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Phosphorus Movement in Calcareous Soils Irrigated with Waste Water from Potato Processing Plants[1]

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ABSTRACT

Total, organic, and acid-hydrolyzable phosphorus and orthophosphate concentrations were determined in waste waters from five potato (*Solanum tuberosum* L.) processing plants and the waste water volumes applied to cropped land were measured monthly for three processing seasons. These P forms were also measured in soil water samples extracted monthly at five depths to 1.5 m. Organic plus hydrolyzable fractions comprised 60 to 70% of the total P in the waste waters and 30 to 40% in the soil water extracts. When the numerical value of the relationship (kg P/ha applied per month) (mm of clay size material in 1.5 m)$^{-1}$ was $<$0.4, the total P concentration in the extracts at 1.5 m was $<$0.05 mg/liter. When the value exceeded 0.4, the total P concentrations in the extracts averaged 1 to 2 mg/liter. The relationship may provide disposal site selection and waste water application rate guidelines for land disposal of waste water high in organic and hydrolyzable P.

Additional Index Words: waste water renovation, phosphate adsorption, organic phosphorus fixation, water quality.

Recent regulations governing waste water discharge into surface waters and increasing costs for waste water treatment have encouraged food processors to develop cropland irrigation systems for processing plant waste water disposal (1, 9, 13). To be effective, land application must remove the phosphorus from waste water before it enters surface or ground waters.

Although considerable data are available for predicting and modeling orthophosphate movement in soils (7, 8, 12), the P in food processing plant wastes may be predominantly of plant or animal origin, and may be combined in organic phosphate forms (9). The compounds do not have the same chemical and physical properties as orthophosphate and cannot be expected to react the same with the soil (5, 6, 11). Applying high-energy or high chemical oxygen demand (COD) materials found in food processing waste waters to soils (9, 13) stimulates biological activity and may solubilize otherwise insoluble soil P compounds (6, 7). Under these conditions, P movement may be greater than predicted by orthophosphate models.

Phosphorus movement depends upon total P application rates, relative amounts in organic forms, solubilities of the P forms, hydrolysis rates to orthophosphate, orthophosphate fixation, precipitation rates, water retention times, and water movement within the soil profile. Recent studies showed that the movement of surface-applied soluble organic P fertilizers in soils was directly related to the water infiltration rates and to the rates at which the applied material was hydrolyzed by soil phosphatase enzymes (10, 11). This paper reports P movement under land application of potato processing plant waste water which is high in both COD and total P (9, 13).

METHODS

Waste water samples from five southern Idaho potato (*Solanum tuberosa* L.) processing plants and soil water extracts from waste disposal fields were sampled monthly for the first 3 years of disposal by land application. Processing plant samples taken at 20-minute intervals over a 24-hour period with an automatic sampling device (4) were composited into a container in a small freezer and immediately frozen and stored until analyzed. Soil water samples were extracted through porous ceramic cups cemented to the bottom of 38-mm-diameter polyvinylchloride tubes at depths of 0.15, 0.30, 0.60, 0.90, 1.20, and 1.50 m at two sites in disposal fields at each potato processing plant. Soil water was drawn into the tubes by applying 0.7 bar suction for 24 to 48 hours. After releasing the suction, samples were pumped from the sample tubes and transferred to storage bottles. Mercuric chloride was added to subsamples to retard hydrolysis of the organic and hydrolyzable P to orthophosphate.

As soon as possible after bringing the samples into the laboratory, orthophosphate and hydrolyzable, organic, and total P concentrations were determined. Orthophosphate was measured by an ascorbic acid method (14) without pretreatment of samples. Acid-hydrolyzable P plus orthophosphate was determined by treating with a sulfuric-nitric acid mixture and autoclaving. The combined phosphates were then measured by the ascorbic acid method. The orthophosphate concentration was subtracted from the value obtained to give acid-hydrolyzable P concentration. Total P was determined by converting all P in the samples to orthophosphate by autoclaving in the presence of potassium persulfate and sulfuric acid. Organic P values were obtained by subtracting the hydrolyzable plus orthophosphate from total P (2).

