

High Pressure Processing- Changes in Quality Characteristic of Various Food Material Processed Under High Pressure Technology

Ravi Shankar

Department of Food Process Engineering, Vaugh School of Agriculture Engineering and Technology,
Sam HigginBottom Institute of Agriculture, Technology and Sciences-Deemed University,
P.O Naini, Allahabad, U.P-211007, India

ABSTRACT: Consumers demand for quality of food has triggered the need for the development of a number of non-thermal approaches to food processing, of which high-pressure technology has proven to be very valuable. This review aims to identify the opportunities and challenges associated with this technology. In addition to discussing the effects of high pressure on food components, this review covers the combined effects of high pressure processing with: gamma irradiation, alternating current, ultrasound, and carbon dioxide or anti-microbial treatment. Further, the applications of this technology in various sectors— fruits and vegetables, dairy, and meat processing—have been dealt with extensively. The integration of high-pressure with other matured processing operations such as blanching, dehydration, osmotic dehydration, rehydration, frying, freezing / thawing and solid-liquid extraction has been shown to open up new processing options. The key challenges identified include: heat transfer problems and resulting non-uniformity in processing, obtaining reliable and reproducible data for process validation, lack of detailed knowledge about the interaction between high pressure, and a number of food constituents, packaging and statutory issues. The aim of this review is the different aspects and potential application of HPT and critically examines HPT related studies. Different types of food product (fruits and vegetables product, Dairy product, Meat product, Starch product etc.) are preserved and maintained the nutritional qualities for longer time.

KEYWORDS: HPT, HPP, Isostatic, Rheology, Sterilization, Pasteurization, Preservation, Operating Cost.

1 INTRODUCTION

Technology Demand for safe food available throughout the year has been increasing throughout the world with busy schedule and increasing consumer's knowledge about the products, so the food technologist has to work on technologies which can satisfy the consumer's demand of safe, fresh, varieties and less expensive foods. Consumers need to make aware of the safety of the technology used for preserved food. The food technologist need to work in the area for the adaptation of the best technology available with can preserve original quality of food as fresh procured and with minimum operating cost for those technological treatments.

"High pressure kills microorganisms and preserves food" was discovered way back in 1899 and has been used with success in chemical, ceramic, carbon allotropy, steel/alloy, composite materials and plastic industries for decades, it was only in late 1980's that its commercial benefits became available to the food processing industries. High pressure processing (HPP) is similar in concept to cold isostatic pressing of metals and ceramics, except that it demands much higher pressures, faster cycling, high capacity, and sanitation (Zimmerman and Bergman, 1993; Mertens and Deplace, 1993). Hite (1899) investigated the application of high pressure as a means of preserving milk, and later extended the study to preserve fruits and vegetables (Hite, Giddings, and Weakly, 1914). It then took almost eighty years for Japan to re-discover the application of high-pressure in food processing. The use of this technology has come about so quickly that it took only three years for two Japanese companies to launch products, which were processed using this technology. The ability of high pressure to inactivate microorganisms and spoilage catalyzing enzymes, whilst retaining other quality attributes, has encouraged Japanese and American food companies to introduce high pressure processed foods in the market (Mermelstein, 1997; Hendrickx, Ludikhuyze, Broeck, and Weemaes, 1998). The first high pressure processed foods were introduced to the Japanese market in 1990 by Meidi-ya, who have been marketing a line of jams, jellies, and sauces packaged and processed without application

of heat (Thakur and Nelson, 1998). Other products include fruit preparations, fruit juices, rice cakes, and raw squid in Japan; fruit juices, especially apple and orange juice, in France and Portugal; and guacamole and oysters in the USA (Hugas, Garcia, and Monfort, 2002). In addition to food preservation, high-pressure treatment can result in food products acquiring novel structure and texture, and hence can be used to develop new products (Hayashi, 1990) or increase the functionality of certain ingredients. Depending on the operating parameters and the scale of operation, the cost of high pressure treatment is typically around US\$ 0.05–0.5 per liter or kilogram, the lower value being comparable to the cost of thermal processing (Thakur and Nelson, 1998; Balasubramaniam, 2003).

The non-availability of suitable equipment encumbered early applications of high pressure. However, recent progress in equipment design has ensured worldwide recognition of the potential for such a technology in food processing (Gould, 1995; Galazka and Ledward, 1995; Balci and Wilbey, 1999). Today, high-pressure technology is acknowledged to have the promise of producing a very wide range of products, whilst simultaneously showing potential for creating a new generation of value added foods. In general, high-pressure technology can supplement conventional thermal processing for reducing microbial load, or substitute the use of chemical preservatives (Rastogi, Subramanian, and Raghavarao, 1994).

Over the past two decades, this technology has attracted considerable research attention, mainly relating to:

- i) the extension of keeping quality (Cheftel, 1995; Farkas and Hoover, 2001),
- ii) changing the physical and functional properties of food systems (Cheftel, 1992), and
- iii) exploiting the anomalous phase transitions of water under extreme pressures, e.g. lowering of freezing point with increasing pressures (Kalichevsky, Knorr, and Lillford, 1995; Knorr, Schlueter, and Heinz, 1998).

The key advantages of this technology can be summarized as follows:

1. it enables food processing at ambient temperature or even lower temperatures;
2. it enables instant transmittance of pressure throughout the system, irrespective of size and geometry, thereby making size reduction optional, which can be a great advantage;
3. it causes microbial death whilst virtually eliminating heat damage and the use of chemical preservatives/additives, thereby leading to improvements in the overall quality of foods; and
4. it can be used to create ingredients with novel functional properties. The effect of high pressure on microorganisms and proteins/ enzymes was observed to be similar to that of high temperature.

As mentioned above, high pressure processing enables transmittance of pressure rapidly and uniformly throughout the food. Consequently, the problems of spatial variations in preservation treatments associated with heat, microwave, or radiation penetration are not evident in pressure-processed products.

The application of high pressure increases the temperature of the liquid component of the food by approximately 3°C per 100 MPa. If the food contains a significant amount of fat, such as butter or cream, the temperature rise is greater (8–9°C/100 MPa) (Rasanayagam, Balasubramaniam, Ting, Sizer, Bush, and Anderson, 2003). Foods cool down to their original temperature on decompression if no heat is lost to (or gained from) the walls of the pressure vessel during the holding stage.

The temperature distribution during the pressure-holding period can change depending on heat transfer across the walls of the pressure vessel, which must be held at the desired temperature for achieving truly isothermal conditions. In the case of some proteins, a gel is formed when the rate of compression is slow, whereas a precipitate is formed when the rate is fast. High pressure can cause structural changes in structurally fragile foods containing entrapped air such as strawberries or lettuce. Cell deformation and cell damage can result in softening and cell serum loss. Compression may also shift the pH depending on the imposed pressure. Heremans (1995) indicated a lowering of pH in apple juice by 0.2 units per 100 MPa increase in pressure. In combined thermal and pressure treatment processes, Meyer (2000) proposed that the heat of compression could be used effectively, since the temperature of the product can be raised from 70–90°C to 105–120°C by a compression to 700 MPa, and brought back to the initial temperature by decompression.

As a thermodynamic parameter, pressure has far-reaching effects on the conformation of macromolecules, the transition temperature of lipids and water, and a number of chemical reactions (Cheftel, 1992; Tauscher, 1995). Phenomena that are accompanied by a decrease in volume are enhanced by pressure, and vice-versa (principle of Le Chatelier). Thus, under pressure, reaction equilibria are shifted towards the most compact state, and the reaction rate constant is increased or decreased, depending on whether the “activation volume” of the reaction (i.e. volume of the activation complex less volume of reactants) is negative or positive. It is likely that pressure also inhibits the availability of the activation energy required for some reactions, by affecting some other energy releasing enzymatic reactions (Farr, 1990). The compression energy of 1 litre of water at 400 MPa is 19.2 kJ, as compared to 20.9 kJ for heating 1 litre of water from 20 to 25°C. The low energy levels

involved in pressure processing may explain why covalent bonds of food constituents are usually less affected than weak interactions. Pressure can influence most biochemical reactions, since they often involve change in volume. High pressure controls certain enzymatic reactions. The effect of high pressure on protein/enzyme is reversible unlike temperature, in the range 100–400 MPa and is probably due to conformational changes and sub-unit dissociation and association process (Morild, 1981).

For both the pasteurization and sterilization processes, a combined treatment of high pressure and temperature are frequently considered to be most appropriate (Farr, 1990; Patterson, Quinn, Simpson, and Gilmour, 1995). Vegetative cells, including yeast and moulds, are pressure sensitive, i.e. they can be inactivated by pressures of ~300–600 MPa (Knorr, 1995; Patterson, Quinn, Simpson, and Gilmour, 1995). At high pressures, microbial death is considered to be due to permeabilization of cell membrane.

For instance, it was observed that in the case of *Saccharomyces cerevasia*, at pressures of about 400 MPa, the structure and cytoplasmic organelles were grossly deformed and large quantities of intracellular material leaked out, while at 500 MPa, the nucleus could no longer be recognized, and a loss of intracellular material was almost complete (Farr, 1990). Changes that are induced in the cell morphology of the microorganisms are reversible at low pressures, but irreversible at higher pressures where microbial death occurs due to permeabilization of the cell membrane. An increase in process temperature above ambient temperature, and to a lesser extent, a decrease below ambient temperature, increases the inactivation rates of microorganisms during high pressure processing. Temperatures in the range 45 to 50°C appear to increase the rate of inactivation of pathogens and spoilage microorganisms. Preservation of acid foods (pH≤4.6) is, therefore, the most obvious application of HPP as such. Moreover, pasteurization can be performed even under chilled conditions for heat sensitive products. Low temperature processing can help to retain nutritional quality and functionality of raw materials treated and could allow maintenance of low temperature during post harvest treatment, processing, storage, transportation, and distribution periods of the life cycle of the food system (Knorr, 1995).

