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Utility of Alumina-buffered Phosphorus Fertilizer for Vegetable Production

Mayuki Tanaka, Robert Snyder, John K. Boateng, William J. Lamont, Michael D. Orzolek, Kathleen M. Brown, and Jonathan P. Lynch[1]
Department of Horticulture, The Pennsylvania State University, University Park, PA 16802

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Abstract. **The utility of alumina-buffered phosphorus (Al-P) fertilizers for supplying phosphorus (P) to bell pepper (*Capsicum annuum L.*) in soils with low-P availability was evaluated. Plants were grown at low-P fertility (about 100 kg·ha^{-1}, low-P control; LPC), with conventional P fertilization (205-300 kg·ha^{-1} annually, fertilizer control; FC), or with one of two Al-P sources (Martenswerke or Alcoa) in 2001–03. The two Al-P fertilizers were applied in 2001; no additional material was applied in 2002-03. Plants grown with Martenswerke Al-P had similar shoot dry weight, root dry weight, root length, leaf P concentration, and fruit yield compared with plants grown with conventional P fertilizer in both 2002 and 2003 seasons. Bell pepper grown with Alcoa Al-P had similar shoot dry weight, root dry weight, root length, leaf P concentration, and fruit yield compared with plants grown without P fertilizer in both seasons. Alcoa Al-P continuously released bioavailable P for 2 years between 2001 and 2002, while Martenswerke Al-P continuously released bioavailable P at least 3 years between 2001 and 2003. These results indicate that some formulations of Al-P can serve as long-term P sources for field vegetable production.**

Low phosphorus (P) availability is a primary constraint for plant growth on earth (Abelson, 1999; Lynch, 1998; Vance et al., 2003). In developed countries where high crop yields are enabled by intensive P fertilization, water pollution by P runoff from agricultural land is a serious problem (Burkholder et al., 1992; Ribaudo, 2000; Sharpley et al., 2000). Moreover, economically recoverable P ores are finite and are projected to be significantly depleted in this century (Cathcart, 1980; Steen, 1998). New agricultural technologies that enable more efficient use of P while minimizing environmental contamination are needed.

A promising technology for improving the P efficiency of horticultural production systems is the use of P buffers as crop fertilizers. A solid-phase-buffered P fertilizer (Al-P) system was developed for maintaining constant availability of P in growth media (Coltman et al., 1982; Elliott, 1989; Elliott et al., 1983; Lynch et al., 1990). This technology employs solid-phase aluminum oxide to adsorb dissolved P and establish an equilibrium between solid phase and solution phase P.

In container production systems with soilless media, the use of Al-P can reduce P concentration in leachate by >90% compared to conventional P fertilizer (Borch et al., 1998 , 2003; Brown et al., 1999, 2002; Lin et al., 1996). Use of Al-P has also been shown to improve drought tolerance by improving root growth and distribution, and by reducing transpiration (Borch et al., 1998, 2003). Marigold (*Tagetes* spp.) had greater growth with Al-P treatments compared with conventional fertilization (Lin et al., 1996). Container-grown Forsythia (*Forsythia intermedia* Zab.) and rhododendron (*Rhododendron catawbiense* Michx.) grown with 0.5% to 1% Al-P produced better plant growth compared to conventional fertilizer (Brown et al., 1999). 'FTE 30' tomato (*Lycopersicon esculentum*) transplants with 1% and 2% Al-P showed greater total root length and specific root length, and the tomato production was equal in size and quality with conventional fertilizer (Brown et al., 2002).

Buffered P sources have primarily been evaluated in soilless media. The benefits of buffered P sources in mineral soils may be reduced by redundancy with natural soil buffering. The objective of this experiment was to evaluate alumina buffered P (Al-P) from two sources in vegetable production in the field.

Materials and Methods

Bell pepper (*Capsicum annuum L.* var. 'King Authur') transplants were obtained from Miller Plant Farm Inc., York, Pa. The pepper transplants (28 to 35 d after seeding) were delivered to the Pennsylvania State Horticulture Research Farm on 25 June 2001, June 2002, and 29 May 2003. Transplants were held in a cold frame and watered until conditions permitted transplanting into the field on 3 July 2001, 18 June 2002, and 26 June 2003.

