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Innovative processing for pre-packaged foods

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ABSTRACT: The increased demand by consumers for fresh-like, safe, nutritious, convenient and flavorful packaged foods have paved the way for the continuous emergence of novel food processing technologies. A number of innovative thermal methods including sous-vide, microwave, radiofrequency and infrared heating and non-thermal methods including high hydrostatic pressure, irradiation and pulsed light technology for processing of packaged foods, have become the subject of active research and development. This article reviews some state-of-the-art approaches used for decontamination of packaged foods with discussion relating to the mechanisms of microbial control, applications to food and limitations associated with their implementation for pre-packaged foods.

KEYWORDS: pre-packaged foods, thermal processing, non-thermal processing, packaging, microorganisms.

1 INTRODUCTION

Traditionally, food has been processed in bulk followed by packaging to mostly act as a barrier to prevent access to spoilage and pathogenic microorganisms. Packaging materials have customarily been chosen to contain, protect and preserve food for a certain period of time. However, with the changes in lifestyle and burgeoning consumer demands for safe, convenience ready-to-eat packaged foods, the primary functions of packaging have shifted. Greater emphasis is nowadays placed on the use of appropriate materials to package foods prior to processing with the view to avoiding post-process recontamination of the product. Research and development in the area of in-package or post-package processing methods therefore not only have to achieve a satisfactory level of decontamination but also be compatible with the food product of interest. Technological advances in processing and packaging machinery have been quite considerable thanks to progress in food engineering technology and packaging material science, delivering higher standards of hygiene, safety and quality assurance. With the increased demand for products of higher nutritional and sensorial quality, novel thermal processing methods such as sous-vide cooking, microwave and radiofrequency heating as well as non-thermal methods such as high pressure processing, irradiation, UV-light have received considerable attention. This article purports to review the various thermal and non-thermal minimal processing methods used for pre-packaged foods and discusses the mechanisms of microbial control and food products affecting these technologies as well as offers insight into the relevant packaging parameters to optimize the efficacy of these processes.

2 INNOVATIVE THERMAL PROCESSING METHODS FOR PRE-PACKAGED FOODS

2.1 SOUS-VIDE PROCESSING

Sous-vide is a French term literally meaning "under vacuum". This technology allows food to be thermally processed using vaccum-packaging in heat-stable, high barrier or air-impermeable multi-laminate plastics. This form of processing is especially amenable for food consisting of partially cooked ingredients alone or combined with raw foods, requiring low temperature storage until the packaged food is thoroughly heated immediately prior to serving (Ghazala, 2004). In short, sous-vide is an "Assemble-Package-Pasteurize-Cool-Store" process.

