Irrigated Water, Polymer Application in

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INTRODUCTION

In the past decade, water-soluble polyacrylamide (PAM) was identified as an environmentally safe and highly effective erosion preventing and infiltration enhancing polymer when applied in furrow irrigation water at $1\,\mathrm{mg\,L^{-1}}-10\,\mathrm{mg\,L^{-1}}$, i.e., 1 ppm–10 ppm.[1–9] Various polymers and biopolymers have long been recognized as viable soil conditioners because they stabilize soil surface structure and pore continuity. The new strategy of adding the conditioner, high molecular weight anionic PAM, *to irrigation water* in the first several hours of irrigation implies a significant costs savings over traditional application methods, in which hundreds of kilograms per hectare of soil additives are tilled into the entire (15 cm deep) soil surface layer. By adding PAM to the irrigation water, soil structure is improved in the important 1–5 mm thick layer at the soil/water interface of the 25%–30% of field surface contacted by flowing water.[7]

In 1995, the U.S. Natural Resource Conservation Service (NRCS) published a PAM-use conservation practice standard for PAM-use in irrigation water.[10] A 3-year study[2] applying these standards showed that PAM at dosage rates of $1\,\mathrm{kg\,ha^{-1}}-2\,\mathrm{kg\,ha^{-1}}$ per irrigation eliminated 94% (80%–99% range) of sediment loss in furrow irrigation runoff, while increasing infiltration 15%–50%. Seasonal application rates using the NRCS standard typically total $3\,\mathrm{kg\,ha^{-1}}-5\,\mathrm{kg\,ha^{-1}}$.

As PAM-use is one of the most effective and economical technologies for reducing soil-runoff, it has branched into stabilization of construction sites and road cuts, with formal statewide application standards set in Wisconsin and several southern states. Recent studies with biopolymers such as charged polysaccharides,[11–14] whey,[15] and industrial cellulose derivatives[11,14] introduce potential biopolymer alternatives to PAM.

POLYACRYLAMIDE

The term polyacrylamide and acronym "PAM" are chemistry jargon for a broad class of acrylamide-based polymers varying in chain length, charge type, charge concentration, and the number and types of side-group substitutions.[16–20] Typically, PAM for erosion control is a charged copolymer with one in five acrylamide chain segments replaced by an acrylic acid entity (Fig. 1), which generally exhibits a negative charge in water. Molecular weights of PAM used for irrigated agriculture range from $12\,\mathrm{million\,g\,mol^{-1}}$ to $15\,\mathrm{million\,g\,mol^{-1}}$ (over 150,000 monomer units per chain). As a result of its structure, PAM attracts soil particles via coulombic and Van der Waals forces.[11,17,21,22] Ionic bridging creates large stable aggregates of PAM and soil, in which charged entities on both the polymer and multiple soil particles are thought to interact with the aid of calcium counterions.[11,22–24] Chain bridging further stabilizes aggregates, whereby the long polymer chain spans between separate soil particles. Despite their large size, PAM copolymers used for erosion control are formulated to dissolve in water, although this sometimes requires vigorous agitation.

PAM Erosion Control

Lentz and Sojka[2] reported a 94% reduction in runoff sediment loss over 3 yr using the NRCS application standard.[10] The 1995 NRCS standard calls for dissolving 10 ppm (or $10\,\mathrm{g\,m^{-3}}$) PAM in furrow inflow water as it first crosses a field—typically the first 10%–25% of an irrigation duration—then halting PAM dosing when runoff begins. Under many circumstances, applying PAM continuously at 1 ppm–2 ppm for the full irrigation cycle can be equally effective, although continuous application at 0.25 ppm PAM was a third less effective.[25–27]

PAM and Infiltration

The infiltration rate of PAM-treated furrows on medium to fine textured soil is usually higher than untreated furrows—typically 15% higher than for untreated water on silt loam soils and up to 50% higher on clays.[28] Bjorneberg[29] reported that in tube diameters > 10 mm, the PAM–water viscosity did not rise sharply until the PAM concentration in the water was > 400 ppm.