This set of experiments was conducted on a field with low-P fertility (100 kg·ha^{-1} available P) in a Clarksburg soil (fine-loamy, mixed, mesic Typic Fragiudalf) at the Horticultural Research Farm, Russell E. Larson Research Center, Rock Springs, Pa., for 3 years, from June to the end of November 2001–03. To assess baseline soil fertility, soil samples were taken before the beginning of each season and sent to the Agricultural Analytical Services Laboratory at Penn State for nutrient analysis. Phosphorus analysis was conducted using the Mehlich III method (Mehlich 1984; Wolf and Beegle, 1995).

A solid-phase buffered alumina P fertilizer (Al-P) (Lynch et al., 1990) was used to regulate P availability in these experiments. Alumina products were manufactured by Martenswerke Inc., Bergheim, Germany (a subsidiary of Albermarle Corp., Baton Rouge, La.) (Mart Al-P) and Alcoa, Port Allen Works, Baton Rouge (Alcoa Al-P) in cooperation with our laboratory. Mart Al-P was made with Compalox J7 alumina and maintained an equilibrium desorption concentration of 370 μM P, while the Alcoa Al-P was made from DD2 alumina and maintained an equilibrium desorption concentration of 128 μM P, measured after the first rinse (Lynch et al., 1990). The Alcoa Al-P had a total P content of 31 g·kg^{-1} and the Mart Al-P had 50 g·kg^{-1}. Both of the alumina products were applied to soils at a concentration of 1% w/v, which is equivalent to 19.6 Mt·ha^{-1} Al-P or 608 kg·ha^{-1} P for Alcoa Al-P and 1013 kg·ha^{-1} P for Mart-Al-P. In practice, 22 kg of each product were applied to a row 9.14 m long by 1.22 m wide on 1.83 m centers utilizing wheeled, hand-propelled drop-type fertilizer spreaders, and incorporated into the soil to a depth of 20 cm by roto-tilling. The two Al-P fertilizers were applied in 2001 and no additional material was applied in 2002–03 in order to determine the length of time that the materials were able to supply P in the soil.

Martenswerke and Alcoa Al-P fertilizers were compared with native low-P availability conditions and to a fertilized control. The fertilized control was included to compare the Al-P fertilizers to P fertilization practices common in Pennsylvania in 2002 and 2003. The fertilized control plots were fertilized with triple super-phosphate (0N–46P–0K) in 2002 at a rate of 202.5 kg·ha^{-1} TSP, or 415 kg·ha^{-1} P, and mono-ammonium phosphate (11N–52P–0K) in 2003 at a rate of 155 kg·ha^{-1} mono-ammonium phosphate, or 414 kg·ha^{-1} P, bringing the total available P to 293 kg·ha^{-1} and 259 kg·ha^{-1}, respectively. These fertilizer rates were determined based on soil test results according to the recommendations of the Analytical Lab using an optimum soil test P for sweet peppers of 60 to 155 µg·g^{-1} (Pennsylvania State Agricultural Analytical Services Laboratory http://www.aasl.psu.edu/Veg%20Recs_page.htm). Commercial fertilizers were applied with a spreader and incorporated as described above for Al-P products.

After the fertilizers were incorporated, raised beds were prepared and black plastic mulch plus drip irrigation tape was applied over the raised beds. Drip tape (Aqua-Traxx, Toro AG; The Toro Company, El Cajon, Calif., Hi-Flo, 0.08 mm thick in a 2,286 m roll, with emitters set at 30.48-cm intervals with a flow rate of 0.831 L·min^{-1} per 30.38 m of row) supplied water, nitrogen (N) and potassium (K) as needed (Orzolek et al., 1997) (see below).

During field preparation each season, the soil was cultivated with a chisel plow, and

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[1]To whom reprint requests should be addressed; e-mail JPL4@psu.edu.

amended with N, K, and S in accordance with the soil test recommendations. In 2001, 74 kg·ha^{-1} K and 44.8 kg·ha^{-1} N (as ammonium nitrate) were applied to the field before bed preparation. Sulfur was incorporated (224 kg ha^{-1}) to lower the soil pH, which was 7.1 before amendment, based on a recommended soil pH of 6.5 (Pennsylvania State Cooperative Extension, 2001). In 2002, N at 89.6 kg·ha^{-1} and K at 165 kg·ha^{-1} were applied before planting. Based on soil test results, no N and K were applied in 2003 except the 31.4 kg·ha^{-1} N applied to fertilizer control plots as part of the mono-ammonium phosphate application described above.

