POLYACRYLAMIDE (PAM) FOR IRRIGATION RUNOFF MANAGEMENT

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Abstract
Nearly two million U.S. irrigated acres safely use PAM for erosion control, water quality protection, and infiltration management, preventing 20 million tons of soil loss annually. Nutrients, pesticides, chemical oxygen demand, weed seeds, and pathogens in runoff from PAM-treated irrigation are greatly reduced. Typical annual PAM application amounts are < 10 kg ha^{-1}. At these rates, infiltration is improved on medium to fine-textured soils. PAM applied at recommended rates has little or no effect on soil microflora and microfauna. Field research has shown that applications of up to 5.4 ton ha^{-1} active ingredient (a.i.) of PAM have only modest effects on soil microflora numbers and function and that PAM degrades at a rate of at least 9.8% y^{-1}. Key points of PAM technology are presented.
Key words: water quality, erosion, infiltration, environmental safety, acrylamide

Introduction

This paper summarizes anionic polyacrylamide (PAM) use for erosion and infiltration management in irrigated agriculture with emphasis on environmental benefits and safety. The full scope of PAM technology was thoroughly reviewed by Sojka et al. (2007). Comprehensive information on PAM use for erosion control also can be found at <http://sand.NWISRL.ars.usda.gov/pampage.shtml>. Lentz et al. (1992) reported the first field research of a practical approach to halting furrow irrigation-induced erosion with PAM. PAM applied in irrigation water at 1-2 kg ha^{-1} per irrigation halted 94% of erosion (Lentz and Sojka, 1994). Soil in the irrigation furrow is only treated as water crosses the field (the advance), and PAM application is halted when runoff begins.

To ensure environmental safety, a food-grade class of anionic PAM is used. Charge density is typically 18 percent, but can range from a few percent to more than 50 percent. These PAM molecules have more than 150,000 chain segments per molecule and a molecular weight of 12 to 15 Mg mole^{-1}; they are manufactured to high purity and are used in many sensitive applications. They have residual acrylamide monomer (AMD) contents of <0.05%, ensuring safety for humans or aquatic species. Common uses of anionic PAMs were listed by

Wallace et al. (1986) and Barvenik (1994) and include sewage sludge dewatering; mineral separation processes; paper manufacture; clarification of refined sugar, fruit juices, and drinking water; thickening agents in animal feeds; antiscaling in steam processes in contact with food; and as a coating on paper used for food packaging.

Flowing irrigation water without PAM detaches and disrupts aggregates, transporting the solids in the flow, leading to erosion and water quality impairment of the runoff and to surface sealing along the flow path that reduces infiltration. Sealing is intensified by water droplets from sprinklers or rain. Droplets have additional kinetic energy, adding to aggregate disruption and dispersion. Bridging cations in the solvating water link the anionic polymer to the predominately anionic mineral and organic particulate surfaces. Dissolved calcium in the solvating water improves PAM efficacy compared to low-electrolyte (pure) water. Because PAM stabilizes surface structure, in most medium-to fine-textured soils, infiltration is increased compared to nontreated water (Lentz et al., 1992; Lentz and Sojka, 1994; Sojka et al., 1998a,b). As technology improves, PAM use with sprinklers may improve uniformity and rate of infiltration (Aase et al., 1998; Bjorneberg et al., 2000; Bjorneberg and Aase, 2000). With PAM in the water, soil structure is stabilized and surface sealing is reduced; water droplets enter the soil where they land, rather than causing surface seals that induce runoff and redistribution of water.

Environmental Considerations

PAM use with irrigation for erosion control benefits water quality in many ways. By preventing erosion, it reduces desorption opportunity of sorbed nutrients and pesticides, and limits dissolution of soil organic matter that would otherwise elevate dissolved organic carbon (DOC) in runoff and raise biological oxygen demand (BOD) (Agassi et al., 1995; Bjorneberg et al., 2000; Lentz et al. 1998, 2001).

Because PAM raises the viscosity of water flowing through soil pores (Malik and Letey, 1992), PAM effects on infiltration are a balance of seal prevention (increased infiltration) and increased viscosity (reduced infiltration). Lentz (2003) used the viscosity effects plus other application and management strategies for furrow, pond, and canal sealing, and improved infiltration uniformity along long irrigation furrows.

