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Influence of polyacrylamide application to soil on movement of microorganisms in runoff water☆

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"Capsule": *Polyacrylamide used in irrigation reduces soil erosion and pathogen transport.*

Abstract

Polyacrylamide (PAM) use in irrigation for erosion control has increased water infiltration and reduced soil erosion. This has improved runoff water quality via lower concentrations of nitrogen, phosphorous, and pesticides, and decreased biological oxygen demand. Since non-toxic high molecular weight anionic PAMs removed clay size sediment particles in flowing water, we hypothesized that PAM would effectively remove or immobilize microorganisms in flowing water. In an agricultural field, we determined the efficacy of PAM-treatment of furrow irrigation water to remove several categories of microorganisms in the inflow and runoff. Treatments were: (1) PAM application and a control; (2) three flow rates; (3) two distances from the inflow point; and (4) three times during each irrigation. After water traveled 1 m at 7.5 and 15.5 l min^{-1}, PAM-treatment reduced total bacterial and microbial biomass and total fungal biomass relative to the control treatment. After water traveled 40 m at 7.5, 15.5, and 22.5 l min^{-1}, PAM-treatment reduced algae, the numbers active and total bacteria, active and total fungal length, and total bacterial biomass, total fungal and microbial biomass relative to the control treatment. Although specific organisms were not identified or monitored in this study, the results clearly have implications for controlling the spread of soil-borne plant pathogens and other classes of harmful organisms within and among fields via irrigation water and in re-utilized return flows. Beyond furrow-irrigated agriculture, new methods to manage overland transmission of harmful microorganisms could potentially help control transport of pathogens from animal waste in runoff and groundwater. Published by Elsevier Science Ltd.

Keywords: Polyacrylamide; Application; Soil; Microorganisms; Movement; Runoff water

1. Introduction

Pollution of surface and groundwater from water flowing over irrigated fields after manure application is an important vector for transport of microorganisms (Khaeel et al., 1980; Mawdsley et al., 1995; Mallin et al., 1997). Irrigation water applied to fields follows natural groundwater drainage patterns and, if containing pathogenic microorganisms, may contaminate adjoining bodies of surface water. These same bodies of water are often used as sources of drinking water and/or for recreational activities. Reducing the transport of enteric bacteria, many of which are pathogenic to humans, or plant pathogens such as *Phytophthora* spp., *Pythium* spp., *Fusarium* spp., and *Polymyxa* spp. that are spread via water, could limit the severity and spread of disease.

Paganyas (1975) gave the first report of polymer use in furrow irrigation water resulting in reduction of sediment transport in the furrows. The effect was not quantified and the specific chemical polymer used was not identified, although its description would suggest some type of polyacrylamide (PAM) formulation. Mitchell (1986) also noted the clarification of runoff streams but did not quantify sediment effects. The effect was also reported by Wallace and Wallace (1986a, b) who noted the potential for soil erosion control. Lentz et al. (1992) and Lentz and Sojka (1994) gave the first detailed reports of PAM use in furrow irrigation for erosion control and increased infiltration, quantifying changes in sediment concentration and accumulation over time, sediment loss, infiltration, and runoff. These results have been consistent in numerous studies for different soils under a wide range of conditions, including sprinkler irrigation (Levin et al., 1991; Ben Hur,

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1994; McCutchan et al., 1994; Trout et al., 1995; Aase et al., 1998; Sojka et al., 1998a, b). Lentz and Sojka (1994) and Lentz et al. (1998a, b) reported that PAM-treatment reduced field sediment loss and improved the runoff water quality parameters *ortho*-P, total-P, nitrate, and biological oxygen demand. On silt loam soils, runoff sediment reduction averaged 94% and infiltration increased 15% in a 3-year series of studies. Other studies have documented how PAM-treatment of furrow irrigation water improved runoff water quality parameters including pesticide loads (Agassi et al., 1995; Bahr et al., 1996; Bahr and Steiber, 1996; Singh et al., 1996).

The most frequent approach in the furrow irrigation studies involved PAM-treatment of the furrow advance stream (only). Efficacious treatment was usually possible with PAM application rates of about 1 kg ha^{-1} (approx. 1 lb $acre^{-1}$) applied at a concentration of 10 ppm only in the advancing furrow stream (the period of the irrigation before runoff, when water is first traversing the dry furrow). McCutchan et al. (1994) reported similar runoff sediment load reductions, although their approach involved application of PAM at 2.5 ppm continuously throughout the irrigation. Increasingly, farmers have found successful results applying area equivalent rates as a small powder patch applied directly to the soil at the water inlet to each furrow immediately before irrigation. Efficacy of the powder patch approach has been verified experimentally.[1] With on-farm cost of PAM ranging from about $7 to 13 ha^{-1}, the practice has been adopted on a million acres in the USA as of 1998 and is also rapidly gaining acceptance overseas. The practice is receiving additional attention throughout the Western USA as several states begin seeking ways to bring irrigation return-flows below mandated total maximum daily loads (TMDLs) for specific contaminants.