Each plot contained four 4.57 m rows of bell pepper within the 9.14 × 0.914 m raised beds (the other half of each bed was planted with another crop). Bell pepper transplants were planted in double rows and staggered on each raised bed, at a density of 30 plants per 4.57 m row. Two rows in the center of the each plot were used as data rows. Pepper fruit were harvested from plants in two central rows. Shoot and root harvests were taken from plants growing in border rows.

The field was irrigated as needed on a weekly basis, to maintain a water application schedule of 3.81 cm per week per bedded acre. The total application of N (as KNO_3) via drip irrigation was 5.6 kg·ha^{-1}, 11.2 kg·ha^{-1} and 5.6 kg·ha^{-1} in 2001, 2002, and 2003, respectively. Each treatment was applied in a single factor (P) randomized complete block design, and was replicated four times.

Bell pepper shoots and roots were collected during week 5 (first blossom opening) and week 7 (early fruit set) of growth in the 2002 and 2003 seasons. Two plants were sampled from each experimental unit. Shoot dry weight (shoot DW), root dry weight (root DW), root length, and root hair length were measured. Root crowns were collected from a 15 × 15 cm rectangle to a depth of 17 cm centered on the plant stem. Six basal roots from each plant were then chosen as sub-samples and dyed in a solution of neutral red. For determination of bell pepper root length, the six basal roots were scanned using a flat bed scanner (Epson America, Inc., Long Beach, Calif.) and root length was estimated using the image analysis software WinRhizo Pro (Regent Instruments Inc., Sainte-Foy, Qc, Canada). For the determination of root DW, the same samples harvested for root length were dried at 60 °C in a forced air oven and weighed. When root crowns were harvested, root sub-samples for root hair length were also collected. For the root hair length determination, roots were dyed in a solution of bromophenol blue. For each sample, five root segments were carefully selected on dissecting microscope (Nikon SMZ-U; Nikon, Melville, N.Y.) and the images were taken using a digital camera (Kodak DC290; Kodak, Rochester, N.Y.). Five root hairs per image were then measured using image analysis software (Scion Image; Scion Corp., Frederick, Md.).

For determination of leaf P, Zn, Fe, and Ca concentrations, youngest fully expanded leaves were collected at 3 (before blossoming), 5 (first blossom opening), and 7 (early fruit set) weeks after transplanting. Thirty leaves were collected from each experimental unit. Total leaf P was determined by a spectrophotometric assay (Murphy and Riley, 1962), and total leaf Zn, Ca, and Fe were determined by atomic absorption spectrophotometry (Perkin Elmer AAnalyst100; Perkin Elmer, Wellesley, MA). Tissue concentrations of Zn, Fe, and Ca are of interest since P availability interacts with the bioavailability and metabolism of these nutrients.

Bell pepper fruits were harvested on two dates, 9 and 11 weeks after transplanting to the field, in all 3 years. Fruits were separated into marketable and nonmarketable classes, counted, and weighed. Bell pepper fruit were graded according to USDA standards (USDA, 1997).

A 5.08-cm-diameter Giddings hydraulic soil probe mounted on a tractor, (Giddings Machine Co. Inc., Windsor, Colo.) was used to retrieve soil cores from each replicate in the raised beds at the termination of the experiment for each season. One core was taken from each replicate and used to determine P-availability. The cores were divided into 10-cm increments up to 30 cm in the 2001 season and up to 40 cm in the 2002 and 2003 seasons. Core samples were air dried, pulverized with a mortar and pestle, and passed through a 2-mm sieve before chemical analysis. Phosphorus availability was assayed via Mehlich III extraction (Mehlich, 1984) and the iron strip method (Menon et al., 1989).

Data were analyzed by analysis of variance (ANOVA). Means were compared using Fisher's protected least significant difference (PLSD). All analyses were performed using StatView 5.0.1 (SAS Institute Inc., Cary, N.C.).

