOSPHORUS FERTILIZER PRODUCTS**

Phosphorus fertilization through drip systems has not been widely used, partially due to concern over chemical plugging of irrigation lines and emitters. This occurs when soluble P fertilizer reacts with water containing appreciable concentrations of Ca²⁺ or Mg²⁺ to form insoluble dicalcium phosphate or dimagnesium phosphate (Eq. 1 and 2). However, the precipitation of these P salts can be avoided if the pH is kept low enough for the salts to remain soluble. A low pH can be maintained by

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using an acidic P source such as orthophosphoric acid (H$_3$PO$_4$) or urea phosphate (UP). The exact amount of acid fertilizer required to decrease the water pH and prevent precipitation can be easily determined from a laboratory titration curve for each irrigation water source. If the irrigation water contains low concentrations of Ca$^{2+}$ and Mg$^{2+}$, chemical precipitation problems resulting from P fertilization are not likely.

\[
\text{Ca}^{2+} + \text{H}_3\text{PO}_4^- + 2\text{H}_2\text{O} \leftrightarrow \text{CaHPO}_4 \cdot 2\text{H}_2\text{O} + \text{H}^+ \quad (\text{dicalcium phosphate})
\]

\[
\text{Mg}^{2+} + \text{H}_3\text{PO}_4^- + 3\text{H}_2\text{O} \leftrightarrow \text{MgHPO}_4 \cdot 3\text{H}_2\text{O} + \text{H}^+ \quad (\text{dimagnesium phosphate})
\]

**Phosphoric Acid**

Phosphoric acid has been used effectively as a P fertilizer for drip irrigation (Table 1). Rauschkelb et al. (1976) demonstrated that H$_3$PO$_4$ was suitable for use in drip irrigation and that plant P uptake during the early growing season could be increased by P additions with irrigation water. They reported that when P was applied as H$_3$PO$_4$ through the drip system at rates of 6 and 12 lb P/acre, tissue P concentrations of tomato (*Lycopersicon esculentum* Mill.) were equivalent to a 23 lb P/acre triple superphosphate (TSP) [Ca(H$_2$PO$_4$)$_2$·H$_2$O] treatment that was band-applied. However, due to high residual soil P, this difference was not sustained throughout the growing season. Additionally, P moved 5 to 10 times further in soil with drip-applied H$_3$PO$_4$ than with spot-applied TSP. To prevent precipitation of insoluble P compounds in the irrigation system, H$_2$SO$_4$ was added to the irrigation water immediately after the H$_3$PO$_4$ to maintain a low pH until the P was completely flushed from the irrigation lines.

Similarly, O’Neill et al., (1979) reported substantially more movement from drip-applied H$_3$PO$_4$ than from spot-placement of TSP applied beneath emitters in a sandy soil. They found that, at equivalent application rates, P from H$_3$PO$_4$ moved into a soil volume two times larger than P from spot-applied TSP. They concluded that H$_3$PO$_4$ resulted in a more favorable soil distribution of P for plant uptake than did TSP.

Since H$_3$PO$_4$ is a strong acid, precautions must be taken when handling the material. Although plastic components used for irrigation pipe, lines, and emitters will not be subject to corrosion, metal components of the irrigation system should be examined and replaced as needed.

**Urea Phosphate**

Urea phosphate (UP) is a promising experimental P source for drip irrigation that overcomes some of the potential safety problems associated with H$_3$PO$_4$. Urea will form an addition product (adduct) with a variety of acids including H$_3$PO$_4$, H$_2$SO$_4$, and HNO$_3$ (Mikkelsen and Bock, 1989). Urea phosphate is made from a 1:1 mole ratio of urea and H$_3$PO$_4$ which combine to form crystals containing 17.7% N and 19.6% P (45% P$_2$O$_5$). The urea and H$_3$PO$_4$ molecules each retain their individual chemical composition and readily dissociate upon dissolution in water. An advantage of UP over H$_3$PO$_4$ is that it is an easily handled solid and does not require special precautions in application. It also provides an N fertilizer source well suited for drip irrigation.