Bacterial spores are highly pressure resistant, since pressures exceeding 1200 MPa may be needed for their inactivation (Knorr, 1995). The initiation of germination or inhibition of germinated bacterial spores and inactivation of piezo-resistant microorganisms can be achieved in combination with moderate heating or other pretreatments such as ultrasound. Process temperature in the range 90–121°C in conjunction with pressures of 500-800 MPa have been used to inactivate spores forming bacteria such as *Clostridium botulinum*. Thus, sterilization of low-acid foods (pH > 4.6), will most probably rely on a combination of high pressure and other forms of relatively mild treatments.

High-pressure application leads to the effective reduction of the activity of food quality related enzymes (oxidases), which ensures high quality and shelf stable products. Sometimes, food constituents offer piezo-resistance to enzymes. Further, high pressure affects only non-covalent bonds (hydrogen, ionic, and hydrophobic bonds), causes unfolding of protein chains, and has little effect on chemical constituents associated with desirable food qualities such as flavor, color, or nutritional content. Thus, in contrast to thermal processing, the application of high-pressure causes negligible impairment of nutritional values, taste, color flavor, or vitamin content (Hayashi, 1990). Small molecules such as amino acids, vitamins, and flavor compounds remain unaffected by high pressure, while the structure of the large molecules such as proteins, enzymes, polysaccharides, and nucleic acid may be altered (Balci and Wilbey, 1999). High pressure reduces the rate of browning reaction (Maillard reaction). It consists of two reactions, condensation reaction of amino compounds with carbonyl compounds, and successive browning reactions including melanoidin formation and polymerization processes. The condensation reaction shows no acceleration by high pressure (5–50 MPa at 50°C), because it suppresses the generation of stable free radicals derived from melanoidin, which are responsible for the browning reaction (Tamaoka, Itoh, and Hayashi, 1991). Gels induced by high pressure are found to be more glossy and transparent because of rearrangement of water molecules surrounding amino acid residues in a denatured state (Okamoto, Kawamura, and Hayashi, 1990). The capability and limitations of HPP have been extensively reviewed (Thakur and Nelson, 1998; Smelt, 1998; Cheftal, 1995; Knorr, 1995; Farr, 1990; Tiwari, Jayas, and Holley, 1999; Cheftel, Levy, and Dumay, 2000; Messens, Van Camp, and Huyghebaert, 1997; Ontero and Sanz, 2000; Hugas, Garriga, and Monfort, 2002; Lakshmanan, Piggott, and Paterson, 2003; Balasubramaniam, 2003; Matser, Krebbers, Berg, and Bartels, 2004; Hogan, Kelly, and Sun, 2005; Mor-Mur and Yuste, 2005).

Many of the early reviews primarily focused on the microbial efficacy of high-pressure processing. This review comprehensively covers the different types of products processed by high pressure technology alone or in combination with the other processes. It also discusses the effect of high pressure on food constituents such as enzymes and proteins. The applications of this technology in fruits and vegetable, dairy and animal product processing industries are covered. The effects of combining high-pressure treatment with other processing methods such as gamma-irradiation, alternating current,

ultrasound, carbon dioxide, and anti-microbial peptides have also been described. Special emphasis has been given to opportunities and challenges in high pressure processing of foods, which can potentially be explored and exploited.

Consumers demand high quality and convenient products with natural flavor and taste, and greatly appreciate the fresh appearance of minimally processed food. Besides, they look for safe and natural products without additives such as preservatives and humectants. In order to harmonize or blend all these demands without compromising the safety of the products, it is necessary to implement newer preservation technologies in the food industry.

2 HIGH PRESSURE PROCESSING

2.1 BASIC HPP PRINCIPLES

Various physical and chemical changes result from the application of pressure. Generally, physical compression during pressure treatment results in a volume reduction and an increase in temperature and energy (Heremans, 2003). In predicting the effect of HPP on foods, it is necessary to consider the net combined pressure-temperature effect of the process.

The following principles govern the behavior of foods under pressure.

- **Le Chatelier's principle.** Any phenomenon (phase transition, change in molecular configuration, chemical reaction) accompanied by a decrease in volume is enhanced by pressure. Accordingly, pressure shifts the system to that of lowest volume (Farkas and Hoover, 2000).
- **Principle of microscopic ordering.** At constant temperature, an increase in pressure increases the degree of ordering of molecules of a given substance. Therefore, pressure and temperature exert antagonistic forces on molecular structure and chemical reactions (Balny and Masson, 1993).
- **Isostatic principle.** Pressure is uniformly distributed throughout the entire sample, whether in direct contact with the pressurizing medium or insulated from it in a flexible container. Thus, the process time is independent of sample size and shape, assuming uniform thermal distribution within the sample. If a food product contains sufficient moisture, pressure will not damage the product at the macroscopic level as long as the pressure is applied uniformly in all directions. For example, a grape can be easily crushed if pressure is applied to it by placing it between two fingers and squeezing along one axis. In contrast, if the grape is exposed to a uniform pressure by submerging it in water inside a sealed flexible bottle and squeezing, the grape retains its shape no matter how hard the bottle is squeezed. In this case, the pressure transmitted from the bottle wall through the water is applied uniformly around the fruit. Similarly, pressure will not damage most foods processed by high pressure, providing the food does not have a porous structure containing air voids. Air pockets will collapse under pressure due to differences between the compressibility of air and water, and unless the food is perfectly elastic and consists of closed-cell foam from which air cannot escape, the food will not be restored to its original size and shape. As a result, foods like strawberries are crushed by HPP, but an air-filled balloon does not burst.

2.2 HIGH-PRESSURE EQUIPMENT

Although the principles of high pressure processing for microbial inactivation have been known since the late 1800s (Hite, 1899), it is only relatively recent developments in mechanical engineering that have permitted large high-pressure vessels to be constructed at reasonable cost with sufficient durability to withstand thousands of pressure cycles without failure. High-pressure processing systems were initially developed in the chemical and material process industries for applications such as making artificial diamonds and sintered materials from powders. It is only during the past two decades that the food industry has begun using pressure treatment for food preservation. HPP is primarily practiced as a batch process where pre-packaged food products are treated in a chamber surrounded by water or another pressure-transmitting fluid. Semi-continuous systems have been developed for pumpable foods where the product is compressed without a container and subsequently packaged "clean" or aseptically. The primary components of an HPP system include a pressure vessel; closure(s) for sealing the vessel; a device for holding the closure(s) in place while the vessel is under pressure (e.g., yoke); high-pressure intensifier pump(s); a system for controlling and monitoring the pressure and (optionally) temperature; and a product-handling system for transferring product to and from the pressure vessel. Normally, perforated baskets are used to insert and remove pre-packaged food products from the pressure vessels. Systems also have provisions for filtering and reusing the compression fluid (usually water or a food-grade solution).

Commercial batch vessels have internal volumes ranging from 30 to more than 600 liters. Avure Technologies, NC Hyperbaric, and Uhde are major suppliers of commercial-scale pressure equipment. Both horizontal and vertical pressure

vessel configurations are available. Commercial-scale, high-pressure processing systems cost approximately \$500,000 to \$2.5 million, depending on equipment capacity and extent of automation. Currently, HPP treatment costs are quoted as ranging from 4–10 cents/lb, including operating cost and depreciation, and are not “orders of magnitude” higher than thermal processing—as is often thought (Sàiz et al., 2008). As demand for HPP equipment grows, innovation is expected to further reduce capital and operating costs.

A typical HPP process uses food products packaged in a high-barrier, flexible pouch or a plastic container. The packages are loaded into the high-pressure chamber. The vessel is sealed and the vessel is filled with a pressure transmitting fluid (normally water) and pressurized by the use of a high-pressure pump, which injects additional quantities of fluid. The packages of food, surrounded by the pressure-transmitting fluid, are subjected to the same pressure as exists in the vessel itself. After holding the product for the desired time at the target pressure, the vessel is decompressed by releasing the pressure-transmitting fluid (Farkas and Hoover, 2000). For most applications, products are held for 3–5 min at 600 MPa. Approximately 5–6 cycles/hr are possible, allowing time for compression, holding, decompression, loading, and unloading. Slightly higher cycle rates may be possible using fully automated loading and unloading systems. After pressure treatment, the processed product is removed from the vessel and stored/distributed in a conventional manner.

Liquid foods can be processed in a batch or semi-continuous mode. In the batch mode, the liquid product is pre-packaged and pressure-treated as described above for packaged foods. Semicontinuous operation requires two or more pressure vessels, each equipped with a free-floating piston that allows each vessel to be divided into two chambers. One chamber is used for the liquid food; the other for the pressure-transmitting fluid. The basic operation involves filling one chamber with the liquid food to be treated. The fill valve is closed and then pressure-transmitting fluid is pumped into the second chamber of the vessel on the opposite side of the floating piston. Pressurization of the fluid in this second chamber results in compression of the liquid food in the first. After an appropriate holding time, the pressure is released from the second chamber. The product discharge valve is opened to discharge the contents of the first chamber, and a low-pressure pump injects pressure-transmitting fluid into the second chamber, which pushes on the piston and expels the contents of the product chamber through the discharge valve. The treated liquid food is directed to a sterile tank from which sterile containers can be filled aseptically. Typically, three pressure vessels are used to create a semi-continuous system capable of delivering a continuous product output. This is accomplished by operating the three vessels such that one is loading, one is compressing, and one is discharging at any point in time (Farkas and Hoover, 2000).

