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Review

Control of waterborne microbes in irrigation: A review

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ABSTRACT

A wide range of plant pathogens have been identified in irrigation water sources and distribution systems. Algae and equipment-clogging biofilms also result from high microbial levels in irrigation water. The literature was reviewed on the effectiveness of water treatment options to control waterborne microbes. Water treatments included chemicals (chlorine, bromine, chlorine dioxide, ionized copper, copper salts, ionized silver, ozone, hydrogen peroxide, and peroxyacetic acid), non-chemical or physical treatments (filtration, heat, and ultraviolet radiation) and ecological alternatives (constructed wetlands, biosurfactants, and slow sand filtration). The objective was to summarize the effective dose for controlling target waterborne microorganisms. The effective dose for chemical water treatments to control plant pathogens was in some cases above documented phytotoxicity thresholds, and for most crops and technologies the phytotoxicity thresholds remain unknown. Most efficacy research has been conducted on chlorine (20 articles) or copper (18), but only 0–7 articles were found on other water treatments currently in use, indicating major knowledge gaps in treatment efficacy. Research is needed on control methods for algae and biofilms, *in vivo* pathogen studies, phytotoxicity thresholds, and the relationship between pathogen inoculum level and disease incidence in irrigation water. Finally, improved overall system design is required for risk management of waterborne microbes in irrigation, including a multiple barrier approach incorporating pre-filtration, multiple treatment stages, and monitoring of water quality.

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1. Introduction

The biological, physical, and chemical characteristics of a water source impact its suitability for irrigation (Cook, 2000; FAO, 1994). Irrigation water can be an inoculum source or dispersal mechanism for diverse biological problems including plant pathogens (Hong and Moorman, 2005; Ristaino and Gumpertz, 2000), algae (Camberato and Lopez, 2010; Dehghanisanij et al., 2005; Juanico et al., 1995) and biofilm-forming organisms (Adin and Sacks, 1991; Yan et al., 2009). Plant pathogens and other microbes are particularly problematic when irrigating with surface or recirculated water sources (Gilbert et al., 1981; Runia, 1994a), and these water sources are increasingly being used in irrigation in order to conserve drinking water supplies (Obreza et al., 2010).

Diverse plant pathogens have been identified in irrigation water including 17 species of *Phytophthora*, 26 species of *Pythium*, 27 genera of true fungi, 8 species of bacteria, 10 viruses, and 13 species of plant parasitic nematodes (Hong and Moorman, 2005). Motile microorganisms such as *Pythium* spp. and *Phytophthora* spp. may be freely present in water, whereas plant pathogens that do not produce swimming structures (for example, *Rhizoctonia solani* and *Thielaviopsis basicola*) are more likely to be carried by bulk flow with soil debris in the water (Baker and Matkin, 1978).

Algae growth can also result from poor biological water quality, and is a costly nuisance in agricultural systems (Camberato and Lopez, 2010; Schwarz and Krienitz, 2005). Algae can clog emitters, resulting in uneven irrigation distribution (Dehghanisanij et al., 2005; Juanico et al., 1995), reduce plant growth through the production of toxic substances (Schwarz and Krienitz, 2005; Schwarz and Gross, 2004), and provide food and habitat for shore flies (*Scatella stagnalis*), which are vectors of plant pathogens (El-Hamalawi, 2007; Hyder et al., 2009). An impermeable-algae layer can form on the surface of the media reducing water permeability (Peterson, 2001). Algae can create a worker hazard when covering walk ways, and reduce aesthetic quality of ornamental potted plants.

Biofilms are a complex matrix of polymers with pathogenic and non-pathogenic microorganisms (Costerton et al., 1995; Maier et al., 2009). Organic compounds on the inside surface of pipes (Maier et al., 2009) and soluble fertilizers provide nutrients for microorganisms and biofilm formation in irrigation pipes. Emitters are clogged directly when biofilm forms a physical barrier, or indirectly by the formation of precipitates with minerals such as iron, manganese and sulfur dissolved in water (Gilbert et al., 1981; Yan et al., 2009). Biofilms are resistant to sanitizing treatment because of their complexity and variability in structure and composition (Berry et al., 2006; Costerton et al., 1995; Tachikawa et al., 2009; Viera et al., 1993).