Soil samples were taken annually at 0.3-m depth increments to 1.5-m and bicarbonate extractable (14) and total P were de-

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Table 1—Total P concentration in potato plant waste water and P fractions in waste water and soil wasters extracted from 1.5 m in disposal fields

Plant	Total P in effluent	P fraction in effluent			P fraction in 1.5-m soil extracts		
		Ortho	Hydrolyzable	Organic	Ortho	Hydrolyzable	Organic
	mg P/liter	%					
1F	12.8 ± 4.6	43	19	38	64	20	16
2F	5.9 ± 2.3	28	23	49	67	17	16
3S	21.8 ± 16.9	29	19	52	--	--	--
4S	8.0 ± 1.8	31	23	46	--	--	--
5F	9.5 ± 2.7	30	25	45	61	21	18

termined. Total P was determined by persulfate digestion. This method was compared with nitric-perchloric acid digestion and sodium carbonate fusion methods for total P before it was selected for use in this study (3). When the samples were autoclaved for 0.5 hours at 123C (2 bar pressure), the persulfate digestion gave total P values as high as the other methods.

The clay-size fraction (<2 μm diameter particles) of each soil depth increment was determined using a standard hydrometer method for particle-size analysis. This fraction was expressed as a depth of clay-size material by multiplying the clay content by the thickness of the depth increment. The increments for clay thickness (mm) were added to give a total depth of clay-size material for the 1.5-m depth of soil.

Wastes from potato processing plants designated as 1F, 2F, and 5F were disposed of by flood irrigation on nearly level borders. Those from plants 3S and 4S were sprinkled onto leveled land. Orchardgrass (*Dactylis glomerata* L.), alta fescue (*Festuca arundinacea* schreb.), or reed canary grass (*Phalaris arundinacea* L.), or mixtures of these species, planted at each disposal site, were harvested for hay or grazed by livestock (13).

RESULTS AND DISCUSSION

Average total P in the processing plant effluent ranged from 5.9 to 21.8 mg/liter over a 3-year period for the five plants sampled (Table 1). Orthophosphate constituted one-third of the P applied and two-thirds of the P extracted in the soil water at 1.5 m. Only waste water data are shown for processing plants 3S and 4S. Insufficient soil water data were obtained to evaluate P movement associated with waste waters from these two processing plants.

Table 2—Monthly total P application rates at three potato processing plant waste disposal fields and suggested maximum monthly application rates

	Plant 1F		Plant 2F		Plant 5F	
	1973	1974	1974	1975	1973	1974
	kg/ha					
Jan.	8.8	77.4	18.4	44.5	30.4	31.9
Feb.	4.0	77.0	13.3	17.7	32.6	12.3
Mar.	39.5	104.0	8.6	8.7	16.5	16.3
Apr.	0.0	10.8	12.5	9.1	35.1	18.4
May	37.5	64.0	14.1	7.4	20.0	24.7
June	34.3	97.1	11.1	10.1	24.1	5.7
July	101.1	28.0	19.2	5.1	4.9	0.0
Aug.	71.6	42.7	0.0	0.3	0.0	0.0
Sept.	77.4	15.2	5.4	1.7	0.0	30.3
Oct.	65.0	45.7	12.0	4.3	12.1	27.2
Nov.	142.0	70.7	10.4	9.9	13.1	19.3
Dec.	39.3	12.3	12.1	3.6	31.1	224.6
Total	620.5	645.0	127.0	122.4	220.0	210.0
Average	51.7	53.7	11.4	10.2	18.3	17.5
Suggested maximum monthly P application rates (kg/ha) based on profile clay-size material content						
Site 1	74		9		104	
Site 2	49		53		113	

Yearly total P applications ranged from 122 kg/ha at plant 2F in 1974 to 645 kg/ha at plant 1F in 1974 (Table 2). Monthly application rates ranged from 0 at several locations to 142 kg/ha during November 1973 at plant 1F. The suggested maximum monthly application rates will be discussed later.

The accumulative depth of clay-size material ranged from 22 mm at site 1 for plant 2F to 282 mm at site 2 for plant 5F (Table 3). Mean total P concentrations in soil water extracted at each depth indicate that P was removed from the water at site 2 at plant 2F and at both sites at plant 5F. Phosphorus removal was not sufficient to meet environmental standards at the other three sites even though site 1 at plant 2F received less P than did the plant 5F sites (Table 2). The data indicate a relationship between the P removal and the accumulative depth of clay-size material, but there is also an effect of P loading. Both sites at plant 1F were obviously overloaded.