Results

Plant growth. Bell pepper growth, measured as shoot DW, was significantly affected by P treatments in both 2002 and 2003 (Table 1). Plants grown with Alcoa Al-P or without P fertilizer (low-P control) had a lower shoot dry weight compared with plants grown with

Table 1. Shoot dry weight of bell pepper grown with fertilizer control (FC), Alcoa Al-P, Mart Al-P, and no added P (LPC). Bell pepper plants were harvested 5 and 7 weeks after transplanting. Values are means of four replications ± SE. Treatments were compared by ANOVA within harvest dates.

	Shoot dry wt (g)			
	2002		2003	
Fertilizer	Week 5	Week 7	Week 5	Week 7
FC	7.6 ± 1.0 ab[z]	17.8 ± 2.4[NS]	6.3 ± 0.6 a	15.4 ± 1.2 a
Alcoa Al-P	5.3 ± 0.6 bc	14.0 ± 2.3[NS]	2.7 ± 0.1 c	9.0 ± 0.9 b
Mart Al-P	7.9 ± 1.0 a	16.3 ± 1.6[NS]	4.6 ± 0.4 b	15.0 ± 1.5 a
LPC	4.6 ± 0.6 c	13.6 ± 2.4[NS]	2.6 ± 0.3 c	9.0 ± 1.8 b

[z]Means within columns followed by the same letter are not significantly different according to Fisher's protected least significant difference (PLSD) at $P \leq 0.05$.

Table 2. Root dry weight of bell pepper grown with fertilizer control (FC), Alcoa Al-P, Mart Al-P, and no added P (LPC). Bell pepper plants were harvested 5 and 7 weeks after transplanting. Values are means of four replications ± SE. Treatments were compared by ANOVA within harvest dates.

	Root dry wt (g)			
	2002		2003	
Fertilizer	Week 5	Week 7	Week 5	Week 7
FC	0.13 ± 0.01 ab[z]	0.32 ± 0.03 a	0.13 ± 0.01 a	0.34 ± 0.08 ab
Alcoa Al-P	0.11 ± 0.02 b	0.28 ± 0.03 ab	0.07 ± 0.01 b	0.23 ± 0.05 ab
Mart Al-P	0.16 ± 0.01 a	0.34 ± 0.02 a	0.10 ± 0.03 ab	0.36 ± 0.05 a
LPC	0.09 ± 0.00 b	0.22 ± 0.04 b	0.08 ± 0.01 b	0.19 ± 0.03 b

[z]Means within columns followed by the same letter are not significantly different according to Fisher's protected least significant difference (PLSD) at $P \leq 0.05$.

Table 3. Root length and root hair length of bell pepper plants grown with fertilizer control (FC), Alcoa Al-P, Mart Al-P, and no added P (LPC). Bell pepper plants were harvested 5 and 7 weeks after transplanting. Values are means of four replications ± SE. Treatments were compared by ANOVA within harvest dates. Variability in root length was higher in 2003 but the same trends in root length are apparent. There were no significant differences in root hair length by 7 weeks after transplanting (not shown).

	Root length (cm)				Root hair length (mm)	
	2002		2003		2002	2003
Fertilizer	Week 5	Week 7	Week 5	Week 7	Week 5	Week 5
FC	576 ± 54 a[z]	651 ± 78 a	682 ± 100[NS]	924 ± 155[NS]	0.60 ± 0.02 ab	0.78 ± 0.04 b
Alcoa Al-P	485 ± 54 ab	540 ± 60 ab	391 ± 36[NS]	616 ± 100[NS]	0.65 ± 0.07 a	0.80 ± 0.03 ab
Mart Al-P	565 ± 48 a	713 ± 91 a	606 ± 206[NS]	791 ± 111[NS]	0.60 ± 0.01 ab	0.88 ± 0.03 a
LPC	392 ± 44 b	287 ± 48 b	484 ± 48[NS]	606 ± 76[NS]	0.51 ± 0.01 b	0.85 ± 0.03 ab

[z]Means within columns followed by the same letter are not significantly different according to Fisher's protected least significant difference (PLSD) at $P \leq 0.05$.
[NS]Nonsignificant.

conventional P fertilizer (FC) or Martenswerke Al-P (Mart Al-P) at week 5 of growth. In the 2002 season, shoot dry weight was reduced by 40% in the low-P control plants and 42% in the Alcoa Al-P plants compared to plants grown with Mart Al-P at week 5 of growth. In the 2003 season, shoot dry weight was reduced by 41% in both the low-P control plants and the Alcoa Al-P plants compared to plants grown with Mart Al-P at week 7 of growth. The patterns for root dry weight were similar to those observed for the shoot dry weight in both 2002 and 2003 seasons (Table 2). Root DW was less affected by the P treatments than shoot dry weight.