The microbiology of PAM-treated soils has not been intensively researched; however, certain key information is known. When PAM is mixed thoroughly with soil, it degrades slowly (about 10% per year) as a result of mechanical degradation, chemical and biological hydrolysis, sunlight, salt, and temperature effects (Azzam et al., 1983; Wallace et al., 1986; Tolstikh et al., 1992). PAM decomposition was shown to be thermodynamically incapable of releasing free acrylamide monomer (AMD; MacWilliams, 1978). Small residual amounts of AMD contained in PAMs are rapidly (tens of hours) metabolized in soil or natural waters by microorganisms as a nitrogen source (Lande et al., 1979; Abdelmagid and Tabatabai, 1982; US EPA, 1985; Shanker et al., 1990).

No adverse effects of PAM on soil microbiology have been reported. Grula et al. (1994) reported that PAMs, depending on molecular weight and the functional groups substituted, are capable of acting as incomplete substrates supporting microbial growth. Longer-chained PAMs are more resistant to metabolism than shorter-chained PAMs. Increased growth and microbial biomass of aerobic bacteria have been reported for soils treated with PAM (Nadler and Steinberger, 1993; Steinberger et al., 1993).

The PAMs developed for use in irrigation erosion control are very large anionic molecules that have been shown to be safe for, and are widely used in, a variety of food, pharmaceutical, and sensitive environmental applications, including finished treatment of potable water (Barvenik, 1994). They should not be confused with, or evaluated with other PAM formulations, especially cationic PAMs, which have known environmental safety concerns related to their specific chemistries (Barvenik, 1994), or with low molecular weight PAMs synthesized in situ for electrophoresis gels (which commonly contain high residual AMD levels because of the difficulty of efficient benchtop polymerization).

Because of the extraordinary efficacy of non-toxic high molecular weight anionic PAMs for removing fine suspended materials in flowing water, we hypothesized that PAM use would have a significant impact on the removal and/or immobilization of microorganisms in flowing water. Our objective was to test this hypothesis by monitoring the effect of PAM-treatment of furrow irrigation water within an agricultural field on several categories of microbial populations in the inflow and runoff.

2. Materials and methods

2.1. Study site

The study was conducted at the USDA Agricultural Research Service's Northwest Irrigation and Soils Research Laboratory in Kimberly, ID. The soil in the test area was Portneuf silt loam (coarse-silty, mixed, superactive mesic Durinodic Xeric Haplocalcid), with 10–21% clay and 60–75% silt, and organic matter of approximately 13 g kg^{-1}. Saturated paste extract electrical conductivity (EC) of this soil ranges from 0.7 to 1.3 dS m^{-1}, with exchangeable sodium percentage (ESP) of 1.4–1.7 and pH of 7.6–8.0 with a $CaCO_3$ equivalent of 2–8%. Slope on this site was approximately 1.5%.

2.2. Experimental design

The experimental design was a randomized complete block with three replications. Treatments were: (1) PAM application and a control (no PAM applied); (2) three flow rates (7.5, 15.5, and 22.5 l min^{-1}) corresponding to three different irrigation dates; (3) distance along the furrow (1 m below the inflow point and 40 m

[1] R.E. Sojka, unpublished data.

down furrow); and (4) time during irrigation (0.5, 3.5 and 6.5 h after initial inflow). Field plots were considered blocks. Three water samples were taken during the course of each irrigation at each sampling point. Plots were 40 m long×4 m wide. Furrows were on 76-cm spacings within each plot and alternate furrows were irrigated during each irrigation. A single irrigated furrow was sampled within each plot on each irrigation date.

2.3. PAM application

The PAM copolymer used was a dry granular material having an approximate molecular weight of 12–15 mg mol^{-1}, with an 18% negative charge density (provided by CYTEC Industries of Wayne, NJ, and marketed under the trade name Superfloc 836A). PAM application involved the spread of granular PAM on the surface of an approximately 0.1 m^2 area of soil in the furrow, corresponding to the first meter of furrow below inflow spigots. Application amounts were 35, 35, and 15 g of material (approx. 28, 28, and 12 g of active ingredient) on three consecutive irrigation dates, respectively. Experience from other experiments[2] has shown that water flowing over these patches of PAM granules results in PAM concentrations of 5–15 ppm (g m^{-3}) during the first 20–40 min during the irrigation, declining to lower concentrations after several hours.