PAM is not regulated under FIFRA (Federal Insecticide, Fungicide and Rodenticide Act, 1996), but it is regarded as a macropollutant with low toxicity and side effects. PAM has been used widely for decades in food, environmental and other sensitive applications, involving significant disposal or release to the environment. Caution is warranted, but the low toxicity of PAMs, especially ***anionic*** PAMs, means that if used to prescribed guidelines, human or environmental health risk is small. Barvenik (1994) and Deskin (1996) summarized PAM safety considerations, noting that PAMs generally exhibit low toxicity to mammals, with high acute LD_{50} by oral and dermal routes ($>5g\ kg^{-1}$). There were no significant adverse effects in chronic oral toxicity studies, no compound-related reproductive lesions in a three-generation rat study, and only slight dermal and ocular irritation at high doses (Stephens, 1991). Human epidemiologic studies showed no association between occupational PAM exposure and tumors, paralleling the chronic animal studies. The large size of these PAM molecules precluded movement across membranes, preventing gastrointestinal absorption (Stephens, 1991).

Rigorous tests of PAM concentration downstream from application sites showed that, properly applied, no serious risk of PAM loss is posed (Lentz et al., 2002; Ferguson, 1997). If a minor PAM loss occurs, its strong surface-attractive properties result in its rapid removal via adsorption on and flocculation of suspended solids in the runoff within a few hundred meters of transport from an application site (Lentz et al., 2002)-actually providing water quality improvement in tail ditches when small PAM losses occur.

Malik et al. (1991) reported that PAM applied via infiltrating water is irreversibly adsorbed in the top few millimeters of soil once dry. Lu and Wu (2003) reported that PAM penetrated into organic matter-free soil at 20 to 30 mm. PAM delivery via furrow streams is very efficient, because it only needs to stabilize the thin veneer of soil directly active in the erosion process. In furrow irrigation, PAM treats about 25% of the field surface area to shallow depth, requiring only 1-2 kg ha^{-1} of PAM per irrigation.

PAMs used for erosion and infiltration managment contain <0.05% AMD. AMD is a neurotoxin, but at this AMD content, anionic PAMs are safe, used as directed at low concentrations (see discussion below). In greenhouse soil, PAM degraded at 10% per year due to physical, chemical, biological, and photochemical processes (Azzam et al., 1983).

Because PAM is susceptible to UV degradation, its breakdown rate at the soil surface may be faster than 10% per year. Indirect evidence of faster breakdown of surface-applied PAM is the gradual loss of treatment effectiveness between irrigations (Lentz et al., 1992). Recent field research using carbon isotope natural abundance ratios showed a PAM degradation rate of at least 9.8% per year (Entry and Sojka, unpublished data, 2006). This rate is conservative, since carbon from degrading PAM molecules may be incorporated into soil organic matter, affecting the soil's apparent isotope signature. While non-ionic and cationic PAM formulations pose risk to aquatic organisms at low concentration (Biesinger and Stokes, 1986; Hamilton et al., 1994), anionic formulations do not. Anionic PAMs specified by NRCS for erosion and infiltration management (NRCS 2001, 2005) show no LC_{50} at concentrations up to 100 ppm. Furthermore, PAM toxicity determined in deionized water has lower LC_{50} values than in natural waters, because of the action of suspended sediments and dissolved organic compounds present in natural waters (Buchholz, 1992; Goodrich et al., 1991; Hall and Mirenda, 1991). Dissolved humic substances raise LC_{50} measurements an order of magnitude for 5 ppm suspended matter (Goodrich et al., 1991) and two orders of magnitude for 60 ppm (Hall and Mirenda, 1991). Carey (1987) and Biesinger et al. (1976) showed that organic carbon and bentonite clay also reduced PAM toxicity to test species. Absence of a measurable LC_{50} for anionic PAM concentrations up to 100 ppm gives a ten-fold safety margin for the 10 ppm PAM concentration applied to agricultural fields using the NRCS application standard. Two to three orders of magnitude of added safety exists even if runoff flows directly into a riparian body (Lentz et al., 2002). Sojka et al. (2007) reviewed a list of aquatic species toxicity, confirming safety of erosion-control concentration levels.

PAM used for erosion control reduces nutrients in runoff carried on or released from sediment. Lentz et al. (1996) applied 0.25 to 0.50 ppm PAM to furrow inflows during a 24 h irrigation; runoff was sampled at 4 and 9 hours for P. PAM had little effect on ortho P but a 25% reduction in total P. Lentz et al. (1998) compared treating furrow advance flow (only) with 10 ppm PAM or treating with 1 ppm PAM throughout the irrigation. Water quality improved compared to controls in both cases. Dissolved reactive P and total P concentrations in control tailwater were five to seven times, and chemical oxygen demand (COD) of controls were four times those measured in PAM treatments. Several reports show that PAM use reduces runoff nutrients (Lentz et al., 2001; Entry and Sojka, 2003; Sojka et al., 2005; Bjorneberg et al., 2000).