Phosphorus treatments affected root length in the 2002 season (Table 3). Plants grown at low-P fertility had consistently less root length, but there were no significant differences observed between plants grown in the FC and the two Al-P plots at weeks 5 and 7 of growth. Root hair length was significantly affected by the P treatments during some harvests, but showed no overall consistent relationship with P fertilization (Table 3).

Plant tissue analysis. In the 2002 season, leaf P concentrations were in the recommended range (3 to 6 mg·g^{-1} DW, Hanlon and Hochmuth, 2000) and were unaffected by P treatments (data not shown). In the 2003 season, leaf P concentration was significantly affected by the P treatments after 3 weeks of growth, and only plants receiving conventional P fertilizer contained tissue levels above the recommended minimum (Fig. 1). Leaf P concentration was reduced by 48% in the low-P control plants, 45% in the Alcoa Al-P plants, and 23% in the Mart Al-P plants compared to plants grown with conventional P fertilizer. After 5 weeks of growth, leaf P concentrations were in the recommended P range for all the P treatments.

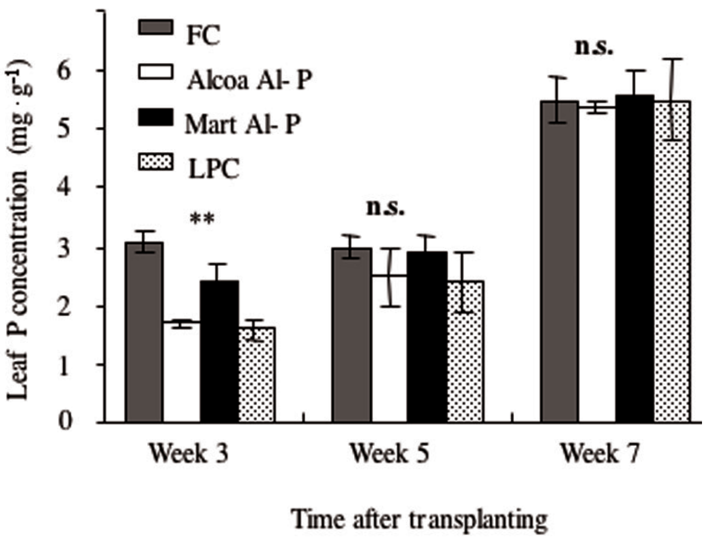

Fig. 1. Leaf phosphorus concentrations of bell pepper grown with fertilizer control (FC), Alcoa Al-P, Mart Al-P, and no added P (LPC) in 2003. Values are means of four replications ± SE. ANOVA results showed significant effects of harvest time ($F = 180$, $P < 0.001$) and P treatment × harvest time ($F = 4.5$, $P < 0.001$). *,**,***Significant treatment differences within harvest times at $P \leq 0.05$, 0.01, and 0.001, respectively.

Analysis of Fe, Ca, and Zn in leaves and fruit revealed few significant differences among P treatments. Leaf Zn concentration was significantly affected by the P treatments in 2002 (Fig. 2) but not in 2003 (data not shown). Plants grown in the fertilized control and Mart Al-P plots accumulated less leaf Zn compared with plants grown in the Alcoa Al-P or low-P control plot and contained less than the recommended Zn range (25 to 75 µg·g^{-1}, Hanlon and Hochmuth, 2000) at week 5 and week 7 of growth in 2002. Similar patterns of Zn accumulation were found in fruit harvested in 2002 and 2003, and fruit Zn concentrations ranged from 20 to 50 µg·g^{-1} (data not shown). Fe and Ca concentrations in leaf samples were within the recommended ranges (Hanlon and Hochmuth, 2000) in all treatments (data not shown).