2.4. Water application

Water was applied as furrow irrigation from a storage pond via spigoted plastic pipe to a conventionally tilled field that had been disked to 10 cm depth in autumn and spring, then roller harrowed following incorporation of fertilizer and herbicides prior to planting. Furrows, 40 m in length, and approximately 10 cm in depth, were prepared with weighted 75°v-shaped furrow shaping tools. Furrow spacing in this crop of edible dry beans (*Phaseolus vulgaris*) was 76 cm. Irrigation was on every other furrow only, in wheel-track furrows on the first irrigation, non-wheel furrows in the second irrigation, and in wheel-track furrows again on the third irrigation. Three water flow rates were used (7.5, 15.0, 22.5 l min^{-1}), which corresponded to the three different irrigation dates: 19 June, 2 July, and 17 July 1997. Per hectare sediment loss and infiltration depth were calculated based on inflow and outflow rate measurements, sediment concentration of outflow, and spacing between irrigated furrows, following previously published protocols (Sojka et al., 1992, 1994). Irrigation water EC was 0.5 dS m^{-1} with a sodium adsorption ratio (SAR) of 0.4–0.7.

[2] R.E. Sojka, unpublished data.

2.5. Sample collection

Water samples for biological analysis were collected from the surface to a 3-cm water depth at the inlet, 1 m below the water inlet (top of furrows), and 40 m below the water inlet (bottom of furrows). Water samples were taken at approximately 30 min following initiation of each irrigation, and at 3.5 and 6.5 h after irrigation was applied. Three separate water samples were taken at each sampling point at each time of sampling. Samples were collected and analyzed for active fungal biomass, active bacterial biomass, total fungal biomass, total bacterial biomass, and algae. Water was collected and stored in air-tight and water-tight plastic 125-ml bottles and prepared for microbial testing within 24-h of collection to minimize the effects of storage on microbial activity (West et al., 1986).

2.6. Microbial analysis

Active and total bacteria and fungi numbers and biomass in leachate and surface flow were determined for each treatment using methods described by Ingham and Klein (1984). Active fungi were estimated by taking a 1.0-ml water sample which was diluted in 9 ml of a phosphate buffer (pH 6.0) and shaken at approximately 120 rpm for 5 min. A 1-ml aliquot was removed and stained with 1 ml of a 20 μg ml^{-1} fluorescein diacetate (FDA) solution in a 0.2 M phosphate buffer for 3 min. One milliliter of 1.5% agar in a 0.1 M phosphate buffer (pH 9.5) was added to the FDA suspension. The sample was mixed and an aliquot placed on a microscope slide containing a cavity of known volume (Ingham and Klein, 1984). Immediately after preparation, slides were examined for FDA-stained hyphal length by epifluorescent microscopy. Total fungal biomass was estimated by measuring the length and diameter of hyphae in 3–60 fields with phase-contrast microscopy. Three slides were evaluated from each sample and 10 fields per slide were evaluated with phase-contrast microscopy for total hyphal length, and three transects were evaluated for FDA-stained (active) hyphal length at 160× total magnification.

Iodonitrotetrazolium (INT) stain was used for counting active bacteria (Stamatiadis et al., 1990). A 1-ml sample of initial soil suspension was diluted to a final dilution in 0.2 mg soil in 4 ml buffer. The suspension was incubated with 4 ml of filtered INT buffer for 60 min in the dark at 20°C. Total bacteria per milliliter of water was estimated from the mean number of bacteria (fluorescent and non-fluorescent bacteria), their average diameter and length per field. Three slides were evaluated for each sample and 10 fields per slide were evaluated using epifluorescent oil-immersion microscopy to determine numbers and size of fluorescent and total bacteria (Lodge and Ingham, 1991).

Bacterial biomass was computed from the numbers of active and total bacteria and active and total fungal biomass were determined from hyphal length. Bacterial biomass was computed from the number of soil bacteria per gram of soil by considering that the bacterial spheres were 1 μm in diameter (Jenkinson and Ladd, 1981). Active and total fungal biomass were computed by considering average hyphal diameter to be 1 μm in diameter and then multiplying by the length of observed hyphae (Jenkinson and Ladd, 1981). A carbon-to-volume conversion factor of 120 μg C mm^{-3} was used for both bacteria and fungi, assuming 1.1 g cm^{-3} wet density, 20% dry matter content, and a 0.41 carbon content in the bacterium or fungus (Jenkinson and Ladd, 1981).

2.7. Statistical analysis

Microbial data were transformed using natural logarithms to achieve a normal distribution; data were then subjected to a general linear models analysis of variance (Kirk, 1982). Residuals were normally distributed with constant variance. Differences among treatment means were computed using the least-square means test ($p \leq 0.05$, $n = 9$).

3. Results

Analysis of variance indicated that treatment×flow rate×distance×time, treatment×flow rate×time, treatment×distance×time, and flow rate×distance×time interactions for the number of active and total bacteria and fungi g^{-1} soil, active bacterial and fungal biomass, total bacterial and fungal biomass, algae, active fungal biomass/active bacterial biomass, total fungal biomass total bacterial biomass microbial biomass were not significant. Therefore, results will be discussed with regard to treatment×flow rate×distance (Kirk, 1982). After water traveled 1 m at the inflow rate of 7.5 l min^{-1}, PAM-treatment reduced the number of total fungi and active bacteria relative to the control treatment (Table 1). After water traveled 40 m at 7.5 l min^{-1}, PAM-treatment reduced the number of active and total fungal, bacterial and microbial biomass compared to the control treatment. After water traveled 1 and 40 m at 15.5 l min^{-1}, PAM-treatment reduced the number of total fungi and bacteria relative to the control treatment. After water traveled 1 or 40 m at 22.5 l min^{-1}, PAM-treatment reduced the number of active and total bacteria and fungi relative to the control treatment.

