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Invited article

Potential application of high pressure carbon dioxide in treated wastewater and water disinfection: Recent overview and further trends

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ABSTRACT

Recently emerging disadvantages in conventional disinfection have heightened the need for finding a new solution. Developments in the use of high pressure carbon dioxide for food preservation and sterilization have led to a renewed interest in its applicability in wastewater treatment and water disinfection. Pressurized CO_2 is one of the most investigated methods of antibacterial treatment and has been used extensively for decades to inhibit pathogens in dried food and liquid products. This study reviews the literature concerning the utility of CO_2 as a disinfecting agent, and the pathogen inactivation mechanism of CO_2 treatment is evaluated based on all available research. In this paper, it will be argued that the successful application and high effectiveness of CO_2 treatment in liquid foods open a potential opportunity for its use in wastewater treatment and water disinfection. The findings from models with different operating conditions (pressure, temperature, microorganism, water content, media …) suggest that most microorganisms are successfully inhibited under CO_2 treatment. It will also be shown that the bacterial deaths under CO_2 treatment can be explained by many different mechanisms. Moreover, the findings in this study can help to address the recently emerging problems in water disinfection, such as disinfection by-products (resulting from chlorination or ozone treatment).

Introduction

For nearly a century, chlorine has played a major role in standards for water disinfection in Europe, the United States, and other countries around the world. The low cost and effectiveness of chlorination provide it with an advantage over other disinfectants. However, chlorine can combine with other chemicals in water to generate cancer-causing by-products. Organochlorides formed after chlorination disinfection are intermediates in the generation of dioxins, compounds that are carcinogenic and toxic to the environment and aquatic species (Boorman et al., 1999; Krasner et al., 2006; Liu and Zhang, 2014; Zhai et al., 2014). Another chemical disinfectant, ozone, which has been successfully used for decades to eradicate viruses, *Giardia*, *Cryptosporidium*, and other known pathogens, is considered to be safer than

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chlorine. However, the disadvantages of ozone disinfection include high cost, requirements for ozone generation equipment and special operators, and the formation of a few disinfection byproducts (DBPs) (Hoigné and Bader, 1988; Krasner et al., 2006), and the lack of residual disinfectants. Physical disinfectants such as ultraviolet (UV) irradiation, electronic radiation, ultrasound, and heating have been applied to replace conventional methods. UV irradiation has long been considered an effective primary solution that is able to damage the genetic structure of bacteria, viruses, and emerging pathogens without generating DBPs; however, its disinfecting activity depends on water characteristics (turbidity, pathogen population, hardness), and there is a need for frequent lamp maintenance and replacement.

Pressurized CO_2 has been applied to inhibit pathogens in food as a cold pasteurization method (Garcia-Gonzalez et al., 2007). Numerous studies have explored the bactericidal effect of CO_2 on microbial growth. The results obtained showed that the inactivation mechanism of high pressure carbon dioxide (HPCD) can take place by extraction of cell membrane components, acidification, denaturation of DNA, change of cell metabolism and lowered pH of cytoplasm (Hong and Pyun, 1999; Spilimbergo et al., 2005; Garcia-Gonzalez et al., 2007). Discoveries providing scientific evidence on HPCD inactivation have continued unabated over the last two decades, especially from 2007 to the present (Fig. 1). While there are approximately 120 published journal articles on this topic, this issue has grown in importance in light of recent food preservation requirements.

Most studies on the use of pressurized CO_2 have been carried out in three separate areas: dried food, liquid food and water treatment (Fig. 1). Much research up to 2009 about HPCD has tended to focus on food sterilization rather than water disinfection. So far this method has only been applied to food. Far too little attention has been paid to water disinfection since the first study of Kobayashi et al. (2007) have successfully carried out an attempt to transfer knowledge of HPCD from food disinfection to water disinfection. In recent years, there has been an increasing interest in applying HPCD to water treatment (Kobayashi et al., 2007, 2009a, 2009b, 2010; Cheng et al., 2011) with the belief that pressurized CO_2 has all the advantages of conventional disinfection methods and