Mikkelsen and Jarrell (1987) found that UP is an effective P fertilizer for drip-irrigated tomatoes in calcareous soil. They reported that less P fertilizer is required to increase tissue P concentrations with drip-applied UP than with TSP spot-placed beneath a drip emitter (Fig. 1). This study also demonstrated that increased P efficiency can be obtained by drip-applying UP. Total P ac-
Table 2. Post-harvest extractable soil P concentrations from the furrow between rows receiving P fertilizer (50 lb P/acre). Phosphorus fertilizer applied as urea phosphate (UP) through drip irrigation or soil-applied as banded ammonium polyphosphate (APP). Adapted from Rubeiz, 1984.

<table>
<thead>
<tr>
<th>Soil depth</th>
<th>Furrow</th>
<th>Shallow drip UP</th>
<th>Deep drip UP</th>
</tr>
</thead>
<tbody>
<tr>
<td>in.</td>
<td>No P</td>
<td>APP</td>
<td></td>
</tr>
<tr>
<td>0-2</td>
<td>15</td>
<td>13</td>
<td>214</td>
</tr>
<tr>
<td>2-4</td>
<td>13</td>
<td>10</td>
<td>98</td>
</tr>
<tr>
<td>4-6</td>
<td>10</td>
<td>10</td>
<td>--</td>
</tr>
</tbody>
</table>

† Shallow and deep drip placed 2 and 6 in. below the soil surface, respectively.

cumulation by the plant shoot increased from 0.004 oz (126 mg) P to 0.012 oz (342 mg) P/plant by drip-applying UP compared with a spot placement of TSP below the emitter (36 lb P/acre).

Urea phosphate was used to fertilize cabbage (Brassica oleracea capitata L.) and squash (Cucurbita pepo L.) which was irrigated through shallow (2 in. deep) or deep-placed (6 in. deep) drip irrigation, or with furrows (Rubeiz, 1984). Yields of squash were 34 to 52% greater and cabbage yields were 22% greater with deep-placed drip irrigation than with furrow irrigation, in which UP was band-applied. Yields equivalent to those of the furrow-irrigated plants were obtained with only half the P and half the water when fertilized through drip-irrigation. Phosphorus deficiencies were noted in crops which had been fertilized with band-applied P immediately prior to planting, while no such symptoms were observed when plants were fertilized at equal rates of UP through drip irrigation during the growing season.

Rubeiz (1984) also compared the movement of P from drip-applied UP with P movement from soil-banded ammonium polyphosphate (15–26–0). In the furrow, between the fertilized beds, P concentrations were increased only in the treatments receiving drip-applied UP (Table 2). In addition to substantial P movement from the drip emitter, he also noted that roots were concentrated in the high-P zone surrounding the emitter. In this experiment, the pH of the irrigation water was decreased from 8.0 to 1.8 following the addition of UP. No plugging of the equipment used for P fertilization was found.

Urea phosphate was used to fertilize lettuce (Lactuca sativa L.), which was irrigated through a buried (3 in. deep) drip irrigation system on a soil with a very high P-fixing capacity (Chase, 1985). Tissue P concentrations and yields were greater in the UP-fertilized plants than in plants receiving equivalent amounts of band-applied TSP. A second lettuce crop which was transplanted into the same phosphate-rich zones near the emitter, but received no additional P, did not have increased tissue P concentrations. This probably was due to the high P adsorption capacity of this soil. Subsequent additions of P into the soil surrounding the emitter would possibly be less than were required for the initial fertilization. As commonly found, concentrations of extractable P near the emitter and P movement in the soil away from the emitter increased as the fertilizer application rate increased (Fig. 2).

**Other Phosphorus Sources**

Rolston et al. (1975) investigated the addition of an organic P compound (glycerophosphate) to irrigation water to achieve enhanced P mobility in soil. This con-

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cept is appealing since glycerophosphate moves freely with soil water until it is enzymatically hydrolyzed by the phosphatase enzyme (Castro and Rolston, 1977). When applied to a clay loam soil, glycerophosphate moved to a maximum depth of 4.5 in., whereas KH₂PO₄ moved to depths no more than 1 in. Rauschkolb et al. (1976) fertilized tomatoes through a drip irrigation system with glycerophosphate, H₃PO₄, or with soil-applied TSP. They found that both glycerophosphate and H₃PO₄ moved far enough into the soil to be useful P fertilizers. Glycerophosphate moved as much as 12 in. and fertilized a soil volume approximately four times greater than that fertilized with equivalent amounts of H₃PO₄ (Fig. 3). Organic P fertilizers have an additional benefit since they generally do not form insoluble salts with Ca²⁺ and Mg²⁺ present in irrigation water. Despite the attractive properties associated with organic P fertilizers, their limited availability and high price currently preclude their use as P fertilizers in agriculture.