The U.S. food industry has gained about 18 years of experience with commercial scale, high-pressure equipment since the introduction of high pressure pasteurization systems during the 1990s. In response to industrial demand for higher volume and throughput, high pressure equipment vendors have focused on improving equipment productivity. Developments have included a doubling of pressure vessel volumes, automated systems for package and vessel loading, and higher horsepower intensifiers to speed up the compression process. Tandem machines (Sàiz et al., 2008), where multiple vessels are serviced by a common bank of high-pressure pumps, have also become available. By sequencing the compression cycles of multiple vessels, it is possible to increase throughput and reduce capital costs by shortening the compression time (through use of multiple pumps) and utilizing the same pumps to pressurize the other vessels during a period of time when the pumps would normally be idle in a single vessel system. With two or more pressure vessels operating under typical food processing conditions, a throughput of approximately 20 million lb/yr is achievable.

2.3 COMMERCIAL APPLICATIONS

High-pressure processing provides a unique opportunity for food processors to develop a new generation of value-added food products having superior quality to those produced conventionally. Strawberry, apple, and kiwi jams represented the first wave of pressure-treated commercial products introduced into the Japanese market in 1990. Avocado based products, especially guacamole, were subsequently commercialized in the United States. Fresherized Foods (formerly Avomex) began the first industrial production of guacamole in North America in 1997. A decade later, by 2007, approximately 120 industrial HPP installations were in use worldwide for commercial scale food production (Sàiz et al., 2008). More than 80% of the equipment was installed after 2000, indicating an accelerated trend in HPP use. According to some industry estimates, high pressure food pasteurization currently represents a \$2 billion market (Hewson, 2008). North America (U.S., Canada, and Mexico), Europe (Spain, Italy, Portugal, France, UK, and Germany), Australia, and Asia (Japan, China, and S. Korea) lead the commercialization of high pressure technology. The total production of pressure-treated food products is steadily growing.

In 2008, it is estimated that 200,000 metric tons/yr (about 450 million lb/year) of pressure-treated products will be commercially available worldwide (Samson, 2008). The novel nature of HPP technology and high equipment costs have been barriers to commercialization, but increased consumer demand for fresher tasting foods containing fewer preservatives is

driving increased usage. HPP can preserve food products without heat or chemical preservatives, and its ability to ensure safety and significantly extend refrigerated shelf life has opened new market opportunities particularly in the area of “natural” preservative-free meat products. Hormel Foods, Kraft Foods, Perdue, Foster Farms, and Wellshire Farms are examples of meat processors that have successfully utilized the technology for a variety of ready-to eat, minimally processed meat products (Samson, 2008). Several seafood processors such as Motivati Seafoods have also employed HPP to improve food safety and shelf life of shellfish with the added benefit of facilitating the removal of flesh from the shell. Other market segments employing pressure treatment include juice, beverage, and vegetable products. The ability of HPP to deliver a “clean” ingredient statement, fresher flavor, and better nutrition provide a unique point of difference for producers. High pressure processing is a paradigm-shifting technology for the food industry that is on-trend with consumer interests. Its use will likely grow as cost declines and food manufacturers identify new applications where HPP can deliver product quality improvements that consumers appreciate and will pay for.

3 HIGH PRESSURE EFFECT ON ENZYMES AND PROTEINS

3.1 ENZYMES

Enzymes are a special class of proteins in which biological activity arises from active sites, brought together by a three-dimensional configuration of molecule. The changes in active site or protein denaturation can lead to loss of activity, or changes the functionality of the enzymes (Tsou, 1986). In addition to conformational changes, enzyme activity can be influenced by pressure-induced decompartmentalization (Butz, Koller, Tauscher, and Wolf, 1994; Gomes and Ledward, 1996). Pressure induced damage of membranes facilitates enzymesubstrate contact. The resulting reaction can either be accelerated or retarded by pressure (Butz, Koller, Tauscher, and Wolf, 1994; Gomes and Ledward, 1996; Morild, 1981). Hendrickx, Ludikhuyze, Broeck, and Weemaes (1998) and Ludikhuyze, Van

Loey, and Indrawati et al. (2003) reviewed the combined effect of pressure and temperature on enzymes related to the ity of fruits and vegetables, which comprises of kinetic information as well as process engineering aspects.

3.2 PROTEINS

High pressure denatures protein depending on the protein type, processing conditions, and the applied pressure. During the process of denaturation, the proteins may dissolve or precipitate on the application of high pressure. These changes are generally reversible in the pressure range 100–300 MPa and irreversible for the pressures higher than 300 MPa. Denaturation may be due to the destruction of hydrophobic and ion pair bonds, and unfolding of molecules. At higher pressure, oligomeric proteins tend to dissociate into subunits becoming vulnerable to proteolysis. Monomeric proteins do not show any changes in proteolysis with increase in pressure (Thakur and Nelson, 1998). High-pressure effects on proteins are related to the rupture on non-covalent interactions within protein molecules, and to the subsequent reformation of intra and inter molecular bonds within or between the molecules. Different types of interactions contribute to the secondary, tertiary, and quaternary structure of proteins. The quaternary structure is mainly held by hydrophobic interactions that are very sensitive to pressure. Significant changes in the tertiary structure are observed beyond 200 MPa. However, a reversible unfolding of small proteins such as ribonuclease A occurs at higher pressures (400 to 800 MPa), showing that the volume and compressibility changes during denaturation are not completely dominated by the hydrophobic effect. Denaturation is a complex process involving intermediate forms leading to multiple denatured products. Secondary structure changes take place at a very high pressure above 700 MPa, leading to irreversible denaturation (Balny and Masson, 1993). When the pressure increases to about 100 MPa, the denaturation temperature of the protein increases, whereas at higher pressures, the temperature of denaturation usually decreases. This results in the elliptical phase diagram of native denatured protein shown in Fig. 1. A practical consequence is that under elevated pressures, proteins denature usually at room temperature than at higher temperatures. The phase diagram also specifies the pressure-temperature range in which the protein maintains its native structure. Zone I specifies that at high temperatures, a rise in denaturation temperature is found with increasing pressure. Zone II indicates that below the maximum transition temperature, protein denaturation occurs at the lower temperatures under higher pressures. Zone III shows that below the temperature corresponding to the maximum transition pressure, protein denaturation occurs at lower pressures using lower temperatures (Messens, Van Camp, and Huyghebaert, 1997).

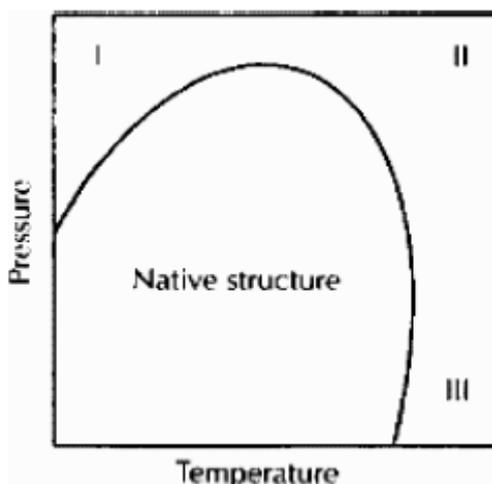


Fig. 1. General scheme for pressure-temperature phase diagram of proteins.(from Messens, Van Camp and Huyghebaert, 1997).

4 COMBINED EFFECT OF HIGH PRESSURE TREATMENT AND OTHER NON-THERMAL PROCESSING METHODS

Many researchers have combined the use of high pressure with other non-thermal operations in order to explore the possibility of synergy between processes. Such attempts are reviewed in this section.

4.1 GAMMA IRRADIATION

Crawford, Murano, Olson, and Shenoy (1996) studied the combined effect of high pressure and gamma-irradiation for inactivating *Clostridium sporogenes* spores in chicken breast. Application of high pressure reduced the radiation dose required to produce chicken meat with extended shelf life. The application of high pressure (600 MPa for 20 min at 80°C) reduced the irradiation doses required for one log reduction of *Clostridium sporogenes* from 4.2 kGy to 2.0 kGy. Mainville, Montpetit, Durand, and Farnworth (2001) studied the combined effect of irradiation and high pressure on microflora and microorganisms of kefir. The irradiation treatment of kefir at 5 kGy and high pressure treatment (400 MPa for 5 or 30 min) deactivated the bacteria and yeast in kefir, while leaving the proteins and lipids unchanged.

4.2 ALTERNATING CURRENT

The exposure of microbial cells and spores to an alternating current (50 Hz) resulted in the release of intracellular materials causing loss or denaturation of cellular components responsible for the normal functioning of the cell. The lethal damage to the microorganisms enhanced when the organisms are exposed to an alternating current before and after the pressure treatment. High-pressure treatment at 300 MPa for 10 min for *Escherichia coli* cells and 400 MPa for 30 min for *Bacillus subtilis* spores, after the alternating current treatment, resulted in reduced surviving fractions of both the organisms. The combined effect was also shown to reduce the tolerant level of microorganisms to other challenges (Shimada and Shimahara, 1985, 1987; Shimada, 1992).

4.3 ULTRASOUND

The pretreatment with ultrasonic waves (100 W/cm² for 25 min at 25°C) followed by high pressure (400 MPa for 25 min at 15°C) was shown to result in complete inactivation of *Rhodotulora rubra*. Neither ultrasonic nor high-pressure treatment alone was found to be effective (Knorr, 1995).