Agassi et al. (1995) studied runoff loss of the herbicide napropamide from Hanford sandy loam soil. Treating with 10 ppm anionic PAM greatly reduced loss of sediment and napropamide. Singh et al. (1996) studied PAM treatment of furrow irrigation on loss of the miticide kelthane from a Capay clay soil. PAM applied at 10ppm greatly reduced sediment and miticide loss and increased infiltration. In Idaho, 10 ppm PAM-treated (only during advance) furrow irrigation runoff was compared to controls for N, total, and ortho P; and the pesticides terbufos, cycloate, EPTC, bromoxinil, chlorpyrifos, trifluralin oxyfluorfen, and pendimethalin in sugarbeet and onion fields (Bahr and Steiber, 1996; Bahr et al., 1996). PAM reduced sediment loss up to 99% and N and P concentrations up to 86% and 79%, respectively, and greatly reduced pesticide losses.

Australian studies compared conservation tillage and PAM to control erosion and prevent endosulfan loss in runoff (Waters et al., 1999a; Hugo et al., 2000). In surface irrigation, either PAM or conservation tillage controlled soil and endosulfan loss by 70%. Oliver and Kookana (2006a,b) reported that PAM reduced loss of endosulfan, bupirimate, and chlorothalonil by 54, 38, and 49%, respectively.

Endemic and manure-applied microorganisms carried by furrow runoff were reduced by PAM in irrigation water (Sojka and Entry, 2000; Entry and Sojka, 2000; Entry et al., 2003). Common removal rates ranged from 50 to 90%. Similarly, PAM reduced runoff loss of weed seeds 62 to 90% for six major weeds (Sojka et al., 2003). Weed seed and microorganism sequestration pointed to management that should reduce pesticide use.

Effects of PAM on bacterial biomass in soils and waters were varied (Mourato and Gehr, 1983; Nadler and Steinberger, 1993; Steinberger et al., 1993; Kay-Shoemake et al.,1998a,b). Larger populations of heterotrophic bacteria were found by Kay-Shoemake et al. (1998a) in PAM-treated soils planted to potatoes, but not if planted to beans. These and other studies showing increased or decreased bacterial numbers for PAM-treated soil suggest that PAM effects are site-, season-, and cultural practice-specific and interact with nutrient levels, crop type, or herbicide regimes. Bacterial enrichment cultures, derived from PAM-treated soils, were capable of growth with PAM as a sole N-source but not a sole C-source, whereas AMD served as either a sole N- or C-source for bacterial growth (Kay-Shoemake et al., 1998b). Grula et al. (1994) showed that PAMs are an N source for bacteria and stimulate growth of a number of Pseudomonas sp.; only cationic PAMs were toxic to cultured organisms for PAM concentrations under 0.2%.

Sojka et al. (2006) reported the effects of ultra-high PAM application rates to irrigated soils. Over a six-year period, 1000 kg ha^{-1} y^{-1} of anionic PAM were added to soil. At the study's end, analyses were done on plots receiving 2691 or 5382 kg a.i. PAM ha^{-1}. Active bacterial, fungal, and microbial biomass were not consistently affected by high PAM additions. Even with these massive PAM applications, effects on microorganisms were moderate and were driven more by sampling date than by PAM treatment. In June and August, active bacterial biomass in soil was 20-30% greater in the controls than where soil was treated with 2691 or 5382 kg PAM ha^{-1}, but there were no significant differences in July. There were no differences in active bacterial biomass between the 2691 or 5382 kg PAM ha^{-1} treatments, regardless of sampling time. Control-treatment active-fungal biomass was 30–50% greater than soil treated with 2691 or 5382 kg PAM ha^{-1} in June and July, but not in August. There was no difference in soil-active-fungal biomass between the 2691 or 5382 kg PAM ha^{-1} on any sampling date. Soil-active microbial biomass was 27-48% higher in control than in soil treated with 2691 or 5382 kg PAM ha^{-1}, except in June, for the 5382 kg PAM ha^{-1} treatment. Nutritional characteristic analysis (Biolog GN) showed separation of the nonamended control soils from high PAM treatments for the June sampling, but not for July or August. Whole-soil, fatty-acid profiles (FAME) showed no soil microbial community change for any PAM application rate or date. In contrast, fatty-acid and Biolog analyses both indicated that the microbial communities present in all plots at the June sampling differed from those sampled in July and August, both taxonomically and metabolically independent of PAM treatment. Thus, despite large PAM additions over six years, there was little consistent effect on soil microbial biomass or metabolic potential (BIOLOG or FAME). Although measurable, effects on soil microbial population were inconsistent and moderate, considering the massive PAM amounts added. This suggests that concerns about PAM effects on soil microorganisms are not warranted, especially when weighed against the substantial erosion prevention and water quality protection resulting from more typical 5 to 10 kg ha^{-1} y^{-1} application rates.