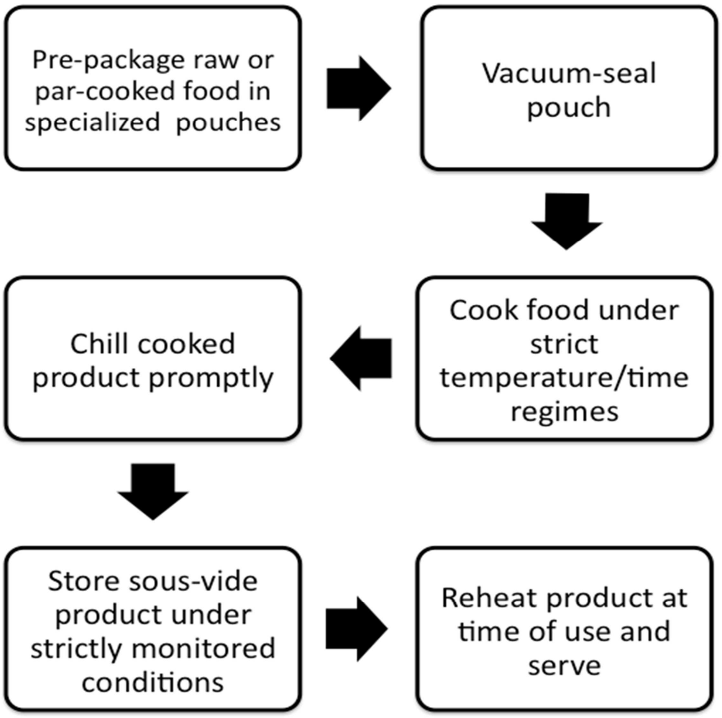
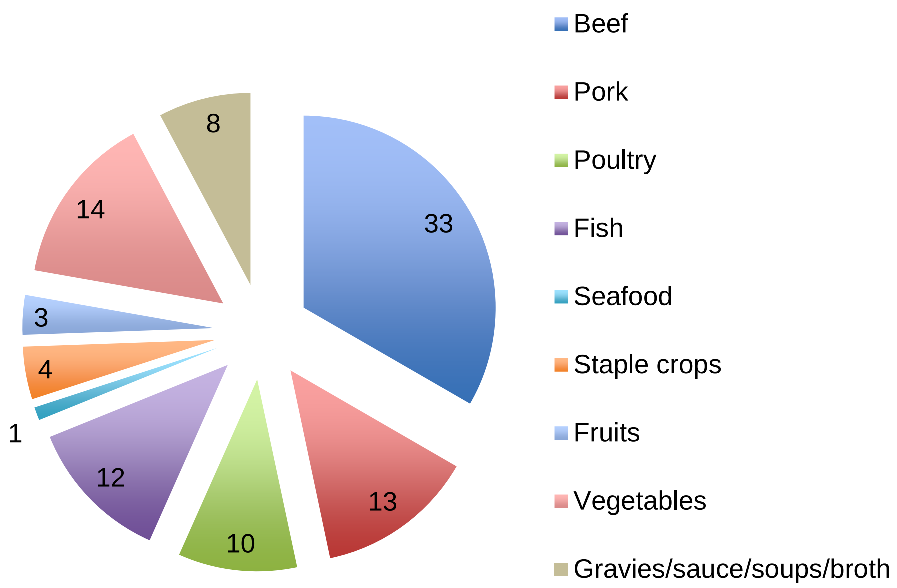


Figure 1 provides a simplified flow diagram that outlines the basic steps in sous-vide processing.

On an industrial scale, pre-packed solid foods are pasteurized in a jacketed tank with a large-capacity and subjected to specific time-temperature regimes and then cooled in a chill tank (3-4°C) to achieve inactivation of microbes and enzymes with minimal chemical changes and alterations in the original organoleptic characteristics (color, flavor and appearance). In addition to requiring minimal preparation and serving steps, it ensures consistency in the quality and presentation of the products (Ghazala, 2004).

2.1.1 Application of SVP for pre-packaged foods

The application of sous-vide has been used widely in the processing of various types of vacuum-packaged raw or par-cooked meat, poultry, fish and even vegetable-based products for the purpose of enhanced sensorial and organoleptic characteristics, and enhanced microbiological safety and quality of these foods with extended shelf-lives. The pie chart in Figure 2 below shows the relative number of publications on the application of sous-vide for different food commodities.



Nyati (2000) compared the microbiological status of various sous-vide animal-derived products and showed that foodborne pathogens, such as *L. monocytogenes*, *Clostridium perfringens*, *Bacillus cereus, Salmonella*, and other *Enterobacteriaceae*, were rendered undetectable after processing. González-Fandos *et al.* (2004) demonstrated the capacity of sous-vide cooking to reduce the counts of *Staphylococcus aureus*, *B. cereus*, *C. perfringens* and *L. monocytogenes* on rainbow trout and salmon and extend shelf-life to > 45 days during storage at 2°C. Similarly, Shakila *et al.* (2009) showed an improvement in the microbiological quality of sous-vide fish cakes during chilled storage (3°C) with an eight-fold increase in its shelf-life compared to their conventionally cooked counterparts.

Significant research has in particular focused on spore-forming microorganisms that constitute a safety risk in sous-vide products, such as *Clostridium botulinum*, *C. perfringens* and *Bacillus* spp. Several studies have demonstrated outgrowth of spores in sous-vide spaghetti and meat-sauce products (Simpson, 1995), carrot, cod and chicken homogenates (Brown and Gaze, 1990) as well as products containing mixtures of beef, pork, vegetables, rice and seafood. Researchers in recent years have also characterized the behavior of *C. perfringens* in sous-vide cooked products. Juneja and Marmer (1996) investigated the growth potential of *C. perfringens* in sous-vide cooked turkey products formulated with 0–3% salt and stored at temperatures of 4–28°C. Overall, storage at 4°C and a salt level of 3% proved to be most effective in controlling spore outgrowth. Outgrowth of *Bacillus* spores in sous-vide products is also a concern and has been extensively studied. Overall, mixed results have been found with respect to outgrowth of *Bacillus* spores. While Knochel *et al.* (1997) and Chavez-Lopez *et al.* (1997) found detectable populations of *Bacillus* spores in vacuum-cooked green beans and pilaf rice, respectively, Aran (2001) demonstrated that addition of calcium lactate (1.5%) and sodium lactate (3%) completely inhibited *B. cereus* outgrowth in beef goulash samples.

