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Review

Multi-scale *Cryptosporidium*/sand interactions in water treatment

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ABSTRACT

Owing to its widespread occurrence in drinking water supplies and its significant resistance to environmental stresses, *Cryptosporidium parvum* is regarded as one of the most important waterborne microbial parasites. Accordingly, a substantial research effort has been aimed at elucidating the physical, chemical and biological factors controlling the transport and removal of *Cryptosporidium* oocysts in natural subsurface environments and drinking water treatment facilities. In this review, a multi-scale approach is taken to discuss the current state-of-knowledge on *Cryptosporidium*–sand interactions at a nano-scale, bench-scale and field-scale relevant to water treatment operations. Studies conducted at the nano-scale and bench-scale illustrate how techniques based on the principles of colloid and surface chemistry are providing new insights about oocyst–sand interactions during transport of *Cryptosporidium* oocysts in granular porous media. Specifically, atomic force microscopy and impinging jet experiments reveal the importance of oocyst surface biomolecules in controlling *Cryptosporidium*/sand interactions by a mechanism of steric hindrance. Traditional bench-scale column transport studies conducted over a broad range of experimental conditions highlight the role of physicochemical filtration and physical straining in the removal of oocysts from the pore fluid. Such experiments have also been used to evaluate the influence of biofilms formed on grain surfaces and the presence of natural organic matter on oocyst–sand interactions. Whilst filtration studies conducted at the plant-scale have been useful for evaluating the effectiveness of various materials as surrogates for *Cryptosporidium* oocysts, at this macro-scale, little could be learnt about the fundamental mechanisms controlling oocyst–sand interactions. This review of the literature on *Cryptosporidium*–sand interactions at different length scales points to the importance of combining studies at the plant-scale with well-controlled investigations conducted at the nano- and bench-scales. Furthermore, because oocyst surface properties play an important role in controlling the extent of interaction with sand surfaces, a thorough discussion of *Cryptosporidium* oocyst characteristics and electrical properties is presented.

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Contents

1. Introduction

The protozoan parasite *Cryptosporidium parvum* (*C. parvum*) has emerged as one of the most important microbial pathogens for drinking water safety and is associated with a high risk of waterborne illness (Lederberg et al., 1992; Rose, 1997). *C. parvum* is commonly transmitted via the faeces of infected mammalian hosts in its environmentally resistant stage—the oocyst (Lederberg et al., 1992; Smith, 1992; Mawdsley et al., 1995). Outside the mammalian host, the oocyst is biologically dormant and incapable of replication (Fayer et al., 1997). However, once infected, wild and domestic mammals may shed a large number of oocysts into the environment (e.g., a calf may excrete up to 10 million oocysts/day) (Rose, 1997). Ingestion of a small number of viable oocysts (as little as 10) can lead to cryptosporidiosis, a diarrhoeal disease that is potentially lethal for immunosuppressed individuals (Wolfson et al., 1985; Lederberg et al., 1992; Casemore et al., 1997; Rose, 1997).

Because *C. parvum* has been detected in a wide range of wild and domestic animals—including cattle, deer, and pigs—the contamination of water supplies by mammalian faecal wastes is of serious concern (Rose, 1997). In fact, surveillance data for *C. parvum* indicates the prevalence of the parasite throughout the environment, and sources are probably present in every surface water catchment (Lisle and Rose, 1995; Ionas et al., 1998; Quintero-Betancourt and Botero De Ledesma, 2000). *C. parvum* has been found in rivers and streams, lakes and reservoirs, raw and treated sewage, and treated surface waters. The parasite is increasingly regarded as an important cause of enteric disease and several waterborne outbreaks of cryptosporidiosis have been documented (Casemore et al., 1997). Outbreaks have been reported in the United Kingdom (Lisle and Rose, 1995) as well as the United States (Lisle and Rose, 1995; SoloGabriele and Neumeister, 1996) most notable of which was the outbreak in Milwaukee where up to 400,000 people were infected and 87 deaths of immunocompromised patients were attributed to the disease (Smith and Perdek, 2004). Occasional outbreaks have occurred with no measured changes in source water quality or treatment processes (Roefer et al., 1996). Such episodes, combined with the serious consequences of cryptosporidiosis outbreaks, have necessitated research on reliable processes to defend drinking water supplies from contamination with *Cryptosporidium*.

Resistance of the *C. parvum* oocyst to several environmental stresses including chlorination during water treatment poses a significant challenge to the protection of drinking water supplies from contamination (Campbell et al., 1982; Hayes et al., 1989; West, 1991; Rose, 1997). As a result, water utilities are showing increased interest in oocyst removal in granular porous media, using approaches such as deep-bed (granular) filtration, riverbank filtration and slow-sand filtration, to ensure the safety of drinking water (Timms et al., 1995; Huck et al., 2002; Tufenkji et al., 2002).

To better understand and predict the removal of *C. parvum* oocysts in these settings, a growing research effort has been directed at elucidating the factors controlling oocyst–sand interactions as well as the fundamental mechanisms governing the filtration of oocysts. Studies related to the general behaviour of *Cryptosporidium* oocysts in granular porous media have been carried out at various length scales, from the micro-scale to the field-scale. The use of atomic force microscopy (AFM) has made possible the characterization of nano-scale interaction forces between oocysts of *C. parvum* and model sand surfaces (Considine et al., 2000, 2001, 2002; Byrd and Walz, 2005). Measurements of oocyst deposition onto flat quartz surfaces in a radial stagnation point flow (RSPF) cell have provided further insight into the factors that influence *Cryptosporidium*–sand interactions at the micro-scale (Kuznar and Elimelech, 2004, 2005). Several researchers have investigated the filtration behaviour of *Cryptosporidium* at the bench-scale, using laboratory columns packed with a wide range of different sediments or model granular materials (Mawdsley et al., 1996; Brush et al., 1999; Harter et al., 2000; Hsu et al., 2001; Logan et al., 2001; Dai and Hozalski, 2002, 2003; Tufenkji et al., 2004; Abudalo et al., 2005; Bradford and Bettahar, 2005; Hijnen et al., 2005; Tufenkji and Elimelech, 2005b). In these studies, various aspects of *C. parvum* transport and removal in granular porous media have been