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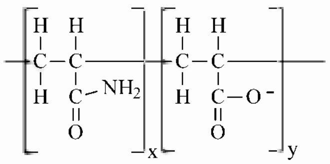

Fig. 1 PAM: Poly(acrylamide-co-acrylic acid).

However, in small soil pores, "apparent viscosity" increases significantly, even at the low PAM concentrations used for erosion control.[30] Most likely, PAM infiltration effects are a balance between prevention of surface sealing and apparent viscosity increases in soil pores.[30–34] In medium to fine textured soils, maintenance of pore continuity via aggregate stabilization is more important. In coarse textured soils, where PAM achieves little pore continuity enhancement, infiltration effects are nil or even slightly negative, particularly above 20 ppm.[28]

Because PAM prevents erosion of furrow bottoms and sealing of the wetted perimeter, water moves about 25% further laterally in silt loams compared to nontreated furrows.[1,2] This can be a significant water conserving effect for early irrigations. Farmers should take advantage of PAMs erosion prevention to improve field infiltration uniformity by increasing inflow rates two to threefold (compared to normal). This reduces infiltration opportunity time differences between inflow and outflow ends of furrows.[28,35]

Sprinkler Application of PAM

Farmers and agronomists are showing interest in PAM for sprinkler irrigation.[5,6,36–40] PAM may prevent runoff/runon problems and ponding effects on stand establishment and irrigation uniformity. Polyacrylamide sprinkler application rates of 2 kg ha^{-1}–4 kg ha^{-1} reduced runoff 70% and soil loss 75% compared with controls.[36] However, the effectiveness of sprinkler-applied PAM is more variable than for furrow irrigation because of application strategies and system variables that affect water drop energy, the rate of water and PAM delivery, and possible application timing scenarios. Multiple groups[6,36–40] report improved aggregate stability from sprinkler-applied PAM, leading to decreased runoff and erosion. Flanagan et al.[5,6] increased sprinkler infiltration with 10 ppm PAM, which they attributed to reduced surface sealing. Polyacrylamide effects under sprinkler irrigation have been more transitory, less predictable and have usually needed higher seasonal field application totals for efficacy. However, farmers with sprinkler infiltration uniformity problems (runoff or runon), e.g., with center pivots on steep or variable slopes, have begun to use PAM. Testimonials claim that PAM-use improves stands because of reduced ponding, crusting and damping off (a plant seedling disease complex).

ENVIRONMENTAL IMPACT OF PAM

The overriding environmental impact of PAM is reduced erosion-induced sediment runoff,[1,2] with corresponding reductions of entrained chemical residue reaching riparian waterways.[41–43] For example, PAM prevents yearly topsoil runoff of up to 6.4 tn acre^{-1}[2] and at least three times that as on-field erosion.[34] Since toxic pesticides and herbicides are transported via soil sediment to open water and then eventually into the air there is an increasing need to prevent soil-runoff. Recently, PAM was shown to sequester biological and chemical contaminants of runoff, providing significant potential for reduced spread of phytopathogens, animal coliforms, and other organisms of public health concern.[44,45]

The main environmental concerns in PAM-use revolve around polymer purity,[46,47] and issues related to biodegradation/accumulation;[48–53] i.e., since PAM degrades slowly, the long-term, unknown effects on organisms must be considered. Biological degradation of PAM incorporated into soil is about 10% per year.[50] However, low application rates and shallow surface application is thought to accelerate degradation via various pathways, including deamination, shear-induced chain scission, and UV photosensitive chain scission.[50–53] Even at 10% annual degradation, PAM accumulation is insignificant at these application rates. Sojka and Lentz[26] showed that only 1%–3% of applied PAM leaves fields in runoff and that this is quickly adsorbed by entrained sediment or ditch surfaces. Barvenik[16,50] noted that anionic PAM is safe for aquatic organisms at surprisingly high concentrations, with $LC_{50} > 50$ times the inflow dosage rates. Water impurities further buffer environmental effects by quickly deactivating dissolved PAM.