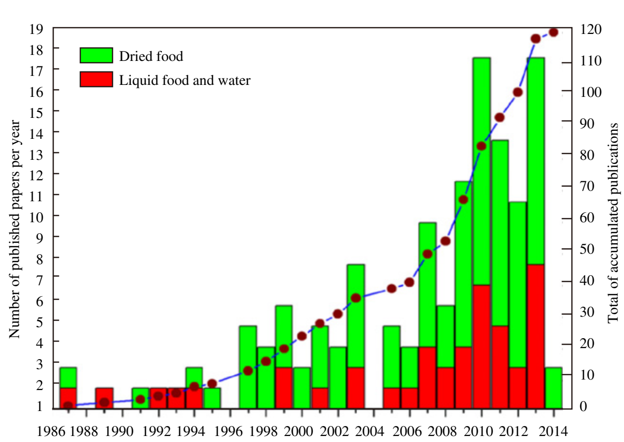

Fig. 1 – Total studies investigated related to using high pressure carbon dioxide in disinfection of dried food, liquid food and water.

overcomes their adverse effects to health. Questions have been raised as to why the major attention on HPCD has been paid to liquid media and water, as shown in Fig. 1. Strong evidence has been found that when experiments using CO_2 under pressure were conducted with high water content or high moisture, the presence of water makes cell walls more permeable to CO_2, with higher diffusivity, higher solubility and lower viscosity than in dried media (Haas et al., 1989; Lin et al., 1993, 1994; Kamihira et al., 1987).

1. Effect of HPCD on microbial disinfection

Many species of microorganisms, including gram-negative and gram-positive bacteria and bacterial spores, have been subjected to CO_2 treatment under various operating conditions. The use of supercritical CO_2 is also of great interest for the inactivation of microorganisms (Kuhne and Knorr, 1990). Pressurized CO_2 has been found to inhibit various microorganisms (bacteria, molds, yeast) (Haas et al., 1989).

1.1. *Gram-negative bacteria inactivation (Escherichia coli)*

Since *E. coli* was successfully inhibited by pressurized CO_2 in the first study (Fraser, 1951), numerous investigations, including at least 20 studies, have attempted to explain the relationship between the inactivation effect of CO_2 and the cell death of *E. coli* (Table 1). Kamihira et al. (1987) found that *E. coli* suspended in distilled water was killed to a 5.1 log reduction by high-pressure CO_2 treatment at 20 MPa and 35°C for 120 min, while Haas et al. (1989) found that with same treatment time this method killed *E. coli* cells suspended in culture broth to 6.3 log. Dillow et al. (1999) confirmed the complete or high inactivation of a wide variety of bacterial organisms, especially *E. coli*, in response to supercritical fluid CO_2 applied in the absence of organic solvents or irradiation. Schmidt et al. (2005) and Cinquemani et al. (2007) have found that *E. coli* was completely inhibited with 5–7 MPa CO_2 in only 20 min. Moreover, an increase of pressure, temperature, or treatment time of CO_2 under pressure enhanced the antimicrobial effect against *E. coli* (Kamihira et al., 1987; Dillow et al., 1999; Wu et al., 2007; Kobayashi et al., 2007, 2009b; Garcia-Gonzalez et al., 2010). Thus the use of pressurized CO_2 has been widely investigated (Wu et al., 2007; Kobayashi et al., 2007, 2009a; Jung et al., 2009; Garcia-Gonzalez et al., 2010; Klangpetch et al., 2011; Cheng et al., 2011).

1.2. *Gram-positive bacteria inactivation*

Several studies have revealed that HPCD is effective against not just gram-negative bacteria (*E. coli*) but also on variety of gram-positive bacteria (Table 2). The cell deaths of *Listeria monocytogenes*, *Bacillus cereus* and *Staphylococcus aureus* (from 7 to 9 log reduction) caused by high-pressure CO_2 were found by many studies (Wei et al., 1991; Lin et al., 1994; Ishikawa et al., 1997; Sirisee et al., 1998; Erkmen, 2000d, 2001a; Spilimbergo et al., 2002, 2003a, 2003b, 2003c; Spilimbergo and Bertucco, 2003; Kim et al., 2008). Wei et al. (1991) successfully investigated HPCD for *L. monocytogenes* inactivation in a distilled water