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Review

High pressure carbon dioxide pasteurization of solid foods: Current knowledge and future outlooks

Giovanna Ferrentino* and **Sara Spilimbergo**

Department of Materials Engineering and Industrial Technologies, University of Trento, via Mesiano 77, Trento 38050, Italy (Tel.: +39 0461 282 485; e-mail: giovanna.ferrentino@ing.unitn.it)

High pressure carbon dioxide (HPCD) technology applied to foods has gained a particular scientific interest considering the number of publications and patents published in the last decades. Although the antimicrobial effect of HPCD has been demonstrated mainly for liquid foodstuffs, very few research papers investigated the possibility to exploit the treatment on solid foods. In this concern, the main objective of the present review is to give a general survey of the published knowledge concerning the HPCD applied to solid foods. Remarks and future outlooks will be highlighted with the aim to suggest a research line to follow for future studies.

Introduction

Manufacturers of food products are currently under increasingly stringent demands concerning the production processes. This is essentially caused by the growing interest of consumers for high-quality and "minimal processing" products, as well as for energy saving and safer production processes. Minimally processed foods are obtained with methods of food safety and preservation that are designed to retain the natural and fresh properties of foods (Manvell, 1997).

Most of the food products contain high levels of nutrients or a high water activity; therefore they are particularly susceptible of microbial spoilage which results in a deterioration of their organoleptic characteristics, and may even risk the health of immune-compromised individuals (Tournas, Heeres, & Burgess, 2006).

Preservation of food products reduces the number of undesirable microorganisms below a specific critical value during the shelf storage period of the product. It is usually performed through different methods as thermal pasteurization up to 80 °C and sterilization up to 120 °C (e. g. fruits, food powders and meat), drying (e. g. vegetables, and herbs), freezing (e. g. meats, fishes, and vegetables), addition of preservatives (e. g. meats, and vegetables), autoclaving (e. g. herbs), gamma irradiation (e. g. vegetables), or ethylene oxide and methyl bromide exposure (e. g. vegetables; spices). These treatments are successful to eliminate the degenerative effects of enzymes and microorganisms, but on the other hand they may also reduce the food quality by causing alterations in the taste and in the organoleptic features of food products. Several authors observed a reduction in vitamin C retention, color degradation, and changes in other quality indicators due to the thermal treatments applied to fruits (Awuah, Ramaswamy, & Economides, 2007; Vikram, Ramesh, & Paprulla, 2005). Others reported that the application of both methyl bromide and ethylene oxide is extremely toxic. Methyl bromide is potentially capable of depleting the atmospheric ozone layer. Ethylene oxide has been banned in Europe because of safety and environmental concerns, and its use for the treatment of ground spices has been revoked in the United States (Thayer, Josephson, Brynjolfsson, & Giddings, 1996). Autoclaving, freezing, drying or exposure to steam have been described as methods which cause degradation of bioactive compounds and the destruction of the delicate tissue of the foods (Howard, 2008).

Alternatives to traditional treatments as the use of ozone, radical species, and high hydrostatic pressure have been proposed in these years (San Martin, Barbosa–Canovas, & Swanson, 2004). The latter has been already used for few years at commercial scale for the decontamination of solid foods such as meat products (Shigehisa, Ohmori, Saito, Taji, & Hayashi, 1991) or ready to eat meals (Cheftel, 1995). Pressures ranging

* Corresponding author.

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from 300 to 700 MPa are usually applied. The process resulted effective on different microbial species but the high equipment cost, the difficulty of controlling and managing an operating pressure in such extreme range of values, the safety concerns represent the potential drawbacks to be overcome.

Among the other innovative preservation methods, high pressure carbon dioxide process (HPCD) has gained great interest in the scientific field. Since the 1980s it has been increasingly investigated as a promising technique to induce a pasteurizing/sterilizing effect when applied both to solid and liquid matrixes. The HPCD preservation method provides several advantages. Carbon dioxide (CO_2) used in this process is not only a powerful solvent for a wide range of compounds of interest in food processing, but is relatively inert, inexpensive, nontoxic, nonflammable, recyclable and readily available in high purity leaving no residue when removed after the process (Clifford & Williams, 2000). Furthermore, it is considered to be a GRAS (Generally Recognized as Safe) solvent, which means it can be used in food products.