4.4 CARBON DIOXIDE AND ARGON

Heinz and Knorr (1995) reported a 3 log reduction of supercritical CO₂ pretreated cultures. The effect of the pretreatment on germination of *Bacillus subtilis* endospores was monitored. The combination of high pressure and mild heat treatment was the most effective in reducing germination (95% reduction), but no spore inactivation was observed. Park, Lee, and Park

(2002) studied the combination of high pressure carbon dioxide and high pressure as a non-thermal processing technique to enhance the safety and shelf life of carrot juice. The combined treatment of carbon dioxide (4.90 MPa) and high-pressure treatment (300 MPa) resulted in complete destruction of aerobes. The increase in high pressure to 600 MPa in the presence of carbon dioxide resulted in reduced activities of polyphenoloxidase (11.3%), lipoxygenase (8.8%), and pectin methylesterase (35.1%). Corwin and Shellhammer (2002) studied the combined effect of high-pressure treatment and CO₂ on the inactivation of pectinmethylesterase, polyphenoloxidase, *Lactobacillus plantarum*, and *Escherichia coli*. An interaction was found between CO₂ and pressure at 25 and 50°C for pectinmethylesterase and polyphenoloxidase, respectively. The activity of polyphenoloxidase was decreased by CO₂ at all pressure treatments. The interaction between CO₂ and pressure was significant for *Lactobacillus plantarum*, with a significant decrease in survivors due to the addition of CO₂ at all pressures studied. No significant effect on *E. coli* survivors was seen with CO₂ addition. Truong, Boff, Min, and Shellhammer (2002) demonstrated that the addition of CO₂ (0.18 MPa) during high pressure processing (600 MPa, 25°C) of fresh orange juice increases the rate of PME inactivation in Valencia orange juice. The treatment time due to CO₂ for achieving the equivalent reduction in PME activity was from 346 s to 111 s, but the overall degree of PME inactivation remained unaltered. Fujii, Ohtani, Watanabe, Ohgoshi, Fujii, and Honma (2002) studied the high-pressure inactivation of *Bacillus cereus* spores in water containing argon. At the pressure of 600 MPa, the addition of argon reportedly accelerated the inactivation of spores at 20°C, but had no effect on the inactivation at 40°C.

4.5 MICROBIAL PEPTIDES

The complex physicochemical environment of milk exerted a strong protective effect on *Escherichia coli* against high hydrostatic pressure inactivation, reducing inactivation from 7 logs at 400 MPa to only 3 logs at 700 MPa in 15 min at 20°C. A substantial improvement in inactivation efficiency at ambient temperature was achieved by the application of consecutive, short pressure treatments interrupted by brief decompressions. The combined effect of high pressure (500 MPa) and natural antimicrobial peptides (lysozyme, 400 µg/ml and nisin, 400 µg/ml) resulted in increased lethality for *Escherichia coli* in milk (Garcia, Masschalck, and Michiels, 1999).

5 OPPORTUNITIES FOR HIGH PRESSURE ASSISTED PROCESSING

The inclusion of high-pressure treatment as a processing step within certain manufacturing flow sheets can lead to novel products as well as new process development opportunities. For instance, high pressure can precede a number of process operations such as blanching, dehydration, rehydration, frying, and solid-liquid extraction. Alternatively, processes such as gelation, freezing, and thawing, can be carried out under high pressure. This section reports on the use of high pressures in the context of selected processing operations.

5.1 BLANCHING

Eshtiaghi and Knorr (1993) employed high pressure around ambient temperatures to develop a blanching process similar to hot water or steam blanching, but without thermal degradation; this also minimized problems associated with water disposal. The application of pressure (400 MPa, 15 min, 20°C) to the potato sample not only caused blanching but also resulted in a four-log cycle reduction in microbial count whilst retaining 85% of ascorbic acid. Complete inactivation of polyphenoloxidase was achieved under the above conditions when 0.5% citric acid solution was used as the blanching medium. The addition of 1% CaCl₂ solution to the medium also improved the texture and the density. The leaching of potassium from the high-pressure treated sample was comparable with a 3 min hot water blanching treatment (Eshtiaghi and Knorr, 1993). Thus, high-pressures can be used as a non-thermal blanching method.

5.2 DEHYDRATION AND OSMOTIC DEHYDRATION

The application of high hydrostatic pressure affects cell wall structure, leaving the cell more permeable, which leads to significant changes in the tissue architecture (Farr, 1990; Dornenburg and Knorr, 1994; Rastogi, Subramanian, and Raghavarao, 1994; Rastogi and Niranjana, 1998; Rastogi, Raghavarao, and Niranjana, 2005). Eshtiaghi, Stute, and Knorr (1994) reported that the application of pressure (600 MPa, 15 min at 70°C) resulted in no significant increase in the drying rate during fluidized bed drying of green beans and carrot. However, the drying rate significantly increased in the case of potato. This may be due to relatively limited permeabilization of carrot and beans cells as compared to potato. The effects of chemical pre-treatment (NaOH and HCl treatment) on the rates of dehydration of paprika were compared with products pre-treated by applying high pressure or high intensity electric field pulses. High-pressure (400 MPa for 10 min at 25°C) and high intensity electric field pulses (2.4 kV/cm, pulse width 300 µs, 10 pulses, pulse frequency 1 Hz) were found to result in drying

rates comparable with chemical pre-treatments. The latter pre-treatments, however, eliminated the use of chemicals (Ade-Omowaye, Rastogi, Angersbach, and Knorr, 2001). maximum value of diffusion coefficient observed represented an eight-fold increase over the values at ambient pressure.

The synergistic effect of cell permeabilization due to high pressure and osmotic stress as the dehydration proceeds was demonstrated more clearly in the case of potato (Rastogi, Angersbach, and Knorr, 2000a, 2000b, 2003). The moisture content was reduced and the solid content increased in the case of samples treated at 400MPa. The distribution of relative moisture (M/Mo) and solid (S/So) content as well as the cell permeabilization index (Z_p) indicate that the rate of change of moisture and solid content was very high at the interface and decreased towards the center (Rastogi, Angersbach, and Knorr, 2000a, 2000b, 2003).

5.3 REHYDRATION

Most dehydrated foods are rehydrated before consumption. Loss of solids during rehydration is a major problem associated with the use of dehydrated foods. Rastogi, Angersbach, Niranjana, and Knorr (2000c) have studied the transient variation of moisture and solid content during rehydration of dried pineapples, which were subjected to high pressure treatment prior to a two-stage drying process consisting of osmotic dehydration and finish-drying at 25°C. The diffusion coefficients for water infusion as well as for solute diffusion were found to be significantly lower in high-pressure pre-treated samples. The observed decrease in water diffusion coefficient was attributed to the permeabilization of cell membranes, which reduces the rehydration capacity (Rastogi and Niranjana, 1998). The solid infusion coefficient was also lower, and so was the release of the cellular components, which form a gel-network with divalent ions binding to de-esterified pectin (Basak and Ramaswamy, 1998; Eshtiaghi, Stute, and Knorr, 1994; Rastogi Angersbach, Niranjana, and Knorr, 2000c). Eshtiaghi, Stute, and Knorr (1994) reported that high-pressure treatment in conjunction with subsequent freezing could improve mass transfer during rehydration of dried plant products and enhance product quality.

Ahromrit, Ledward, and Niranjana (2006) explored the use of high pressures (up to 600 MPa) to accelerate water uptake kinetics during soaking of glutinous rice. The results showed that the length and the diameter of the rice were positively correlated with soaking time, pressure and temperature. The water uptake kinetics was shown to follow the well-known Fickian model. The overall rates of water uptake and the equilibrium moisture content were found to increase with pressure and temperature. Zhang, Ishida, and Isobe (2004) studied the effect of high pressure treatment (300–500 MPa for 0–380 min at 20°C) on the water uptake of soybeans and resulting changes in their microstructure. The NMR analysis indicated that water mobility in high-pressure soaked soybean was more restricted and its distribution was much more uniform than in controls. The SEM analysis revealed that high pressure changed the microstructures of the seed coat and hilum, which improved water absorption and disrupted the individual spherical protein body structures. Additionally, the DSC and SDS-PAGE analysis revealed that proteins were partially denatured during the high pressure soaking. Ibarz, Gonzalez, Barbosa-Canovas (2004) developed the kinetic models for water absorption and cooking time of chickpeas with and without prior high-pressure treatment (275–690 MPa). Soaking was carried out at 25°C for up to 23 h and cooking was achieved by immersion in boiling water until they became tender. As the soaking time increased, the cooking time decreased.

High-pressure treatment for 5 min led to reductions in cooking times equivalent to those achieved by soaking for 60–90 min. Ramaswamy, Balasubramaniam, and Sastry (2005) studied the effects of high pressure (33, 400 and 700 MPa for 3 min at 24 and 55°C) and irradiation (2 and 5 kGy) pre-treatments on hydration behavior of navy beans by soaking the treated beans in water at 24 and 55°C. Treating beans under moderate pressure (33 MPa) resulted in a high initial moisture uptake (0.59 to 1.02 kg/kg dry mass) and a reduced loss of soluble materials. The final moisture content after three hours of soaking was the highest in irradiated beans (5 kGy) followed by high-pressure treatment (33 MPa, 3 min at 55°C). Within the experimental range of the study, Peleg's model was found to satisfactorily describe the rate of water absorption of navy beans.

5.4 FRYING

A reduction of 40% in oil uptake during frying was observed, when thermally blanched frozen potatoes were replaced by high pressure blanched frozen potatoes. This may be due to a reduction in moisture content caused by compression and decompression (Rastogi and Niranjana, 1998), as well as the prevalence of different oil mass transfer mechanisms (Knorr, 1999).

5.5 SOLID LIQUID EXTRACTION

The application of high pressure leads to rearrangement in tissue architecture, which results in increased extractability even at ambient temperature. Extraction of caffeine from coffee using water could be increased by the application of high pressure as well as increase in temperature (Knorr, 1999). The effect of high pressure and temperature on caffeine extraction was compared to extraction at 100°C as well as atmospheric pressure. The caffeine yield was found to increase with temperature at a given pressure. The combination of very high pressures and lower temperatures could become a viable alternative to current industrial practice.