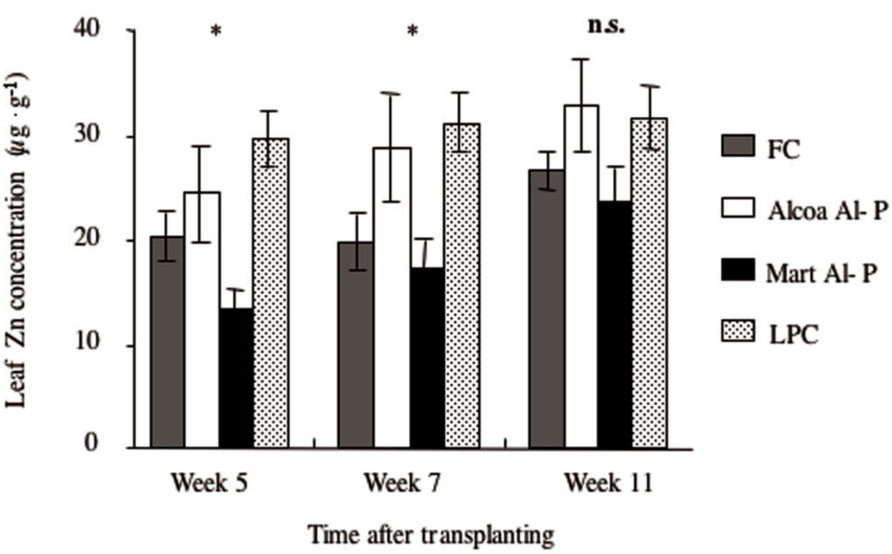

Fig. 2. Leaf Zn concentrations of bell pepper grown with fertilizer control (FC), Alcoa Al-P, Mart Al-P, and no added P (LPC) in 2002. Values are means of four replications ± SE. ANOVA results showed significant effects of harvest time ($F = 3.7$, $P = 0.036$) and P treatments ($F = 8.3$, $P = 0.003$), but no P treatment × harvest time interaction. *,**,***Significant treatment differences within harvest times are nonsignificant or significant at $P \leq 0.05$, 0.01, and 0.001, respectively.

Fruit yield and quality. Yield of marketable fruit was significantly affected by P treatments in the three seasons. In the 2001 season, plots amended with Mart Al-P and Alcoa Al-P produced significantly greater yields than plots receiving no P fertilizer (Table 4). However, in the 2002 season, Alcoa Al-P plot produced half the amount of marketable fruit compared with Mart Al-P or the FC plot. A similar pattern was observed in the 2003 season. Yields were low in these experiments because we planted late and we only harvested twice, while it is typical practice in Penn. to harvest at least four times.

Soil P availability. Al-P treatments increased soil bioavailable P (estimated by iron strip-P method) and available P (estimated by Mehlich III method) compared with the low-P control, but the increase depended on sampling depth (Fig. 3). Mart Al-P usually maintained greater soil bioavailable and available P in the topsoil than the Alcoa Al-P or the low-P control plot. The buffered fertilizers increased bioavailable P from 20 to 40 cm in 2002. By the third year after application (2003), the Alcoa Al-P was not significantly different from the unfertilized control.

Discussion

The ability of alumina buffered P (Al-P) to supply P to a vegetable crop (bell pepper) in a low fertility soil was evaluated in a three-year field trial. Plants grown in soil amended with Martenswerke Al-P received adequate P nutrition over the duration of the trial, with improved marketable fruit yield and growth compared to plants grown under low-P fertility. Overall, peppers grown in soil amended with Martenswerke Al-P had leaf P concentrations similar to plants grown under high fertility (FC), except during the first part of the 2003 growing season, when leaf P concentrations were somewhat lower (Fig. 1). The lower leaf P concentration may have resulted from small root systems that had not begun to explore the soil adequately, and the fact that overall P availability in the plots amended 2 years before with the Martenswerke Al-P was lower than the P availability of the fertilized control. During subsequent vegetative growth, plants grown with the Martenswerke Al-P developed their root systems (Tables 2 and 3) and acquired sufficient P (Fig. 1). Though leaf P was low in the beginning of 2003, the yield of pepper fruit was not significantly different from the fertilized control.