After water traveled 1 m at 7.5 l min^{-1}, PAM-treatment reduced total bacterial and fungal biomass and total bacterial biomass relative to the control treatment (Table 2). After water traveled 40 m at 7.5 l min^{-1}, PAM-treatment reduced active microbial biomass, total fungal and bacterial biomass, total microbial biomass, and algae and increased both the active fungal/active bacterial ratio (AF/AB) when compared to the control treatment. After water traveled 1 m at 15.5 l min^{-1}, PAM-treatment reduced active and total bacterial biomass, total fungal biomass, active microbial biomass, total microbial biomass and the total fungal/total bacterial ratio (TF/TB) relative to the control treatment

Table 1
Movement of microbial numbers across an agricultural soil with and without polyacrylamide dissolved in water at these different rates of flow[a,b]

Treatment	Flow distance (m)	Active fungi	Total fungi	Active bacteria	Total bacteria
		$\times 10^4$ = (μm hyphae ml^{-1} water)		$\times 10^5$ = (bacteria ml^{-1} water)	
7.5 l min^{-1}					
Control	1	0.32 f	265 b	12.36 e	12.76 c
Polyacrylamide	1	0.26 f	0.00 d	2.34 f	12.91 c
Control	40	3.67 e	360 b	10.61 e	22.82 b
Polyacrylamide	40	0.00 f	0.00 d	2.91 f	12.06 c
15.5 l min^{-1}					
Control	1	20.83 c	827 a	80.42 c	13.85 c
Polyacrylamide	1	9.25 dc	215 c	25.73 d	6.32 d
Control	40	41.67 bc	826 a	81.31 c	30.51 b
Polyacrylamide	40	4.63 e	32 c	26.3 d	12.10 c
21.5 l min^{-1}					
Control	1	229.94 a	827 a	234.88 a	41.23 b
Polyacrylamide	1	60.03 b	215 b	145.44 b	33.04 b
Control	40	183.64 a	715 a	299.34 a	96.5 a
Polyacrylamide	40	18.52 c	31 c	133.23 b	39.8 b
Inflow		0.00 f	0.00 d	3.86 f	15.83 c

[a] Field length was 42.5 m. Top of field was sampled 1.0 m from the inflow. Bottom of field was sampled 40 m from the inflow.
[b] In each column, values followed by the same letter are not significantly different as determined by Fisher's protected least significant different test ($p \leq 0.05$; $n = 9$).

Table 2
Movement of microorganisms as biomass and sediment across an agricultural soil with and without polyacrylamide dissolved in water at these different rates of flow[a,b]

Treatment	Flow distance (m)	Active fungi	Active bacteria	Total fungi	Total bacteria	Algae	Active microbes	Total microbes	AF/AB[c]	TF/TB[d]	Sediment loss (kg ha^{-1})	Infiltration (mm h^{-1})
		(μg carbon ml^{-1} water)										
7.5 l min^{-1}												
Control	1	0.01 d	0.14 f	0.52 f	25.3 bc	10.8 cd	0.15 fg	25.8 d	0.07 b	0.02 c	–	–
Polyacrylamide	1	0.01 d	0.05 f	0.09 f	2. 8 g	2.5 d	0.06 g	2.89 e	0.20 b	0.03 c	–	–
Control	40	0.07 d	0.52 de	25.31 dc	24.6 bc	64.4 b	4.19 cd	24.8 d	7.10 a	1.02 c	85 a	43 a
Polyacrylamide	40	0.00 e	0.21 ef	0.19 f	2.4 g	5.31 d	0.11 fg	2.59 e	0.00 b	0.08 c	54 a	28 a
15.5 l min^{-1}												
Control	1	0.42 dc	1.60 c	259.0 b	27.7 b	25.3 cd	2.02 dc	389.7 b	0.26 b	9.35 b	–	–
Polyacrylamide	1	0.19 d	0.63 d	156.4 c	12.6 fg	2.5 d	0.82 ef	169.1 c	0.30 b	12.31 a	–	–
Control	40	0.83 bc	1.63 c	371.4 a	58.8 a	58.3 b	2.47 cd	430.2 a	0.50 b	6.31 b	5250 a	58 a
Polyacrylamide	40	0.09 d	0.52 de	25.3 de	22.4 bc	5.3 d	0.62 ef	47.7 d	0.17 b	1.12 c	163 b	42 b
21.5 l min^{-1}												
Control	1	3.98 a	4.59 a	15.9 e	15.6 cde	516.9 a	8.57 a	30.6 d	0.86 b	1.05 c	–	–
Polyacrylamide	1	3.72 a	2.92 b	4.11 ef	6.6 g	599.5 a	6.67 ab	10.7 e	1.27 b	0.62 c	–	–
Control	40	2.85 a	4.32 a	12.9 e	18.4 bcd	659.0 a	7.21 a	31.8 d	0.65 b	0.70 c	11,291 a	108 a
Polyacrylamide	40	0.35 cd	2.66 b	0.52 f	7.9 g	72.7 bc	3.00 bc	8.5 e	0.13 b	0.06 c	280 b	109 a
Inflow		0.00 e	0.75 d	31.6 d	16.6 cd	321.9 b	0.75 ef	48.3 d	0.00 b	1.90 c	–	–