5.6 PRESSURE SHIFT FREEZING AND PRESSURE ASSISTED THAWING

Slow freezing may cause extensive structural damage due to the formation of larger ice crystals. It may also result in higher enzyme and microbial activities as well as increased oxidation rates, resulting from increased solute concentration and the insolubility of oxygen in ice. Rapid freezing using cryogenics induces cracking because of two effects: the initial decrease of volume due to cooling and the subsequent increase in volume due to freezing (Kalichevsky, Knorr, and Lillford, 1995). The reduction in freezing point under pressure causes super cooling upon pressure release and promotes rapid ice nucleation and growth throughout the sample, producing small ice crystals, rather than an ice front moving through the sample. Generally, thawing occurs more slowly than freezing, potentially allowing further damage to the sample. High pressure induced thawing reduces the loss of the water holding capacity and improves color and flavor preservation in fruit. Benet, Schlueter, and Knorr (2004) provided an extensive terminology for freezing and thawing processes including pressure-shift thawing.

5.7 GELATION AND RHEOLOGY

High pressure causes gelation of protein as well as polysaccharides. This phenomenon may be used for the modification of functional properties of foods. High pressure induced polysaccharide gels could be created during cold storage of pasteurized kiwi or strawberry puree (Knorr, 1999). Abbasi and Dickinson (2001) reported pressure-induced gelation of skim milk powder dispersions before and after high pressure treatment containing 9-15% casein in the presence of various sugars such as sucrose, glucose, and fructose. The gel like characteristics could be obtained after high-pressure treatment at much lower levels of casein. The gel behavior was independent of the type of sugars, duration, and intensity of pressure and process temperature. Pressure-induced gelation was inhibited at total sugar contents higher than 45-50%. Famelart, Chapron, Piot, Brule, and Durier (1998) showed that no gel formation was observed following high-pressure treatment (200 or 400 MPa for 10 or 30 min) of milk. Ultrafiltered and microfiltered milk concentrate could form gel, but the firmness of gels decreased with an increase in citrate concentration and increased with an increase in protein concentration and the maximum gel firmness was observed at pH 5.9. Whey concentrate formed gels at pH 9.0. The increase in the protein content of whey concentrate had no effect on the firmness of whey concentrate gels whereas increasing the pressure from 200 to 400 MPa resulted in firmer gels. Keim and Hinrichs (2004) indicated that the application of high pressure (600 MPa for 0-30 min at 30°C) formed stable gel of whey protein isolate. These workers also showed that the content of the native whey protein fractions alpha-lactalbumin and beta-lactoglobulin A and B, decreased and the amount of intermolecular disulfide bonds increased with prolonged pressure holding time. The gels became stronger and more elastic with increasing holding time.

Ahmed and Ramaswamy (2003) showed that both pressure and heat-induced glocomarcopeptide samples followed the Herschel-Bulkley model and indicated the presence of yield stress. It exhibited shear-thinning behavior. The consistency coefficient and apparent viscosity were reported to increase with pressure up to 300 MPa and after 300 MPa these values decreased. Dickinson and James (1998) studied the effect of high pressure and thermal treatment on flocculation and rheology of model oil-in-water emulsions stabilized by beta-lactoglobulin. HPP induced significant levels of flocculation in the model oil-in-water emulsions and altered the droplet size distribution and rheological behavior. The proportion of unadsorbed protein greatly influenced the extent of flocculation. Elevated pressure treatment (800 MPa for 60 min at ambient temperature) was found to be equivalent to relatively mild thermal treatment (65°C for 5 min). The changes in rheological properties of these systems following high-pressure treatment were attributed to pressure-induced denaturation and gelation of beta-lactoglobulin in the continuous phase of the emulsion (Dickinson and James, 1999). Arora, Chism, and Shellhammer (2003) studied the effect of high pressure treatment on the stability and the rheology of acidified model oil-in-water emulsions containing canola oil, whey protein isolate, polysorbate 60, soy lecithin, and xanthan. Exposure to high pressures up to 800 MPa for 5 min at 30°C did not significantly affect the equivalent surface mean diameter, flow behavior, and viscoelasticity.

The pressure treatment had a negligible effect on emulsion stability, whereas the presence of xanthan (0.2% w/w) resulted in improved stability. Soy lecithin-stabilized emulsions resulted in larger mean particles sizes and lower emulsion volume indices than the other emulsions, indicating that the potential instability and application of pressure further destabilized these emulsions. Ahmed and Ramaswamy (2004, 2005) demonstrated that under pressure xanthan gum displayed pseudoplastic behavior with yield stress, and the Herschel-Bulkley model could be used to describe the flow behavior. The application of pressure induced slight structural breakdown in the gum, which exhibited slight thixotropicity at higher concentration. The consistency coefficient and apparent viscosity were affected by both the applied pressure and the concentration of the gum, whereas the flow behavior index and yield stress were affected by concentration.

6 SOME PRACTICAL CHALLENGES

Although HPP offers a number of opportunities, there are several challenges, which have to be addressed before a wider industrial application is considered.

6.1 HEAT TRANSFER UNDER HIGH PRESSURE AND PROCESS IN-HOMOGENEITIES

Most of the high-pressure applications in food are not only pressure dependent but also temperature dependent. In most studies available in literature, the contribution of temperature during the treatment has not been considered. The evolution of temperature is very important on account of its effect on food gelling, protein stability, fat migration, freezing etc. The main difficulty in monitoring or modeling heat transfer in high pressure processes is the lack of data on thermophysical properties under pressure. Denys, Van Loey, Hendrickx, and Tobback (1997) stated that the temperature history of a product under pressure is essential for the optimization and design of industrial processes.

6.1.1 THERMAL EFFECTS DURING HIGH PRESSURE PROCESSING

During high pressure processing, the temperature of food material increases as a result of physical compression. The pressure increase during the come-up time from an initial pressure P_s to P_1 increases the temperature. The magnitude of temperature increase, in part, depends upon the initial temperature, material compressibility and specific heat, and the target pressure. The maximum product temperature at process pressure is independent of the compression rate as long as heat transfer to the surroundings is negligible. It is further interesting to note that while the rate of temperature increase of the water-like substances is in phase with the change in pressure, fatty substances often exhibit a time delay of 30–60 s before reaching the maximum temperature (T_1). This may be attributed to the difference in their respective molecular structure (Rasanayagam, Balasubramaniam, Ting, Sizer, Bush, and Anderson, 2003). During the pressure holding time (P_1 to P_2), the temperature of the product

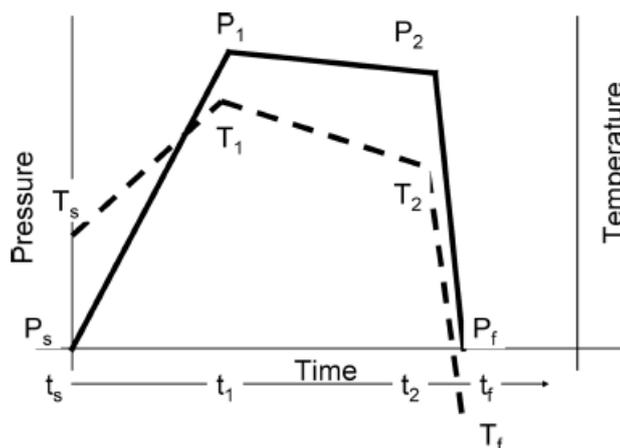


Fig. 2. Variation of pressure and temperature in a non-insulated high-pressure vessel

decreases from T1 to T2 due to heat loss through the pressure vessel. Immediately after depressurization, the product temperature returns to a value, slightly lower than the initial temperature. Thus, high pressure offers a unique way to increase the temperature of the product only during the treatment.

6.1.2 PRESSURE NONUNIFORMITY

Minerich and Labuza (2003) demonstrated that the process of homogeneity in pressure vessels is still an issue that needs attention. Using custom made copper tablets the authors demonstrated that the density of the tablet increased proportionately as the pressure increased between 400 and 600MPa. The change in density of the tablet placed in the geometric center of a large food product, such as a ham, indicated that the ham received approximately 9MPa less pressure than the processing system delivered ($P < 0.017$), challenging the assumption that all foods follow the isostatic rule. Authors, finding may have implications when determining the microbial lethality for large food items pasteurized or sterilized using high pressure. More research is needed to evaluate pressure uniformity within a larger pressure volume as well alternative approaches that can verify the above findings.