In situations where irrigation water contains low concentrations of Ca²⁺ and Mg²⁺, and there is consequently little concern over the formation of insoluble P salts, a variety of soluble P fertilizers has been successfully used in drip irrigation. These include: potassium phosphate [K₂HPO₄] (Bar-Yosef, 1977; Bar-Yosef and Sheikholslami, 1976; Kafka and Bar-Yosef, 1980); monoammonium phosphate [NH₄H₂PO₄] (Goldberg et al., 1971; Paterson, 1980, Papadopoulos, 1985); diammonium phosphate [(NH₄)₂HPO₄] (Keng et al., 1982); and ammonium polyphosphate (meron and Levin, 1985; Klein and Spieler, 1987).

**SOIL REACTION**

**Phosphorus Movement**

The extent of P movement from the emitter into soil is largely dependent on the P adsorption capacity of the soil and the P application rate. Phosphorus leaving the emitter will move primarily as soluble orthophosphate with water until it begins to react with the soil (Novak et al., 1975). The equilibrium of P between the solid and solution phases in the soil has been well described by a variety of models such as the Langmuir equilibrium equation or the constant-capacitance model (Enfield and Ellis, 1983; Goldberg and Sposito, 1984).

The extent of P movement from the initial point of application is dependent on the saturation of soil reaction sites. Logan and McLean (1973) described the downward movement of P as progressive adsorption by successive soil layers. Phosphorus will continue to move from the emitter into an expanding volume of soil as long as the sorption capacity of that soil volume is exceeded. As the reaction sites are saturated in the soil, P moves with the water to unsaturated sites farther from the source (Rauschkolb et al., 1976). While P is being applied to a limited soil volume near the emitter, it will continue to move at some rate, determined by the characteristics of the particular soil, from the emitter with the irrigation water. Movement of water and P in soil macropores will also result in P movement from the emitter. After P application ceases, adsorption of soluble P will begin to reach a quasi-equilibrium in the fertilized volume of soil. The disappearance of P from the soil solution generally is described as a fast initial reaction (hours) followed by a much slower reaction (days) (Fig. 4). The initial reac-

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![Fig. 3. The soil distribution of extractable P following addition of 14 lb P/acre to a drip irrigation system as (i) H₃PO₄ or (ii) glycerophosphate. Isogram lines are ppm extractable soil P (adapted from Rauschkolb et al., 1976).](image-url)
tion usually is due to sorption reactions while precipitation of relatively insoluble P compounds controls the slower reaction (Enfield and Ellis, 1983).

The increased movement and plant uptake associated with drip-irrigated P compared with other P fertilization methods likely is due to the concentrating effect resulting from drip-application where only a portion of the soil receives water and nutrients. The effective application rate of drip-applied P fertilization consequently is very high as a result of applying the P over a very small surface area. For example, if 20 lb P/acre were applied uniformly through 2500 emitters/acre, this would provide 0.008 lb P/emitter. If the P were applied within 4 in. of the emitter, P concentration within this 4 in. radius would be equivalent to 1000 lb P/acre. Thus, the increased mobility of drip-applied P is comparable to P movement observed at very high P application rates (Logan and McLean, 1973).

Adsorption and precipitation of P in soil are influenced by pH (Sample et al., 1980). When an acidic P fertilizer is introduced through the irrigation system, the newly applied acid dissolves some of the previously formed P precipitates and P continues to move to the outer edge of the ever-increasing zone of acidification or neutralization. As this sequence is repeated with each application of acidic fertilizer, P moves continually farther from the emitter.