Leaf Zn concentrations for plants from

Table 4. Marketable yield of bell pepper fruit grown with conventional P fertilizer (FC), Alcoa Al-P, Mart Al-P, and no added P (LPC). Bell pepper plants were harvested 9 and 11 weeks after transplanting. Values are means of four replications ± SE. Treatments were compared by ANOVA within seasons (year).

	Yield (kg·ha^{-1})		
Fertilizer	2001	2002	2003
FC	NA[z]	9603 ± 609 a	14276 ± 1510 a
Alcoa Al-P	7044 ± 486 a[y]	4426 ± 1274 b	5853 ± 631 b
Mart Al-P	8456 ± 543 a	10235 ± 1686 a	10103 ± 1375 ab
LPC	3884 ± 787 b	5368 ± 2064 b	6103 ± 2100 b

[z]Conventional phosphorus fertilizer was not applied in 2001.

[y]Means within columns followed by the same letter are not significantly different according to Fisher's protected least significant difference (PLSD) at $P \leq 0.05$.

both the Martenswerke Al-P and fertilized control plots were low compared to plants from the Alcoa Al-P amended plots and from the low fertility controls early in the second growing season (2002) (Fig. 2). Increased shoot biomass may have diluted the leaf Zn concentration, or Zn may have precipitated as Zn-phosphate, due to the higher concentrations of P in the fertilized control and Martenswerke Al-P amended plots (Gianquinto et al., 2000; Zhu et al., 2001; Singh et al., 1988). However, yield of bell pepper in 2002 was not affected by these lowered leaf Zn levels.

Although Alcoa Al-P improved crop yield compared with unfertilized controls during the first year of the study, it failed to provide sufficient P during the second and third years, resulting in lower yield than the other fertilized treatments (Table 4). Leaf P and Zn concentrations in Alcoa Al-P plants were similar to peppers grown in the low fertility control plots during 2002 and 2003 (Fig. 1 and 2).

The Alcoa and Martenswerke Al-P products were desorbing P at concentrations of 128 μM-P and 250 μM-P, respectively, at the beginning of the trial. The Alcoa product appeared to have reduced desorption after one year in the soil (Fig. 3), and maintained soluble soil P levels too low for optimum growth during the last 2 years of the study. The Martenswerke Al-P product, however, was able to maintain adequate P desorption for 2 years in the soil, with a slight decrease in desorption that lowered initial P uptake levels for transplants at the beginning of the third year, but ultimately did not affect crop yields for that season. The inability of the Alcoa Al-P to supply enough P for adequate plant growth and fruit production may have been due to lower initial bound P levels, reduced P desorption, or to faster desorption of bound P during the initial year.

Studies have shown that unrinsed Al-P applied to soilless medium will initially leach excess or loosely bound P (Brown, 1999, 2003; Lin, 1996). Phosphorus leaching in this situation will quickly decrease during the first few weeks and will then stabilize at a lower level of desorption. In our field trials, the Al-P materials used were desorbing at much higher levels than in the studies referenced above. Therefore, during the first year of the field study, both products may have desorbed at an initially high rate. In the case of the Martenswerke product, desorption had leveled off to an adequate amount of P the second and third years, but in the Alcoa product, its P reserves were sufficiently depleted to produce only inferior plant growth for the second and third years of the trial.

Previous studies evaluated the effectiveness of alumina-buffered P fertilizers in soilless media or sand. In natural soils a variety of processes buffer P availability to plants, including interactions with soil biota and secondary minerals, some of which have similar surface chemistry as the Al-P material. Many agricultural lands are limited by low-P availability, and there is concern over loss of P as a pollutant from high input agricultural systems in the United States. A P management system is needed that balances the needs of crop productivity and environmental health. Our results indicate that buffered P sources such as Al-P could be used to lower application rates of soluble P fertilizer while ensuring crop yields similar to those obtained by conventional fer-