6.1.3 COMPRESSION HEATING OF FOOD MATERIALS

All compressible substances change temperature during physical compression and this is an unavoidable thermodynamic effect (Ting, Balasubramaniam, and Raghubeer, 2002). Water has the lowest compression heating values, while fats and oils have the highest. For example, at pressures normally encountered during HPP (400–1000 MPa), under adiabatic conditions near room temperature, water typically changes 3°C for every 100 MPa pressure change. Further, the compression heating value for water increases with temperature. Since water is the main ingredient in most foods, adiabatic temperature changes exhibited by most foods are very similar to that of water, except for oil and alcohol. Fats and oils show the highest compression heating values (6 to 8.7°C per 100 MPa) (Rasanayagam Balasubramaniam, Ting, Sizer, Bush, and Anderson, 2003). Similarly, the temperature of pressure transmitting fluid will also change after compression depending on its own thermal properties and will influence the temperature of the sample. This process can introduce additional temperature gradients in the product (Denys, Van Loey, and Hendrickx, 2000a). The difference between the temperature of a product (say, meat) and pressuring fluid (water), over a range of pressures under adiabatic compression, is shown in Fig. 10. This difference can also be attributed to the differences in the thermal properties. Balasubramanian and Balasubramaniam (2003) studied the apparent temperature increase of selected pressure-transmitting fluids (food-grade water-based glycol at different concentrations or 2% sodium benzoate solution) during HPP using a pilot scale food processor, together with the effects of these fluids on the inactivation of *Bacillus subtilis*. The highest temperature increase was reported for pressure-transmitting fluid containing 75% glycol,

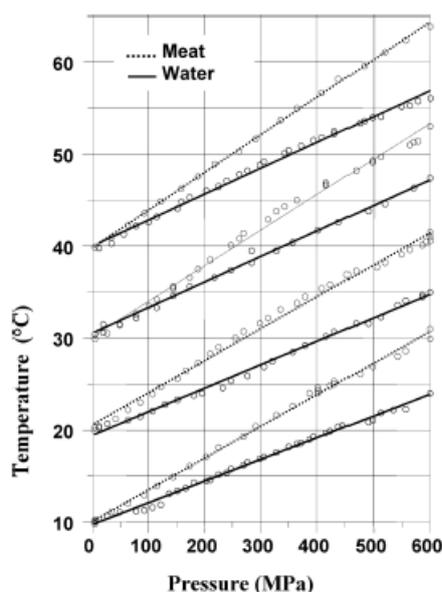


Fig. 3. Difference between the temperature of the product (meat) and pressuring fluid (water) over a range of pressure under adiabatic compression (Knorr, 2004).

whereas the fluid containing the highest amount of water (2% sodium benzoate solution) showed the lowest temperature increase, initial temperature, holding time, target pressure, compressibility, and rate of heat loss to the surroundings. Fluid properties such as thermal conductivity, viscosity, and specific heat also affected the temperature change. Change in pressure transmitting fluid temperature as a result of compression heating and subsequent heat transfer should be considered in HPP microbial inactivation.

7 APPLICATION OF HPT IN FOOD PRESERVATION

HPT finds application in food preservation in many ways. Some example of areas where HPT has more potential is discussed under the following headings.

7.1 FRUITS AND VEGETABLES

HPT does not depreciate the nutritional and sensory characteristics of food, and yet it maintains the shelf life. As compared the effect of HPT with water blanching on the microbial safety, quality (softness), and functionality (poly phenol oxidase (PPO) activity, leaching of potassium, and loss of ascorbic acid) of potato cubs. Total inactivation of microbes and PPO activity occurred at 200C (using dilute citric acid solution at 0.5 at 1.0 % as immersion medium). Water-balanced and high pressure treated potato cubes had similar softness but potassium leaching was reduced by 20 % in addition, ascorbic acid was better retained (90% at 50C to 35% at 500C) in high pressure treated vacuum packaged samples.

7.2 MEAT AND FISH INDUSTRY

Researchers have studied the application of HPT in the meat industry using several combinations of pressure, time and temperature. The high pressure inactivates *Citrobacter freundii*, *Pseudomonas fluorescens*, and *Listeria innocua* were completely inactivated at pressures more than 280,200 and 400 MPa, respectively at 200C. They also noticed a paler color in samples of minced beef treated at pressures more than 150 MPa, and grayish color in samples at pressures more than 350 MPa. Total inhibition of microorganisms occurred at 400-500 MPa. However, *pseudomonas spp.* was detected after 3-9 days at 30C, which means that they were not fully inactivated but stressed during HPT. Therefore, HPT should be coupled with some other treatment (e.g, moderate temperature of 500C) to eliminate viable *pseudomonas spp.* The effects of HPT on color and myoglobin content of minced beef samples packaged under vacuum, air or oxygen. They noticed a pink color of meat treated at 200-350 MPa (increase in lightness, color values) which turned Grey brown at 400-500 MPa (a decrease in L values). They suggested that meat discoloration during HPT is due to whitening effect of 200-300 MPa, caused by globin denaturation, heme displacement or release or oxidation of ferrous myoglobin to ferric myoglobin at 400 MPa.

Table 1. Application of HPT in Fruits and Vegetables.

Product	Pressure(MPa)	Holding time (min)	Temperature (°C)
Potato cubes	400	15	5-50
Chopped tomatoes	400,600 or 800	3.5-7.0	
Apricot nectar, distilled water	600-900	1-20	20
Jams			
White and red grape must	304-811	1-5	25
Angelica keiskei juice	0.01	7	25
Fresh apples, pears, bananas		6,15	25
Citrus juice	300-375	1-1.5	0-5
Orange juice	350	1	30
Vegetables juices ,carrot, cauli flower, spinach, tomatoes, strawberries	300,370	10	35
Guava puree	400,600	15	25
Extrac virgin olive and seed oils(grape seed, sunflower, soyaben, peanut	700	10	25

Table 2. Application of HPT in retention of sensory and nutritional characteristics of fruits and vegetables.

Product	Process and Quality attributes
Avocado puree	Prevent discoloration , Inhibit of undesirable browning reactions in presence of low pH
Banana puree	Prevent discoloration, reduction in polyphenol oxidase activity when combined with blanching
Black beans	Cooking ,increasing water absorption, reduced cooking time
Jam	Commercial production ,improved retention of colour and flavor of fresh fruit
Orange juice, Pink grape juice,	Preservation ,retention of colour and cloud stability during storage
Potato	Freezing ,reduction in freezing time in potato cylinder
Tomato juice	Juice production ,modification of physical and sensory properties

7.3 DAIRY AND EGG INDUSTRY

High pressure technology may also have application in the dairy and egg industries due to changes induced the functional properties of whey protein as well as in other milk components and native constituents. The pressure was applied to the protein before homogenization or to the emulsion prepared with native WPC. Functional properties of WPC were examined along with the relationship between stability of WPC emulsions and degree of adsorption of the protein emulsifier. They found that oil-in water emulsions (0.4 wt % protein, 20 vol % n-Tetradecane, pH 7) prepared with pressure treated WPC solutions gave a broader droplet size distribution than emulsions made with native untreated protein. An inverse relationship was obtained between emulsifying efficiency and applied pressure plus treatment time. Also, HPT had little effect on the stability of WPC emulsions made with native protein. The high pressure slightly improved the microbiological quality of milk without modifying lacto peroxidase activity (a native milk enzyme). β -lactalbumin and bovine serum albumin were pressure resistant (400 MPa for 60 min.). The increase in cheese yield was found (at 300 and 400 MPa) in conjunction with additional β -lactoglobulin and moisture retention. They concluded that HPT can improve the coagulation properties of milk and can increase moisture retention of fresh cheese.

Table 3. Application of high pressure technology in the Meat industry

Meat type	Pressure(MPa)	Holding time (min.)	Temperature (°C)
Minced beef muscle	230	20	4,25,35,50
Minced beef muscle	50-400	20	20
Minced beef muscle	200-450	20	
Minced beef muscle	200-500	20	25
Pork slurries	300	10	
Surimi pate	100-600	10	05
Minced macked meat	203	60	2-8
Creamed salamon	700	03	2 or 25
Freshly ground raw chicken meat	408-818	10	
Minced pork	800	20	20
Fresh beef	800-1000	20	25
Lamb meat	200	30	30
hams	300	5,15,25	20

Table 4. Application of HPT in Dairy and egg industry

Milk type	Pressure (MPa)	Holding time (min)	Temperature (°C)
Raw milk	100-400	10-60	20
Whey protein concebrtrate	200,400 or 800	10,20 or 40	20
Skim milk	310	0.05	25
Goat milk	500	10	25 or 50
Skim milk	250,450 or800	10,20 or 40	25
Fresh goat milk cheese	400 or 500	5,10 or 15	2,10 or 25
Whipped and coffee cream	100-550	10	10-24
Milk	50-350	12	20

8 PACKAGING REQUIREMENTS OF HIGH PRESSURE PROCESSED FOODS

High-pressure technology involves different packaging considerations, based on whether a product is processed in-container or packaged after processing. Continuous or semi-continuous systems are used in the case of pumpable products, which are aseptically packaged after pressure treatment. On the other hand, flexible or partially rigid packaging is best suited for batch in container processing. The effectiveness of HPP is greatly influenced by the physical and mechanical properties of the packaging material. The packaging material must be able to withstand the operating pressures, have good sealing properties, and the ability to prevent quality deterioration during the application of pressure. At least one interface of the package should be flexible enough to transmit the pressure. Thus, rigid metal, glass, or plastic containers cannot be used. The headspace must also be minimized while sealing the package, in order to ensure efficient utilization of the package as well as space within the pressure vessel. This also minimizes the time taken to reach the target pressure.

Nachamanson (1995) showed that film barrier properties and structural characteristics of polymer based packaging material were unaffected when at pressures of 400 MPa, when exposed for 30 min at 25°C. Masuda, Saito, Iwanami, and Hirai (1992) examined the effect of high pressure on water vapor and oxygen permeability, tensile strength, and heat seal performance of gas barrier composite films. Dobias, Voldrich, Marek, and Chudackova (2004) examined the suitability of several homogeneous and multi-layered packaging for: changes in mechanical properties (tensile and seal strengths), transparency, water vapor permeability, migration characteristics into fatty food simulants, and transfer of water and olive oil into the materials; a pressure of 600 MPa was applied for 60 min. HPP was particularly found to affect the sealability of single layered films and the overall migration. Schauwecker, Balasubramaniam, Sadler, Pascall, and Adhikari (2002) investigated the migration of 1,2-propanediol (PG) through selected food packaging films exposed to HPP. No detectable PG migration into the Polyester/Nylon/Al/PP meal ready- to eat (MRE) type pouches was observed. PG migration into the Nylon/EVOH/PE (EVOH) pouches was similar at 30, 50, and 75°C after ten minutes under atmospheric pressure. However, the PG migration into the EVOH pouches significantly decreased when treated with high pressure at 30, 50, and 75°C. At 75, and 50°C, the PG migration was significantly higher than the amounts detected at 30°C. Visible signs of delamination between the polypropylene (PP) and aluminum (Al) layers were observed in the MRE pouches processed at ≥ 200 MPa and 90°C for ten minutes. This delamination appeared to occur between the PP and Al layers. The Differential scanning calorimetric analyses and Fourier Transform Infrared (FTIR) spectra were similar for the high-pressure treated pouches when compared to their respective controls. This indicated that there was no HPP induced molecular changes to the treated pouches.