[a] Field length was 42.5 m. Top of field was sampled 1.0 m from the inflow. Bottom of field was sampled 40 m from the inflow.
[b] In each column, values followed by the same letter are not significantly different as determined by Fisher's protected least significant difference test ($p \leq 0.05$; $n = 9$).
[c] AF/AB, active fungal/active bacterial ratio.
[d] TF/TB, total fungal/total bacterial ratio.

(Table 2). After water traveled 40 m at 15.5 l min^{-1}, PAM-treatment reduced active and total bacterial biomass, active and total fungal biomass, algae, active and total microbial biomass, and the TF/TB ratio relative to the control treatment. After water traveled 1 m at 22.5 l min^{-1}, PAM-treatment reduced active and total bacterial biomass, total microbial biomass and the TF/TB ratio relative to the control treatment (Table 1). After water traveled 40 m at 22.5 l min^{-1}, PAM-treatment reduced active and total bacterial fungal biomass, active and total microbial biomass and algae relative to the control treatment.

Mean sediment loss in the PAM and control treatments did not significantly differ when water flow was at 7.5 l min^{-1}, but was nearly eliminated in the PAM-treatment compared to the control treatment when water flow was at 15.5 and 21.5 l min^{-1}. Mean infiltration in the PAM and control treatments did not significantly differ when water flow was at 7.5 and 21.5 l min^{-1}, but was less in the PAM-treatment than the control treatment when water flow was at 15.5 l min^{-1}. Estimation of infiltration from small flumes using this method are reliable for production-sized fields of several hundred meters but generally recognized as error prone for measurements on short furrow segments (Trout and Mackey, 1988a, b). Consequently, despite the small apparent infiltration differences measured, actual treatment differences may or may not have occurred, and only the grand means for flow rates are meaningful as overall estimates of infiltration for the study. As infiltration is not regarded as germane to the results, the lack of precision for this study is not a problem.

The number of active and total bacteria and fungi g^{-1} soil, active bacterial and fungal biomass, total bacterial and fungal biomass, algae, active fungal biomass/active bacterial biomass, total fungal biomass/total bacterial biomass microbial biomass were not correlated with sediment loss.

4. Discussion

The results of our study parallel the findings of the larger body of PAM literature for use of PAM to control irrigation-induced erosion with regard to erosion and sediment loss prevention. Various PAM formulations are routinely used in municipal water treatment facilities for sewage sludge dewatering and for finish treatment of potable drinking water. The ability of PAM to flocculate microorganisms and remove them from water treatment facilities has been understood for some time. The findings with regard to sequestration of microbiological organisms in flowing irrigation water, however, are entirely new and have significant implications for both phytosanitary considerations in crop agriculture and, ultimately, for public health.

While speculative, it is possible to identify important eventual implications of perfection of this technology. This could eventually include the potential to reduce or eliminate the vectoring of plant diseases on an irrigation district-wide basis since, in many irrigation schemes, as much as 20% of the water flowing across a given field runs off and is collected as return flow for downstream use by other farms along the canal system path. Both of these effects carry the further potential to reduce the need for application of plant disease-combating agrichemicals. Obviously, enlightened exploitation of this effect could also conceivably reduce transmission of other organisms in overland flow situations that affect crop and animal production and/or public health. These speculations are supported by subsequent research by the authors. In a series of subsequent and ongoing studies (Entry and Sojka, unpublished data) PAM alone and in combination with other materials was shown to be an effective sequestering agent for several classes of specific micro-organisms of concern to public health. Results paralleled or exceeded results reported here.

Pollution of surface and groundwater from both human and animal waste has been well documented (Sorber and Moore, 1987; Donnison and Cooper, 1989; Walker et al., 1990). Liquid-waste discharge into soil follows natural groundwater drainage patterns and may contaminate adjoining bodies of surface water. These same bodies of water are often used for sources of drinking water and/or for recreational activities. Keeping lakes and streams free of intestinal pathogens is an important water quality concern nationally. Although further research is needed to develop this technology, treating irrigation return flows or other agricultural or industrial waste waters with polyacrylamide could act as a filter to remove nutrients and other pathogenic microorganisms in both ground- and surface water.