If the P concentrations in the soil water extracted (P_e) at 1.5 m divided by the P concentration in the waste water

Table 3—Particle-size distribution, accumulative depth of clay-size material, and mean total P concentration in soil water extracted at six potato processing plant waste disposal sites

Depth	Sand	Silt	Clay	Accumulative depth of clay-size material	Mean total P concentration in extracted water
mm	%			mm	mg/liter
			Plant 1F		
Site 1					
0.0–0.3	39	45	16	48	4.26
0.3–0.6	44	43	13	87	1.35
0.6–0.9	67	23	10	117	1.78
0.9-1.2	55	31	14	159	1.92
1.2-1.5	73	18	9	186	1.19
Site 2					
0.0-0.3	48	34	18	54	6.74
0.3-0.6	54	32	14	96	4.96
0.6-0.9	87	9	4	108	5.55
0.9-1.2	90	7	3	117	2.92
1.2-1.5	90	7	3	123	2.08
			Plant 2F		
Site 1†					
0.0-0.3	46	36	18	14	1.32
0.3-0.6	85	10	5	17	1.60
0.6-0.9	96	2	2	19	1.70
0.9-1.2	97	1	2	20	1.72
1.2-1.5	97	1	2	22	1.40
Site 2					
0.0–0.3	54	29	17	51	0.74
0.3-0.6	66	25	9	78	0.62
0.6–0.9	71	23	6	96	0.82
0.9-1.2	58	36	6	126	0.04
1.2-1.5	70	24	6	132	0.04
			Plant 5F		
Site 1					
0.0–0.3	66	22	12	36	0.33
0.3–0.6	49	33	18	90	0.13
0.6–0.9	57	28	15	135	0.86
0.9–1.2	51	33	16	183	0.14
1.2-1.5	24	50	26	261	0.03
Site 2					
0.0-0.3	38	44	18	54	0.17
0.3-0.6	64	23	13	93	0.11
0.6–0.9	26	51	23	162	0.48
0.9-1.2	32	49	19	219	0.04
1.2-1.5	25	54	21	282	0.03

† This is the particle-size distribution for that fraction of the soil which passed a 2-mm sieve. The profile contained 70 to 80% gravel or cobble at all depths.

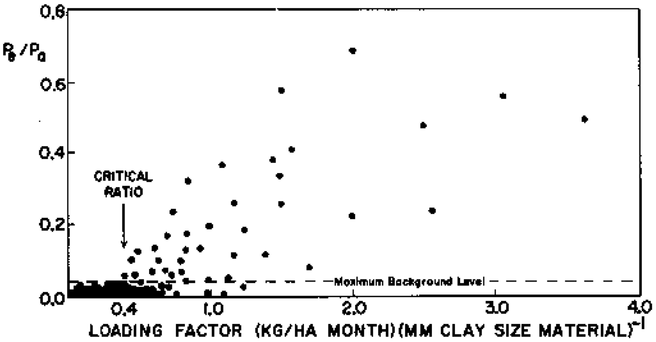

Fig. 1—Fraction of applied total P, extracted at 1.5 m (P_e/P_a) as affected by application rates and soil texture.

being applied (P_a) is plotted against a loading factor that is calculated as the kg P/ha added per month divided by the accumulative depth of clay-size material in mm, a critical ratio between the P application rate and the clay-size material can be developed (Fig. 1). This critical ratio appears to be 0.4 (kg/ha per month) (mm clay-size material)$^{-1}$ for the six sites sampled. The line labeled "Maximum background level" represents the P_e/P_a values obtained when P_e is below 0.05 mg/liter total P. The points below the line represent soil water samples that contained no more P than the samples extracted before potato processing plant waste water was applied to the disposal sites. The points above the line represent water samples where the soil had not completely removed the P applied in the waste water. The limited data available from the four 3S and 4S disposal sites fit the relationship. The value of 0.4 appears to have a safety factor built in for most normal soil profiles, since the high P_e/P_a values in the 0.4 to 0.7 range in Fig. 1 are from site 1 at plant 2F, which has very little P removing ability because of its very low clay content and high hydraulic conductivity. This site contains from 70 to 80% gravel and cobble.