Drip irrigation alone can have an effect on P availability in soil. Bacon and Davey (1982) reported elevated concentrations of extractable P in the wetted zone beneath the emitter for 6 to 23 hours after a water-only irrigation cycle. They attributed this phenomenon to solubilization of native P associated with amorphous iron phosphate compounds that were reduced during the anaerobic phase of the irrigation. Addition of some N fertilizers can have an acidifying effect on soil following nitrification, which may result in a dissolution of native P (Haynes and Swift, 1987). For example, Mikkelsen and Jarrell (1987) noted an increase in extractable soil P following urea fertilization through drip irrigation as the soil pH beneath the emitter decreased from 7.6 to 7.1. Increased concentrations of extractable P measured in this calcareous soil probably were due to dissolution of native calcium phosphate minerals as the soil pH below the emitter was decreased. Additional research concerning the significance of the solubilization of native P as a consequence of drip irrigation and fertilization is needed.

Other Soil Reactions

Acidification of the root zone, caused directly by acid additions or indirectly through nitrification of added N, can also result in increased dissolution of other soil constituents. Mikkelsen and Jarrell (1987) measured increased soil concentrations of extractable Fe, Mn, and Zn beneath the emitter after additions of UP or the adduct urea + H₂SO₄. Haynes and Swift (1987) found increased concentrations of extractable Cu as well as Fe, Mn, and Zn in soil beneath drip emitters after fertilization with acid-forming (NH₄)₂SO₄. This increase in soluble micronutrients may be beneficial where these elements are limiting to crop growth. However, as acidic or acid-forming materials are continually applied to the same soil region (e.g., with perennial crops or with annual crops using permanently placed drip lines), it is possible that Al³⁺ and one or more of the above micronutrients could be dissolved to concentrations that could become deleterious to plant growth. More research is required to examine the long-term implications of acidification of the root zone from drip irrigation and possible means of alleviating potential problems.

Soil texture plays an important role in determining the extent of movement of drip-applied P. For example, the movement of P from an emitter was 2 times greater horizontally and 3 times greater vertically in a sandy soil than in a clay soil under the same irrigation and fertilizer conditions (Bar-Yosef and Sheikholislami, 1976). This probably occurred because (i) P adsorption is generally greater in clay than in silt or sand, and (ii) movement of water and fertilizers in soil pores may be greater in sandy soils than in clay-textured soils. These two factors are jointly responsible for the typical observation of increased mobility of P in coarse-textured soils.

Knowledge of soil texture alone, however, is not sufficient to predict the movement of drip-applied P. For example, Chase (1985) noted only limited P mobility (5 in.) when UP was applied at very high concentrations (1070 lb P/acre) in a coarse-textured medial (volcanic) soil. Phosphorus movement was less than expected on this coarse-textured soil due to the extreme affinity of this volcanic soil for P. Many soil characteristics must be considered when applying P fertilizer through drip irrigation. In soils that excessively limit P movement from the emitter, it may be necessary to soil-apply P in order to achieve an adequate P concentration in the root zone.

Although the use of P in drip irrigation has been well documented and is becoming more widespread, many questions remain unanswered. For example, the general reactions of drip-applied P with soil can be described, but factors such as the frequency of P application and the emitter discharge rate have unknown effects on P movement and phytoavailability. A more complete understanding of fertilizer P movement from the emitter over

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Fig. 4. Phosphorus sorption by a single soil sample after repeated additions of P (adapted from Enfield and Ellis, 1983).
time and the accompanying soil reactions would aid in predicting P movement under various conditions. Additionally, the effect of acidification and repeated wetting and drying cycles on dissolution of soil minerals still is not clear.

SUMMARY

Although the use of P fertilizers in drip irrigation systems has not generally recommended, research results have shown that this method of P application can offer several advantages. Drip irrigation allows placement of P fertilizer directly into the plant root zone during critical times of nutrient demand. This directed application of P can result in more efficient plant use of the fertilizer than when P is broadcast or band-applied. Less P fertilizer is required when it is drip-applied than with other methods to achieve comparable tissue P concentrations and yields. The soil distribution of drip-applied P is equal or superior to band- or spot-applied P in meeting plant nutritional requirements. A variety of soluble P fertilizers has been successfully used with drip irrigation. However, when P fertilizers are added to irrigation water containing appreciable concentrations of Ca$^{2+}$ or Mg$^{2+}$, the pH must be maintained low enough to prevent precipitation of relatively insoluble P salts. A low pH is generally maintained by adding an acidic P source such as H$_3$PO$_4$ or UP to the water. The pH required to prevent chemical precipitation should be determined from a titration curve with specific irrigation water and P fertilizer.

REFERENCES