The water used to irrigate this study had been held in an on-farm reservoir for several days prior to irrigating, providing time for considerable algal growth. Beyond the sequestration apparent from data presented in the tables, there was also a dramatic visual treatment effect. Water running off control furrows was turbid and sediment-laden in all cases, and furrow bottoms, following each irrigation, showed the effects of erosional scouring and sediment transport and redeposition. In PAM-treated furrows, water was completely clear and, within half an hour of irrigation initiation on all three irrigation events, the sequestration of algae (and presumably other organisms) was apparent in the form of thick algal mats adhering to the furrow sides in the upper reaches of the PAM-treated furrows.

The PAMs developed for use in irrigation erosion control are very large anionic molecules that have been shown to be safe for a variety of food, pharmeceutical, and sensitive environmental applications (Barvenik, 1994). They should not be confused with, or evaluated with, other PAM formulations, especially cationic PAMs, which have known safety concerns related to their specific chemistries (Barvenik, 1994). Environmental regulation, safety and toxicity issues related to PAM use have been extensively reviewed in recent years (Barvenik, 1994; Seybold, 1994; Barvenik et al., 1996; Deskin, 1996).

The abundance of amide functional groups in the PAM polymer can make it a ready microbial nitrogen source. Kay-Shoemake et al. (1998a) found that KCl-extractable NO_3 and NH_4 was higher in soil irrigated with water containing 10 mg l^{-1} PAM applied to potato (*Solanum tuberosum* L.) fields. However, they reported that there was no difference in KCl-extractable NO_3 and NH_4 concentrations when the same amount and type of irrigation water was applied to bean fields.

Several studies found that PAM degradation in soil is fairly rapid (Lande et al., 1979; Shanker et al., 1990; Kay-Shoemake et al., 1998b). PAM was completely degraded within 5 days after applying 500 mg PAM kg^{-1} garden soil (Shanker et al., 1990). Lande et al. (1979) applied 25 mg PAM kg^{-1} soil and reported that the half-life of AMD monomer in agricultural soils was 18–45 h. Soil microorganisms are capable of utilizing PAM as a sole source of N, but not C (Kay-Shoemake et al., 1998a). The effect of PAM application to water or soils on soil microorganisms has been variable (Nadler and Steinberger, 1993; Steinberger et al., 1993; Kay-Shoemake et al., 1998a, b). Changes in soil microorganisms are likely dependent on soil moisture, temperature, carbon, and nutrient status as well as the amount and type of PAM application. The effect of PAM on soil microorganisms may have been obscured by other parameters (Kay-Shoemake et al., 1998a, b)

The most effective and environmentally safe PAMs are large negatively charged molecules (Lentz et al., 1993; Barvenik, 1994). It has been suggested that divalent cations in water bridge the PAM and soil, increasing soil cohesion and strengthening aggregates contacted in the furrow (De Boodt et al., 1990; Barvenik, 1994; Lentz and Sojka, 1994). Soil particles at the furrow's soil–water interface are bound together, preventing detachment and transport of sediments in runoff. It is likely that similar mechanisms are responsible for the removal of the microorganisms we saw in this study. It is entirely possible that the efficacy of PAM-treatment for microbial immobilization may be influenced by the surface properties of specific micro organisms, and specific testing will be necessary to determine this.

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References

Aase, J.K., Bjorneberg, D.L., Sojka, R.E., 1998. Sprinkler irrigation runoff and erosion control with polyacrylamide—laboratory tests. Soil Sci. Soc. Am. J. 62, 1681–1687.

Abdelmagid, H.M., Tabatabai, M.A., 1982. Decomposition of acrylamide in soils. J. Environ. Qual. 11, 701–704.

Agassi, M., Letey, J., Farmer, W.J., Clark, P., 1995. Soil erosion contribution to pesticide transport by furrow irrigation. J. Environ. Qual. 24, 892–895.

Azzam, R., El-Hady, O., Lofty, A.A., Hegela, M., 1983. Sand-RAPG combination simulating fertile clayey soils, Parts I to IV. Int. Atomic Energy Agency. SM-267/15:321–349.

Bahr, G., Steiber, T., Campbell, K., 1996. Reduction of nutrient and pesticide loss through the application of polyacrylamide in surface irrigated crops. In: Proc. 6th Annual Nonpoint Source Water Quality Monitoring Results Workshop. Boise State University, Boise ID. 9, 10 and 11 January 1996.

Bahr, G., Steiber, T., 1996. Reduction of nutrient and pesticide loss through the application of polyacrylamide in surface irrigated crops. In: Sojka, R.E., Lentz, R.D. (Eds.), Managing Irrigation-Induced Erosion and Infiltration with Polyacrylamide. Proceedings: College of Southern Idaho, Twin Falls, ID, 6–8 May 1996.

Barvenik, F.W., 1994. Polyacrylamide characteristics related to soil applications. Soil Sci. 158, 235–243.