A range of water treatments are available for management of microbial water quality problems. Available treatments include chemicals (chlorine, bromine, chlorine dioxide, ionized copper, copper salts, ionized silver, ozone, hydrogen peroxide, and peroxyacetic acid), non-chemical or physical treatments (filtration, heat, and ultraviolet (UV) radiation) and ecological alternatives (biosurfactants, constructed wetlands and slow sand filtration). Efficacy of control of microbes depends on the target organisms, and the dose with respect to concentration or intensity and contact time (Ehret et al., 2001; Lane, 2004; Runia, 1995; Stewart-Wade, 2011; Van Os, 2010). Water quality parameters, such as the concentration of suspended solids, presence of ions, pH, and temperature also affect disinfestation strength of water treatments (Copes et al., 2004; Huang et al., 2011).

Literature reviews have been conducted on the presence of plant pathogens in irrigation water (Hong and Moorman, 2005) and alternative water treatments to control microbial growth in irrigation (Ehret et al., 2001; Lane, 2004; Newman, 2004; Runia, 1995; Stewart-Wade, 2011; Van Os, 2010). However, a comprehensive review of the alternatives to control plant pathogens, algae, and biofilms in irrigation systems is needed for irrigation specialists designing water treatment options, in addition to plant pathologists and agronomists. The objective of this article was to summarize the effective dose for controlling target waterborne microorganisms. This review includes a brief description of the mode of action of each technology; the dose response for control of pathogens, algae and biofilms; threshold concentrations leading to crop phytotoxicity; and interactions with water contaminants and water chemistry. Design considerations for effective water treatment, and research priorities were identified.

2. Review of water treatment efficacy

2.1. Chemical water treatments

2.1.1. Chlorine

2.1.1.1. Mode of action. Chlorine is an oxidizer that removes electrons from reactants (such as a pathogen cell membrane), and in the process chlorine becomes reduced to chloride (Cl^-). Chlorine can be applied to irrigation water as a gas (Cl_2); as a liquid, mainly as either sodium hypochlorite (NaOCl) or purified hypochlorous acid (HOCl); or as a solid, most commonly as calcium hypochlorite ($Ca(ClO)_2$). The mode of action of chlorine for control of microorganisms is through both oxidation and chlorination (Deborde and von Gunten, 2008). The two main pH-dependent forms of free chlorine in water are hypochlorous acid (HOCl, a strong oxidizer that predominates below pH 7.5), and hypochlorite (OCl^-, a weak sanitizer that predominates at higher pH) (Morris, 1966).

2.1.1.2. Dose response. Chlorine illustrates a wide range in dosage is required to control different pathogenic organisms, and life stages within organisms (Table 1). High mortality of oomycete zoospores has been observed with 2 mg L^{-1} of free chlorine (Hong et al., 2003; Lang et al., 2008). A dosage rate of 2 mg L^{-1} is typically used in irrigation (Fisher et al., 2008a,b). In contrast, mortality of mycelia and sporangia of oomycetes required 4 mg L^{-1} with 0.5 and 8 min contact time, respectively (Hong et al., 2003). *Fusarium oxysporum* and *R. solani* required 8 mg L^{-1} with 5 min contact time and 10 mg L^{-1} with 10 min contact time to achieve mortality greater than 90%, respectively (Cayanan et al., 2009a). The concentration required to control bacterial pathogens ranged from 0.1 to 4 mg L^{-1} (Poncet et al., 2001; Robbs et al., 1995; Roberts and Muchovej, 2009; Thompson, 1965). Between 5 and 30 mg L^{-1} controlled algae in studies by Chase and Conover (1993) and Rav-Acha et al. (1995). Commercial greenhouse recycled irrigation water treated with 4 mg L^{-1} of chlorine (applied as sodium hypochlorite) with 30 min contact time completely eliminated Cucumber leaf spot virus (CLSV) inoculum, but 3 mg L^{-1} had no effect on virus viability (Rosner et al., 2006). Nematodes are highly resistant to chlorination (Grech and Rijkenberg, 1991; Stanton and O'Donnell,