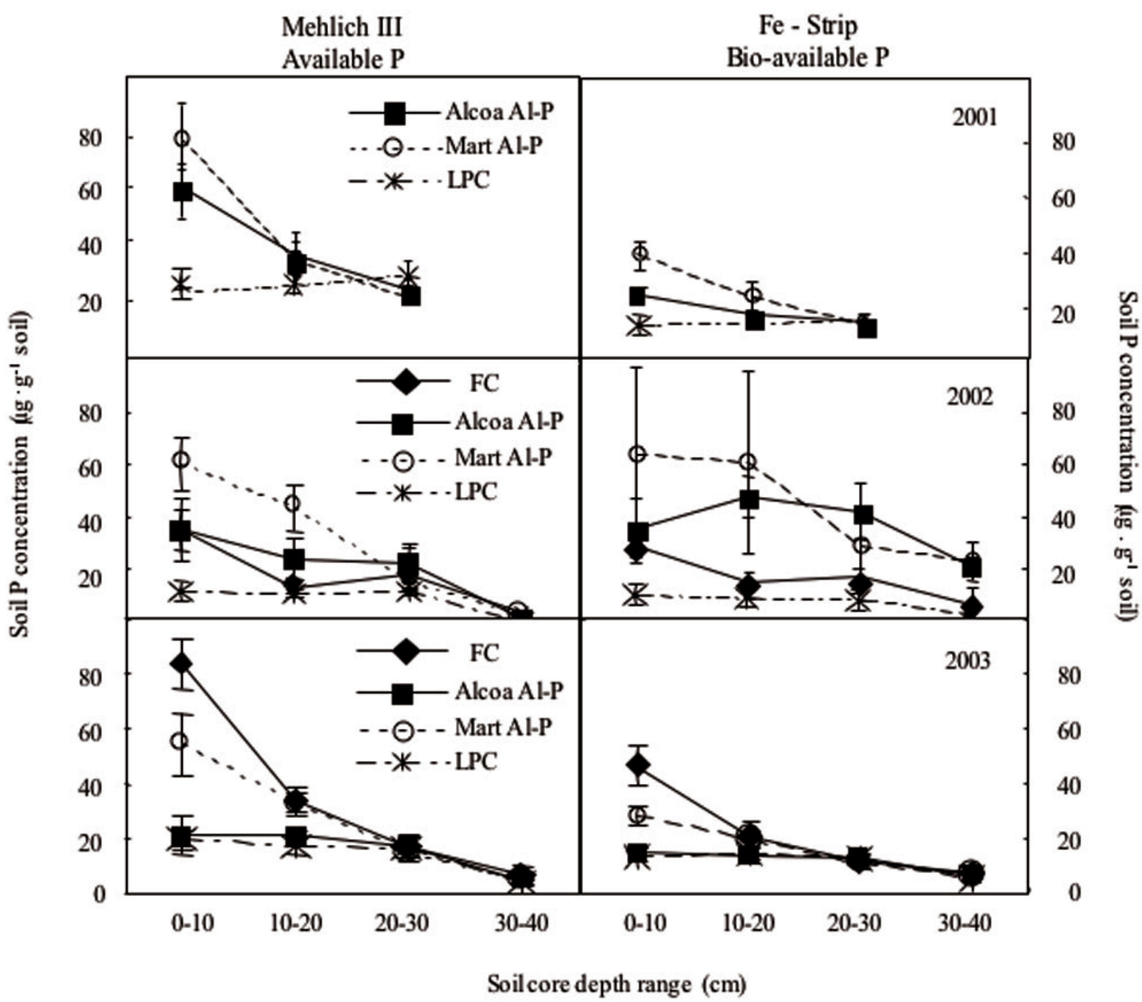

Fig. 3. Phosphorus concentration in soil amended with Alcoa Al-P, Mart Al-P, and no added P (LPC) in 2001 and with fertilizer control (FC), Alcoa Al-P, Mart Al-P, and no added P (LPC) in 2002 and 2003. Values shown are means of four replications ± SE for each sampling depth and year. Figures in left column are for Mehlich III, and the right column for Fe-strip. X coordinate values are the sampling depths from the soil surface.

tilization practices. The Martenswerke product produced good crop yields over 3 years, but results from the third season show that some amendment with P fertilizer may be needed after 3 years. Possible benefits of buffered P sources in natural soil include reduced P runoff, improved root growth, and better micronutrient nutrition (Boateng 2002). Phosphorus buffers that eventually may be used in field agriculture could derive from waste materials containing Fe or Al oxides to reduce cost.

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