Barvenik, F.W., Sojka, R.E., Lentz, R.D., Andrawes, F.F., Messner, L.S., 1996. Fate of acrylamide monomer following application of polyacrylamide to cropland. In: Sojka, R.E., Lentz, R.D. (Eds.), Managing Irrigation-Induced Erosion and Infiltration with Polyacrylamide. Proceedings: College of Southern Idaho, Twin Falls, ID, 6–8 May 1996.

Ben Hur, M., 1994. Runoff, erosion and polymer applications in moving-sprinkler irrigation. Soil Sci. 158, 283–290.

De Boodt, M.F., Hates, M.H.B., Herbillon, A. (Eds.), 1990. Soil Colloids and Their Associations in Aggregates (NATO ASI Series B: Physics Vol. 215). Plenum Press, New York.

Deskin, R., 1996. Product stewardship considerations in the use of polyacrylamides in soil erosion. In: Sojka, R.E., Lentz, R.D. (Eds.), Managing Irrigation-Induced Erosion and Infiltration with Polyacrylamide. Proceedings: College of Southern Idaho, Twin Falls, ID, 6–8 May 1996.

Donnison, A.M., Cooper, R.N., 1989. Fecal coliform decline on pasture irrigated with primary treated meat-processing effluent. New Zealand J. Agric. Res. 32, 105–112.

Grula, M.M., Huang, M.L., Sewell, G., 1994. Interactions of certain polyacrylamides with soil bacteria. Soil Sci. 158, 291–300.

Ingham, E.R., Klein, D.A., 1984. Soil fungi relationships between hyphal activity and staining with fluorescein diacetate. Soil Biol. Biochem. 16, 273–278.

Jenkinson, D.S., Ladd, J.M., 1981. Microbial biomass in soil: measurement and turnover. In: Paul, E.A., Ladd, J.N. (Eds.), Soil Biochemistry (Vol. 5). Marcel Dekker, New York, pp. 415–471.

Khaeel, R., Reddy, K.R., Overcash, M.R., 1980. Transport of potential pollutants in runoff water from land areas receiving animal wastes: a review. Water Research 14, 421–436.

Kay-Shoemake, J.L., Watwood, M.E., Lentz, R.D., Sojka, R.E., 1998b. Polyacrylamide as an organic nitrogen source for soil microorganisms with potential effects on inorganic soil nitrogen in agricultural soil. Soil Biol. Biochem. 30, 1045–1052.

Kay-Shoemake, J.L., Watwood, M.E., Sojka, R.E., Lentz, R.D., 1998b. Polyacrylamide as a substrate for microbial amidase in culture and in soil. Soil Biol. Biochem. 30, 1647–1654.

Kirk, R.E., 1982. Experimental Design: Procedures for the Behavioral Sciences, 2nd Edition. Brooks Cole Publishing Co, Belmont, CA.

Lande, S.S., Bosch, S.J., Howard, P.H., 1979. Degradation and leaching of acrylamide in soil. J. Environ. Qual. 8, 133–137.

Lentz, R.D., Sojka, R.E., 1994. Field results using polyacrylamide to manage furrow erosion and infiltration. Soil Sci. 158, 274–282.

Lentz, R.D., Shainberg, I., Sojka, R.E., Carter, D.L., 1992. Preventing irrigation furrow erosion with small applications of polymers. Soil Sci. Soc. Am. J. 56, 1926–1932.

Lentz, R.D., Sojka, R.E., Carter, D.L., 1993. Influence of polymer charge type and density on polyacrylamide ameliorated irrigated furrow erosion. In: Proc. 24th Annual International Erosion Control Association Conference, 23–26 February 1993, Indianapolis, IN, pp. 159–168

Lentz, R.D., Sojka, R.E., Robins, C.W., 1998a. Reducing phosphorous losses from surface-irrigated fields: emerging polyacrylamide technology. J. Environ. Qual. 27, 305–312.

Lentz, R.D., Sojka, R.E, Robins, C.W., 1998b. Reducing soil and nutrient losses from furrow irrigated field with polymer applications. Adv. Geoecol. 31, 1233–1238.

Levin, J., Ben-Hur, M., Gal, M., Levy, G.J., 1991. Rain energy and soil amendments effects on infiltration and erosion of three different soil types. Aust. J. Soil Res. 29, 455–465.

Lodge, D.J., Ingham, E.R., 1991. A comparison of agar film techniques for estimating fungal biovolumes in litter and soil. Agric. Ecosyst. Environ. 5, 31–37.

MacWilliams, D.C., 1978. Acrylamides. In: Kirk, I., Othmer, D.F. (Eds.), Encyclopedia of Chemical Technology, 3rd Edition (Vol. 1). Wiley, New York, pp. 298–311.