Care must be taken by PAM supplies to ensure polymer purity, since the acrylamide monomer (AMD) used to synthesize PAM is a neurotoxin. The EPA recently reviewed the use of PAM with USDA and PAM industry scientists, and concluded that the AMD concentrations of $< 0.05\%$ found in products for use during furrow irrigation are acceptable, with minimal amounts of monomer released into the environment.[26,53] The first step in the biodegradation of PAM is early removal of the amine group from the polymer backbone,[46,47,54–56] with reversion to AMD thermodynamically unfavorable.[53] Although these environmental issues about PAM are raised, PAM is widely recognized as a safe, environmentally friendly, hygenically safe, and cost-effective flocculating agent. It has been used industrially for decades as a soil conditioner, in food processing, and in various water treatment processes.

BIOPOLYMER ALTERNATIVES TO PAM

PAMs successful use in irrigation water to reduce erosion and improve infiltration has raised questions of whether it is the "best" polymer for the application. There is increasing anecdotal and scientific evidence[57,58] that PAM efficacy varies with different soils and waters. Variations include sodicity, texture, bulk density, and surface charge-related properties. It would be beneficial to have a wide array of polymers with potentially different soil-stabilizing mechanisms, applicable to different soil types.

Of course, any reduction in price would also benefit farmers. The market price of PAM, i.e., several dollars per kilogram, is high relative to many commodity polymers, such as polyethylene, polypropylene, and polystyrene. Treatment for 1 year can cost up to $25 per hectare, which is still cost competetive with conventional erosion abating technologies such as straw bales, settling ponds, and underground or drip irrigation systems.

The increasing market pull of organic farming techniques is a strong reason to explore alternatives to PAM. Polyacrylamide cannot be used during organic farmering because it is a synthetic polymer derived from nonrenewable resources. Natural polymers, which often degrade via relatively benign routes, may be more suitable. Biopolymer alternatives to PAM would likely have marketing advantages due to public *perception* of being safer.

Cellulose and starch xanthates were among the first industrial biopolymers shown to stabilize soil.[11,14] Menefee and Hautala[14] reduced sediment runoff by nearly 98% by surface treating 20° sloped plots with cellulose xanthate solution (0.4%). Orts et al.[11] added cellulose xanthate to the irrigation water of lab-scale mini-furrows, and reduced erosion 80% when xanthate was applied at concentrations of 80 ppm or greater, which is well above the standard PAM application rate of 10 ppm and even 5 ppm.

Chitosan, the biopolymer derived from crab and shrimp shells, was shown to reduce erosion losses as effectively as PAM in lab-scale mini-furrow at concentrations of 20 ppm.[22] With such favorable lab test results, chitosan was further tested in a series of field tests at the USDA Northwest Irrigation and Soil Research Lab, Kimberly, Idaho.[22] In the field tests, chitosan reduced erosion-induced soil losses by, at best, half of the control, but far less effectively than PAM. Such poor comparative results, however, do not mean that chitosan had no effect on the irrigation. Observations of the furrows treated with chitosan revealed remarkable results in the first ~20 m of the furrow. In fact, chitosan acted as such an effective flocculating agent that it removed fine sediments, and even algae from the irrigation water. Perhaps chitosan binds so readily with sediment that it flocculates out of solution near the top of the furrow. The major drawback of chitosan is its market cost of over $3 kg^{-1}, roughly twice the price of PAM.

CONCLUSION

U.S. agricultural PAM-use for erosion control and infiltration improvement reached 400,000 ha in 1999,[59] with U.S. and worldwide markets expected to grow as farmers recognize PAMs efficacy, and as government-mandated water quality legislation is realized. The success of PAM in agriculture opens the possibility to explore other Ag-related uses for PAM,[45] as well as the potential to find alternatives to PAM. For example, modified polysaccharides[11–14] and cheese whey, the protein concentrate from cheese processing, are particularly interesting natural soil stabilizers, and could be used to treat irrigation water.

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