So far most of the research has been focused on suspensions of pure cultures of different microorganisms inoculated or naturally occurring in liquid food products (e.g. fruit juices, beer, wine and milk) which affect the food spoilage and give main concern to health (Arreola, Balaban, Wei, Peplow, & Marshall, 1991; Del Pozo-Insfran, Balaban, & Talcott, 2006). The method seems to be very promising because HPCD (or dense phase CO_2) is able of killing bacteria, yeast and fungi at moderate pressure and low temperature preserving more quality attributes of the products than traditional treatments (Ferrentino, Plaza, Ramirez-Rodrigues, Ferrari, & Balaban, 2009; Spilimbergo & Ciola, 2010).

Three recent reviews compile the relevant current knowledge about the potential of HPCD treatment and summarize the most significant state of the art, including the most important applications and data for the treatment applied to a wide range of microorganisms mainly in liquid substrates (Damar & Balaban, 2006; Garcia-Gonzalez *et al*., 2007; Spilimbergo & Bertucco, 2003).

Compared to liquids, the HPCD process applied to solid foods is less studied due to the complexity of the matrix, which can make the CO_2 bactericidal action more difficult, and to the lack of information about the inactivation mechanism which is almost obscure and scarcely studied.

The aim of the present review is to provide the status of the art of HPCD process applied to solid foodstuffs with the examination of almost all the literature published on this subject including the most relevant patents.

The review has been constructed as follows: a description of the application of the process for each category of solid foods tested so far (meats, fruits and vegetables, food powders, sprouts seeds, spices and herbs, fishes) has been addressed. For each category of solid foods a discussion of the main effects of the HPCD treatment on microbial inactivation and quality attributes of the foods has been reported considering all significant articles published in the field.

A brief section of the review is dedicated to the description of the main results obtained by different authors when the HPCD process is carried out in combination with some pretreatments or additives.

Finally a reflection on the important aspects of the process, its limits and potentials, the lack of scientific information to fill up, and a direction to orientate the research will be evidenced.

Application of HPCD treatment to solid foods

The effects of the HPCD treatment on the microbial inactivation and quality attributes of food matrixes are reported in the following sections. The process has been applied to meats (chicken, pork, and beef), vegetables (celery, and spinach), seeds and food powders (alfalfa seeds, cocoa powder, and ginseng), fruits (cut pieces of pears, strawberries, honeydew melon, and cucumber), spices and herbs (chives, thyme, oregano, parsley, and mint), and fish (shrimp, and oyster). Considering the different characteristics and behaviors of each substrate to the treatment, the literature review has been reported separately for each category of solid matrix.

Table 1 is a compilation of the experimental results that can be found in the literature with indication of the type of food, microorganism, the present industry conventional treatment, and the conditions of HPCD treatment with the corresponding achieved microbial inactivation. Table 2 reports the desired level of microbial inactivation required by law (Regulation (EC) No. 2073/2005) for each type of microorganism and foodstuffs mentioned. Table 3 summarizes the description and the main observations of the effects of the treatment on the appearance, and some quality attributes of the foods subjected to the process.

Meats

Microbial inactivation

The HPCD technology in particular in supercritical state (31 °C and 7.4 MPa) has been widely investigated and applied to meat considering the ability of CO_2 to extract and fractionate fats from ground beef into lower melting temperature components, as well as for the removal of cholesterol (Chao, Mulvaney, Bailey, & Fernando, 1991). Apart from this application, the treatment has been also applied to test the efficacy on the inactivation of bacteria strains to induce pasteurization. Sirisee, Hsieh, and Huff (1998) tested the tolerance of *Escherichia coli* and *Staphylococcus aureus* in ground beef to HPCD treatment carried out at 42.5 °C and 31.03 MPa. Ground beef samples were mixed with the suspended microbial cultures and then placed in the reactor to be processed. The experimental results highlighted the longer treatment time needed to inactivate both target microbes compared to the same treatment carried out on the same microorganisms in a liquid phosphate buffer