Mallin, M.A., Burkholder, J.M., McIver, M.R., Shank, G.C., Glascow Jr., H.B., Touchette, B.W., Springer, J., 1997. Comparative effects of poultry and swine waste lagoon spills on the quality of receiving waters. J. Environ. Qual. 26, 1622–1631.

Mawdsley, J.L., Bardgett, R.D., Merry, R.D., Pain, B.F., Theodorou, M.K., 1995. Pathogens in livestock waste, their potential for movement through soil and environmental pollution. Applied Soil Ecology 2, 1–15.

McCutchan, H., Osterli, P., Letey, J., 1994. Polymers check furrow erosion, help river life. Calif. Agricul. 47, 10–11.

Mitchell, A.R., 1986. Polyacrylamide application in irrigation water to increase infiltration. Soil Sci. 141, 353–358.

Nadler, A., Steinberger, Y., 1993. Trends in structure, plant growth and mocroorganism interrelations in the soil. Soil Sci. 115, 114–122.

Paganyas, K.P., 1975. Results of the use of series "K" compounds for the control of irrigational soil erosion. Soviet Soil Sci. 5, 591–598.

Seybold, C.A., 1994. Polyacrylamide review: soil conditioning and environmental fate. Comm. Soil Sci. Plant Anal. 25, 2171–2185.

Shanker, R., Ramakrishna, C., Seth, P.K., 1990. Microbial degradation of acrylamide monomer. Arch. Microb. 154, 192–198.

Singh, G., Letey, J., Hanson, P., Osterli, P., Spencer, W.F., 1996. Soil erosion and pesticide transport from an irrigated field. J. Environ. Sci. Health B31 (1), 25–41.

Sojka, R.E., Lentz, R.D., Ross, C.W., Trout, T.J., Bjorneberg, D.L., Aase, J.K., 1998a. Polyacrylamide effects on infiltration in irrigated agriculture. J. Soil and Water Cons. 53 (4), 325–331.

Sojka, R.E., Carter, D.L., Brown, M.J., 1992. Imhoff cone determination of sediment in irrigation runoff. Soil Sci. Soc. Am. J. 56, 884–890.

Sojka, R.E., Lentz, R.D., Foerster, J.A., 1994. Software utilizing Imhoff cone volumes to estimate furrow-irrigation erosion. J. Soil Water Conserv. 49, 400–406.

Sojka, R.E., Lentz, R.D., Westermann, D.T., 1998b. Water and erosion management with multiple applications of polyacrylamide in furrow irrigation. Soil Sci. Soc. Am. J. 61, 1672–1680.

Sorber, C.A., Moore, B.E., 1987. Survival and Transport of Pathogens in Sludge-amended Soil: a Critical Literature Review (Environmental Protection Agency Report EPA 600 S2-87 028). Water Engineering Research Laboratory, Cincinnati, OH.

Stamatiadis, S., Doran, J.W., Ingham, E.R., 1990. Use of staining inhibitors to separate fungal and bacterial activity in soil. Soil Biol. Biochem. 22, 81–88.

Steinberger, Y., Sarig, S., Nadler, A., Barnes, G., 1993. The effect of synthetic soil conditioners on microbial biomass. Arid Soil Res. Rehabil. 7, 303–306.

Tolstikh, L.I., Akimov, N.I., Golubeva, I.A., Shvetsov, I.A., 1992. Degradation and stabilization of polyacrylamide in polymer flooding conditions. International Journal of Polymeric Material 17, 177–193.

Trout, T.J., Mackey, B.E., 1988a. Furrow flow measurement accuracy. J. Irrig. Drain. Engng 114, 244–255.

Trout, T.J., Mackey, B.E., 1988b. Inflow–outflow infiltration measurement accuracy. J. Irrig. Drain. Engng. 114, 256–265.

Trout, T.J., Sojka, R.E., Lentz, R.D., 1995. Polyacrylamide effect on furrow erosion and infiltration. Trans. ASAE 38 (8), 761–765.

US EPA, 1985. Health and Environmental Effects Profile for Acrylamide. Office of Research and Development, US Environmental Protection Agency, Washington, D.C.

Wallace, A., Wallace, G.A., 1986a. Effects of very low rates of synthetic soil conditioners on soils. Soil Sci. 141, 324–327.

Wallace, G.A., Wallace, A., 1986b. Control of soil erosion by polymeric soil conditioners. Soil Sci. 141, 363–367.

Wallace, A., Wallace, G.A., Abouzamzam, A.M., 1986. Effects of excess levels of a polymer as a soil conditioner on yields and mineral nutrition of plants. Soil Sci. 141, 377–379.

Walker, S.E., Mostaghimi, S., Dillaha, T.A., Woests, F.E., 1990. Modeling animal waste management practices: impacts on bacteria levels in runoff from agricultural land. Transactions ASAE 33, 807–817.

West, A.W., Ross, D.J., Cowling, J.C., 1986. Changes in microbial C, N, P, and ATP contents, numbers and respiration on storage of soil. Soil Biol. Biochem. 18, 141–148.