Wallace et al. (1986) also reported on the effects of ultra-high rates of PAM application to soil. They compared the effect of adding 1 and 5% by weight of anionic PAM to soils with controls. The 1% PAM rate increased vegetative growth of wheat and tomato. The 5% rate produced growth results equivalent to controls.

Acrylamide Monomer (AMD)

Concern over PAM use is generally less for PAM itself than for residual AMD, a production contaminant. AMD is a neurotoxin and a suspected carcinogen in humans and animals (Garland and Patterson, 1967; WHO, 1985). High-dose AMD exposures have resulted in isolated human fatalities, temporary injury, or impairment with ingestion or extensive exposure to concentrations > 400 ppm AMD (Garland and Patterson, 1967). Exposure levels required to cause neurotoxic or carcinogenic effects in humans are several orders of magnitude above conceivable exposure resulting from environmental applications (10 ppm PAM, <0.05% AMD). The National Institute of Occupational Safety and Health (NIOSH) recommends an exposure limit of 0.03 mg m^{-3}, equivalent to 0.004 mg/kg/day for an 8-hour work day (NIOSH, 1992). For a 100 kg human, that equals 0.4 mg AMD, or 80% of the AMD per kg of the PAMs used for erosion control.

PAM does not degrade to AMD in soil due to the high-temperature requirement for that reaction (Mac Williams, 1978; Johnson, 1985; Wallace et al., 1986). Release of AMD by photodegradation of PAM is highly unlikely because the UV wavelengths at the earth's surface do not favor the reaction (Caulfield et al., 2003a,b; Crosby, 1976; Decker, 1989; Diffey, 1991; Suzuki et al., 1978, 1979) . Also, AMD is easily metabolized by microorganisms in soil and biologically active waters, with a half-life in tens of hours (Lande et al., 1979; Shanker et al., 1990). Bologna et al. (1999) showed that AMD is not absorbed by plants and breaks down rapidly when exposed to living plant tissue.

Many reports have drawn attention to health concerns related to AMD (Tareke et al., 2002; Ahn et al., 2002; Andrzejewski et al., 2004; Bacalski et al., 2003; Konings et al., 2003; Palevitz, 2002; Roach et al., 2003; Rosen and Hellenas, 2002; Svensson et al., 2003; Zyzak et al., 2003). Their papers and others report AMD content of cooked, baked, and fried foods. The range of AMD found in food tested by Svensson et al. (2003) was 25-2300 μg kg^{-1} AMD. Mean values for some popular foods were potato chips (1360 μg kg^{-1}), french fries

(540 μg kg^{-1}), bread crisps (300 μg kg^{-1}), cookies (300 μg kg^{-1}), tortilla chips (150 μg kg^{-1}), popcorn (500 μg kg^{-1}), and breakfast cereals (220 μg kg^{-1}). Various meat products ranged 30 to 64 μg kg^{-1}. The Food and Agricultural Organization and World Health Organization concluded that food contributes significantly to total AMD exposure, with average intake of 0.3 to 0.8 μg of AMD per kg of body weight per day. AMD concentrations in these common foods are 5 to 460 times greater than maximum residual AMD concentrations expected in irrigation water treated with 10 ppm of PAM products containing < 0.05% AMD. Yet, no neurotoxic effects are expected from AMD ingested in diets that include these foods. Human exposure to AMD from environmental uses of PAM containing <0.05% AMD applied at recommended rates is a substantially smaller AMD exposure risk than from common foods.

Conclusions

Anionic polyacrylamide (PAM) has proven to be a safe and economical soil and water additive for halting irrigation-induced erosion and managing infiltration. By far, its most significant environmental effects are preservation of soil sustainability through erosion prevention and improvement of return-flow water quality. In addition, there are numerous ancillary on-farm management benefits. PAM use for erosion control is one of the most user-friendly and farmer-accepted management practices to emerge in recent years to help farmers optimize production while protecting the environment.

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