Using this empirical value of 0.4, we calculated suggested maximum monthly P application rates for the six disposal sites (Table 2). Application rates for both sites at plant 5F and for site 2 at plant 2F never exceeded the suggested loading maximum for P removal in 1.5 m. The reason site 1 at plant 2F was exceeded was the low clay content rather than the P loading rate. Application rates at plant 1F exceeded the suggested ratio of 0.4 for several months each year. Table 3 shows a 30 to 70 times higher P concentration at the 1.5-m depth in the profiles that have been overloaded than in those that have been properly loaded. More P will be removed by soil below the 1.5-depth and, using this same ratio, the additional soil depth required to remove the P can be estimated.

It should be realized that using the clay-size fraction content to calculate the empirical ratio value inserts several factors into the calculation that are affected by soil texture. The higher the clay and fine material content, the higher the water-holding capacity, and usually the lower the hydraulic conductivity. Thus, the water will be held in the sampling zone longer. The longer retention time will allow more organic and hydrolyzable P to be converted to orthophosphate. The longer retention time will allow more orthophosphates to be precipitated with soil solution cations and to react with the soil colloidal material. The clay-type, organic matter, and fine calcareous material contents will not be the same at all locations and will affect both the organic P conversion rate to orthophosphate and the orthophosphate fixation rate (7).

Bicarbonate-extractable P tended to increase to an equilibrium value unique to each location for those sites not overloaded with P (Table 4). All sites that received more P than could be removed from solution were still increasing in bicarbonate-extractable P after 4 years. Overloaded sites seemed to recover after 2 to 3 months under proper loading and were then effective in removing P until they were overloaded again. The two examples shown are typical for the 10 locations sampled, where one is properly managed and the other is overloaded. Data for the other sites are not shown in Table 4 because the P removal followed one of these two examples, depending on relationships between loading rate and clay-size material content. Total P increases were measurable only down to 0.9 m after 3 years of waste water application. High total P variability masked any increases below this depth.

No attempt is made here to predict how long properly loaded sites will effectively remove P from applied waste water. However, the fact that bicarbonate-extractable values remained constant for 3 years suggests that the P not being removed by the crop is probably being precipitated by the cations in these calcareous soils. How long a site will effectively remove P from solution will depend on the orthophosphate immobilization mechanism. The P and other plant nutrients in the potato processing plant waste water should be applied, where practical, to larger cultivated areas, thus making better use of the P applied (13).

CONCLUSIONS

Land disposal will effectively remove P from potato processing plant waste water if the loading rates are adjusted to fit the disposal sites. After 4 years, the total P concentration was < 0.05 mg/liter before the water reached a depth of 1.5 m on properly managed potato processing plant waste water sites. This concentration meets the suggested P levels set by states that have established suggested P concentration in waters returning to

Table 4—Bicarbonate extractable orthophosphate and total P from two waste disposal sites

	Bicarbonate extractable orthophosphate				Total P			
Soil depth	1972	1973	1974	1975	1972	1973	1974	1975
m	mg P/liter							
				Plant 5F—Site 2				
0.0-0.3	11.0	25.7	51.3	47.0	720	759	816	825
0.3-0.6	4.2	17.6	15.7	18.0	642	687	684	820
0.6-0.9	--	18.2	17.5	18.1	638	654	804	795
0.9-1.2	3.6	16.9	15.4	15.0	726	732	724	710
1.2-1.5	3.5	15.1	14.7	13.8	708	735	708	730
				Plant 1F—Site 1				
0.0-0.3	40.6	--	52.5	62.0	531	--	405	611
0.3-0.6	20.0	--	31.6	42.1	439	--	525	575
0.6-0.9	9.4	--	13.8	21.8	419	--	342	450
0.9-1.2	11.3	--	16.5	19.0	392	--	475	468
1.2-1.5	6.6	--	10.0	17.7	401	--	454	396

the groundwaters (1). The overloaded sites, however, did not provide the renovation necessary to remove the P sufficiently to meet these requirements within the 1.5-m sampling depth. Greater depths or lower application rates will be required for adequate P removal at these sites. The data obtained from this study indicate that a satisfactory monthly P application rate (kg/ha) for a particular site can be approximated by multiplying the accumulative depth (mm) of clay-size material in the P cleanup zone by 0.4. Gravelly and very sandy disposal sites cannot be expected to be as effective in removing P from waste waters as soils containing more clay-size particles.

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