Caner, Hernandez, Pascall, and Riemer (2003) used C mode scanning acoustic microscopy (C SAM) and scanning electron microscopy (SEM) to examine structural damage to films and found no marked changes. However, structural damage to the metallized PET was identified. Goetz and Weisser (2002) studied the permeation and migration of volatile compounds through plastics used in food packaging. The extent of permeation and migration was found to depend on pressure and time; some reversible structural changes were also detected. Caner, Hernandez, and Pascall (2000) studied the permeance and transmission rates of water vapor, CO₂, and O₂ of various laminated flexible films exposed to high pressure processing. Prolonged exposure had a greater effect on the permeance of inorganic layers in some films, than lower pressure/time combinations. Metallized PET was most adversely affected by high pressure, the water vapor transmission being more severely affected than gas transmission. The increase in permeance of all most films was less than 11%, making them suitable for use in high pressure processing. The permeance of metallized PET, on the other hand, increased by 150% hence it was deemed to be unsuitable. Caner, Hernandez, Pascall, Balasubramaniam, and Harte (2004) studied the effect of high-pressure processing on the sorption behavior of D-limonene in selected packaging materials such as monolayer polypropylene, multilayer polyethylene/ nylon/ethylene vinyl alcohol/ polyethylene, and metallized PET/ethylenevinyl acetate/linear LDPE films. It was shown that with the exception of the metallized PET/ethylenevinyl acetate/linear LDPE films, high-pressure processing did not markedly affect D-limonene in the liquid simulated foods or the packaging films. Caner, Hernandez, and Harte (2004) reviewed the effects of high-pressure processing on packaging materials, the commercial applications of HPP in food processing, packaging materials suitable for high pressure processing, effects of HPP on barrier properties of packaging films, and mechanical properties of flexible packaging films after high pressure processing.

Lambert, Demazeau, Largeteau, Bouvier, Laborde, and Cabannes (2000) studied the effect of high pressure on tensile strength, heat seal strength, delamination, film structure, oxygen barrier permeability, water vapor barrier permeability, and migration characteristics. They observed that the package prepared by cast coextrusion was susceptible to de-lamination, whereas the packages prepared by tubular extrusion were more robust in terms of barrier properties, migration, and overall integrity. Kuebel, Ludwig, Marx, and Tauscher (1996) showed that systems containing the aroma compounds p-cymene and acetophenone were quickly absorbed by packaging films, leading to a rapid reduction in aroma concentration. It was observed that the distribution of aroma compounds was a function of polarity. Under elevated pressures, the concentration

of aroma compounds decreased less than under atmospheric pressure. High pressure raised the diffusion barrier of polymers, probably due to the transition of the material into a glassy state.

Rubio, Lagarón, Muñoz, Almenar, Catalá, Gavara, and Pascall (2005) studied the effect of high-pressure treatments (400 and 800 MPa, 5 and 10 min, 40, and 75°C) on EVOH-based packaging materials and they were compared with the morphological effects produced by sterilization (120°C, 20 min). The oxygen barrier and morphological properties of the treated packaging structures were analyzed and compared with those of the untreated samples. The results indicated that high-pressure treatment scarcely affects packaging materials, especially when compared to the detrimental consequences of retorting.

9 EFFECT OF HIGH PRESSURE ON TOXINS, ALLERGENS, AND NUTRIENTS

Information relating to the effects of high pressure on toxins, allergens, and nutrients are rare. There are no published reports available on the toxicity of high-pressure processed foods. It is well known that high pressure processed food can modify the activity of some enzymes and the structure of some proteins. Although covalent bonds are not affected, hydrogen bonds as well as hydrophobic and intermolecular interactions may be modified or destroyed. Allergenicity is a key concern in the safety assessment of novel foods. The incidence of food allergies is rapidly increasing, as is their severity and the number of foods involved. In heat-treated products, protein denaturation reduces the allergenicity of many foods, but heat-denatured proteins can also present new antigenic sites. New studies on the putative allergenicity of high-pressure processed foods may be needed.

10 REGULATORY ASPECTS

Developing methods and techniques for validating any process can be challenging. For example, the U.S. Food and Drug regulations for pasteurization (21 CFR 131.3 and 21 CFR 1240.61) and sterilization (21 CFR 108, 113 and 114) primarily stipulate minimum temperature and time requirements for processing foods. Such information does not exist for high-pressure processed products and it is important to establish microbiological criteria for safe production of foods by HPP (Sizer, Balasubramaniam, and Ting, 2002). In the United States, the Food, Drug, and Cosmetic Act (FD&C Act), which requires all foods to be processed, packaged, and held under sanitary conditions, is the basis by which FDA promulgates specific regulations. Currently, high pressure pasteurized products (such guacamole and oysters etc.), distributed under refrigerated conditions. Similar to thermally pasteurized products, high pressure pasteurized products are required to be processed under GMP conditions and relevant commodity specific regulations (e.g., juice HACCP, Pasteurized Milk Ordinance (PMO), Sea Food HACCP etc). The potential for temperature abuse during refrigerated storage and distribution has to be carefully evaluated and minimized. Processors must also work with equipment vendors to ensure that any part of the pressure vessel, which may have incidental contact with the food, is only made from approved materials. Currently, high pressure sterilized low-acid shelf stable products are not commercially sold in the United States. However, various laboratories worldwide are conducting research which can aid in establishing criteria for the production of safe high pressure processed low-acid foods.

In EU countries, the national regulations relating to the application of the precautionary principle for new products have been replaced by a EU regulation for novel foods and ingredients (CE 258/97), which came into force in 1997. This legislation for “novel foods” establishes an evaluation and a license system, compulsory for all new foods and processes. High pressure processed foods are deemed to be “new” as well as “novel.” In order to simplify the regulation, it was recently admitted that any new product could be treated at a national regulation level, if it is possible to show that the product is substantially equivalent to a product already on the market.

11 CONCLUSION

In the coming years, HPP is likely to be used commercially with increasing demand, increasing production in turn lowering operating cost. Destruction of microorganisms and inactivation of enzymes at low or moderate temperatures without changing organoleptic and nutritional properties shows that high-pressure technology has the potential to be used in the development of a new generation of value added foods. HPP is not likely to replace traditional processing methods. Furthermore, predictable changes in functional characteristics of proteins and complex carbohydrates (where little work has been done), mean that there are some exciting avenues of work in HPT treatment of foods that remains to be explored. Although a lot of research has been conducted in the area of high pressure technology a lot remains to be done in terms of understanding the critical limits of the process and the extent to which this might ensure appropriate treatment of food material. The critical process factors in HPT include pressure, time at pressure, time to achieve treatment pressure,

decompression time, treatment temperature (including adiabatic heating), product initial temperature, vessel temperature distribution at pressure, product pH, product composition, product water activity, packaging material integrity and concurrent processing aids. Nevertheless, their novel physico-chemical and sensory properties offer exciting opportunities for industry. The combination of HPP with other processing options such as heat, gamma-irradiation, ultrasound, carbon dioxide, and anti-microbial peptides, can lower the pressures required. The process can be integrated to other processes such as blanching, dehydration, osmotic dehydration, rehydration, frying, extraction, gelation, freezing, and thawing. High capital expenditure may limit its application initially but this will be offset by lower operating costs since the energy used to pressurize is less than the energies used in thermal processing and other benefits with respect to product originality. With further progress of technology and its commercialization, it is expected that the cost of the equipment will come down in the near future and the high-pressure processed safe and nutritious products will be available to all consumers at an affordable cost.

ACKNOWLEDGEMENT

We are appreciative of the SHIATS University for its continuous support in the development of important technologies for the future use. The effort of higher authorities to promote the technologies has been very valuable in the promotion of new technologies. A special thanks goes to the dean and head of department for believing in our dream to develop new technologies. Many people have contributed either directly or indirectly to make this work a reality.

REFERENCES

- [1] Lopez FR, Carrascosa AV, Olano A (1996) The effect of high pressure whey protein denaturation and cheese making properties of raw milk. *J Dairy Sci* 79: 929-936.
- [2] Kunio K, Masao I, Yasuhiro Y, Kunihiro O, Takayuki F, et al. (1994) Comparison of keeping quality between pressure processed jam and heat processed changes in flavor components, hue and nutrients during storage. *Bio Sci Biotech Biochem* 58: 1386-1391.
- [3] Tauscher BK (1998) Effects of high and chemical reactions effects on nutrients pressure treatment to nutritive substances and natural pigments & fresh novel foods by high pressure. VTT symposium 186. Technical research center for Finland Helsinki, Finland.
- [4] Tauscher BK (1999) High pressure and chemical reactions effects on nutrients and pigments. *Emerging food Sci Tech Tempere Finland* 58: 22-24.
- [5] Cheftel JC (1995) Review: High pressure microbial inactivation and food preservation. *Food Sci Technol Int* 1: 75-90.
- [6] Leadly CE, Williams A (1997) High pressure technology of food and drinks an over-view of recent developments and future potential in: *New Technologies Bull.No.14, Mar CCFRA, Chipping Campden, Glos, UK.*
- [7] Bridgman PW (1914) The coagulation of albumen by pressure. *J Biol Chem* 19: 511-512.
- [8] Erkmén O, Karatas S (1997) Effects of high hydrostatics pressure on *Staphylococcus aureus* in milk. *J Food Eng* 33: 257-262.
- [9] Adapa S, Schmidt KA, Toledo R (1997) Functional properties of skim milk processed with continuous high pressure throttling. *J Dairy Sci* 80: 1941-1948.
- [10] Buchheim W, Frede E (1996) Use of high pressure treatment to influence the crystallization of emulsified fats. *Lebensm U Milchwirts* 117: 228-237.
- [11] Butz P, Edenharter R, Fister H, Tauscher B (1997) The influence of high pressure technology on anti mutagenic activities of fruits and vegetables juices. *Food Res Int* 30: 287-291.
- [12] Carlez A, Chefel JC, Veciana NT (1995) Changes in colour and myoglobin of minced beef due to high pressure processing. *LWT Food Sci Technol* 28: 528-538.
- [13] Lee DU, Park JY, Kang JI, Yeo IH (1996) Effect on high hydrostatic pressure on the shelf life and sensory characteristics of angelica keiskei juice. *Korean J Food Sci Technol* 28: 105-108.
- [14] Donshi G, Ferrari G, Matteo MD (1996) High pressure stabilization of orange juice evaluation of the effect of process conditions. *Ital J Food Sci* 8: 99-106.
- [15] Eshtiaghi MN, Knorr D (1993) Potato cubes response to water blanching and high hydrostatics pressure. *J Food Sci* 58: 1371-1374.
- [16] Felipe X, Capellas M, Lawm AJR (1997) Comparison of the effect of high pressure treatment and heat pasteurization on the whey proteins in goat's milk. *J Agri Food Chem* 45: 627-631.

- [17] Gaucheron F, Famelart MH, Mariette F, Raulot K, Michel F, et al. (1997) Combined effects of temperature and high pressure treatment on physiological characteristics of skim milk. *Food Chem* 59: 439-447.
- [18] Yen G, Lin H (1996) Comparison of high pressure treatment and thermal pasteurization effect on the quality and shelf life of guava puree. *Int J Food Sci Technol* 31: 205-213.
- [19] Hite BH (1999) The effect of pressure in the preservation of milk bulletin of the west virginia University Agricultural Experiment Station 58: 15-35.
- [20] Kloczko I, Radomski M (1996) Preservation of fruits & vegetables and juices by high hydrostatics pressure. *Przemysl Spozywczy* 50: 25-26.
- [21] O'brien JK, Marshall RT (1996) Microbiological quality of raw ground chicken processed at high isostatic pressure. *J food Prt* 59: 146-150.
- [22] Pehesson PE (1996) Application of high pressure pasteurization to citrus processing in: Institute of Food technologies. *Ann Meet Book of Abstracts*: 108.
- [23] Shigehisa T, Ohmori T, Saito A, Taji S, Hayashi R (1991) Effects of high hydrostatics pressure on characteristics of pork slurries and inactivation of microorganisms associated with meat products. *Int J food Microbiol* 12: 207- 215.
- [24] Marta C, Montserrat MM, Esther S, Reyes P, Buenaventura G (1996) Population's aerobic mesophils and inoculated *E.Coli* during storage of fresh goat's milk cheese treated with pressure. *J Food Prot* 59: 582-587.
- [25] Carlez A, Chefel JC, Rose JP, Richard N, Saldana JL, et al. (1992) Effect of high pressure and bacteriostatic agents on the destruction of *Citrobacter freundii* in minced beef muscle in Balny, Hayashir.
- [26] Carlez A, Chefel JC, Rosec JP, Richard N (1993) High pressure inactivation of *Citrobacter freundii*, *Pseudomonas fluorescens* and *Listeria innocua* in inoculated minced beef muscle. *LWT-Food Sci Technol* 26: 357-363.
- [27] Balasubramaniam, V.M., and Farkas, D. 2008. High Pressure Processing. *Food Sci. and Technol. Int.* In press.
- [28] Balasubramaniam, V.M., Ting, E.Y., Stewart, C.M., and Robbins, J.A. 2004. Recommended laboratory practices for conducting high pressure microbial inactivation experiments. *Innovative Food Sci. and Emerging Technol.* 5(3): 299-306.
- [29] Balny, C. and Masson, P. 1993. Effects of high pressure on proteins. *Food Rev. Int.* 9(4): 611-628. Black, E.P., Setlow, P., Hocking, A.D.,
- [30] Stewart, C.M., Kelly, A.L., and Hoover, D.G. 2007. Response of spores to high-pressure processing. *Comp. Rev. Food Sci. Food Safety* 6(4): 103-119. Cheftel, J.C. 1995. Review: High pressure, microbial inactivation, and food preservation. *Food Sci. and Technol. Int.* 1: 75-90.
- [31] Rastogi N.K, Raghavarao K.S.M.S, Balasubramaniam V. M, Niranjana K and Knorr D 2007. Opportunities and Challenges in High Pressure Processing of Foods. *J. Food Science and Nutrition*, 47:69–112
- [32] Kadam PS, Jadhav B A, Salve R V and Machewad G M 2012. Review on the High Pressure Technology (HPT) for Food Preservation. *J. Food Process Technol*, 3:1 :1-5
- [33] Hayman, M., Baxter, I., Oriordan, P.J., and Stewart, C.M. 2004. Effects of high-pressure processing on the safety, quality, and shelf life of ready-to-eat meats. *J. of Food Prot.* 67(8): 1709-1718.
- [34] H., Adams, R.M., Farkas, D.F., and Morrissey, M.T. 2002. Use of High-pressure Processing for Oyster shucking and shelf-life extension. *J. Food Sci.* 67(2): 640-645.
- [35] Heremans, K. 2003. The effect of high pressure on biomaterials. In "Ultra High Pressure Treatments of Foods" ed. Marc E.G. Hendrickx and Dietrich Knorr. pp. 23-52. Kluwer Academic/ Plenum Publishers, New York.
- [36] Hite, B.H. 1899. The effect of pressure in the preservation of milk. Washington, Va. Univ., Agriculture Experiment Station, Bulletin, 58: 15-35.
- [37] Hogan, E., Kelly, A., and Sun, D.W. 2005. High pressure processing of foods: An overview. In "Emerging technologies for food processing" ed. Sun, D.W., pp. 3-32. Elsevier Academic Press, London.
- [38] Margosch, D., Ehrmann, M.A., Buckow, R., Heinz, V., Vogel, R.F., and Gänzle, M.G. 2006. High-pressure mediated survival of *Clostridium botulinum* and *Bacillus amyloliquefaciens* endospores at high temperature. *Applied and Environ. Microbiol.* 72(5): 3476-3481.
- [39] Matser A.M., Krebbers B., Berg, R.W., and Bartels, P.V. 2004. Advantages of high pressure sterilisation on quality of food products. *Trends in Food Sci. and Technol.* 15(2): 79-85.
- [40] Patazca, E., Koutchma, T., and Balasubramaniam, V.M. 2007. Quasiadiabatic temperature increase during high pressure processing of selected foods. *J. Food Eng.* 80(1): 199-205.
- [41] Patterson, M.F. 2005. Microbiology of pressure-treated foods – A review. *J. Applied Microbiol.* 98(6): 1400-1409.
- [42] Rasanayagam, V., Balasubramaniam, V.M., Ting, E., Sizer, C.E., Bush, C., and Anderson, C. 2003. Compression heating of selected fatty food materials during high pressure processing. *J. Food Sci.* 68(1): 254-259.
- [43] Rastogi, N.K., Raghavarao, K.S.M.S., Balasubramaniam, V.M., Niranjana, K., and Knorr, D. 2007. Opportunities and challenges in high pressure processing of foods. *Crit. Rev. in Food Sci. Nutr.* 47(1): 69-112.
- [44] San Martin, M.F., Barbosa-Canovas, G.V., and Swanson, B.G. 2002. Food processing by high hydrostatic pressure. *Crit. Rev. in Food Sci. Nutr.* 42: 627-645.

- [45] Sáiz, A.H., Mingo, S.T., Balda F.P., and Samson C.T. 2008. Advances in design for successful commercial high pressure food processing. *Food Australia*, 60(4): 154-156. Samson, C. Tonello. 2008. Personal communication. NC
- [46] Hyperbaric, Spain. Smelt, J.P.P.M. 1998. Recent advances in the microbiology of high pressure processing. *Trends in Food Sci. Technol.* 9(4): 152-158. Tauscher, B. 1995. Pasteurization of food by hydrostatic high pressure: chemical aspects. *Zeitschrift fuer Lebensmittel Untersuchung und Forschung* 200: 3-13.
- [47] Torres, J.A. and Velazquez, G. 2005. Commercial opportunities and research challenges in the high pressure processing of foods. *J. Food Eng.* 67(1-2): 95-112.

AUTHOR'S BIOGRAPHY



RAVI SHANKAR- AMIMI, AMIAEI, AMIE, Pursuing M.Tech (4th sem) in Food Technology (Food Process Engineering), Department of Food Process Engineering, Vaugh School of Agriculture Engineering and Technology, SHIATS-Deemed University, P.O-Naini, Allahabad, U.P-211007, India. B.E in Food Technology, SLIET, Sangrur, (P.T.U) Punjab, India.

CORRESPONDENCE AUTHOR'S ADDRESS

Ravi Shankar

Duplex no. 40, Dev Villa, Post Office Road, Mango, Jamshedpur, Jharkhand-831001

r.shankar.mail@gmail.com