2.1.2 Limitations of SVP for pre-packaged foods

Although foods subjected to SVP generally have enhanced nutritional and sensorial properties compared to their more thoroughly heat-treated counterparts, they also raise several microbiological safety concerns, especially if process controls are not in place. Generally, short shelf-life products (< 10–14 days) subjected to sous-vide cooking undergo a 6-*D* reduction in the numbers of vegetative pathogens (process lethality equivalent to 12 min at 70°C) (Holdsworth and Simpson, 2008). This process is considered adequate for targeting *L. monocytogenes*, a psychrotrophic vegetative pathogen (Holdsworth and Simpson, 2008); however, it is unable to achieve a satisfactory inactivation of psychrophilic nonproteolytic *C. botulinum* type B and E spores, which can potentially outgrow during refrigeration and produce toxins (Holdsworth and Simpson, 2008). In addition, the existing preservation hurdles can also inhibit the spoilage microbiota and the absence of apparent signs of spoilage in terms of product color, odor and taste may mislead consumers into eating products that are unfit for consumption due to compromised safety. Moreover, improper chilling in the post-processing stage provides an environment that is conducive for the growth of psychrotrophic and mesophilic pathogens. Nonsporeforming facultative anaerobic psychrotrophs considered prime hazards in sous-vide processed products include *L. monocytogenes, Yersinia enterocolitica* and *Aeromonas hydrophila* (Juneja, 2003). Nonsporeforming facultative anaerobic mesophilic pathogens such as *Salmonella*, *S. aureus*, or enteropathogenic strains of *E. coli* may constitute a risk if foods are subjected to temperature abuse (Juneja, 2003). Post-process recontamination can also occur. Even products such as meats and cheese that have been processed to kill *L. monocytogenes*, can still be recontaminated with the pathogen when opened, sliced or repackaged at retail if stringent hygienic practices are not observed (Ghazala, 2004). Hence, it is recommended to vacuum-package the food together with another hurdle such as the addition of preservatives, a low pH, or low water activity to reduce the risk of foodborne illness (Juneja, 2003).

Sous-vide process is quite a gentle cooking method for delicate foods. This process relies on the application of an extended mild heat treatment at a precisely controlled temperature, followed by chilled storage at temperatures of 3°C for ensuring longevity of the product. Since these foods are not sterile, they are only expected to have a shelf-life of less than 42 days (Ghazala, 2004), however, the quality and shelf-life of the product also relies on the use of high-quality raw materials and clean equipment to package every item. It is thus necessary to exercise care and good hygienic practices at every step in the manufacturing, distribution, storage, and reuse stages of this type of product.

Moreover, accidental recontamination of the products during the on-going processing phase is also a potential concern. Packaged products can be cooked in different types of industrial equipment using different heating media. Water is a common heating and cooling medium. However, water also acts as a vehicle for microbes. During heating of vacuum-packed products, fluid can enter through package leaks and cause recontamination. One leaky pouch could cause the heating and cooling water as well as other pouches in the entire batch to become contaminated (Martens, 1995).

2.2 MICROWAVE HEATING (MW)

Microwaves are a form of electromagnetic radiation characterized by the wavelength and frequency of the waves used in food processing (915-2450 Hz). Microwave heating is generated by the conversion of electromagnetic energy to thermal energy. The technology of microwave heating of foods has garnered scientific and consumer interests due to its volumetric origin, rapid increase in temperature and relative ease of cleaning (Ahmed and Ramaswamy, 2007). Unlike more traditional forms of thermal processing, such as pasteurization and retorting which are characterized by a slow thermal diffusion process, the volumetric nature of heat generated by microwaves can substantially reduce the total heating time, thereby minimizing the overall severity of the process and leading to a greater retention of the desirable quality attributes of the product (Sumnu and Sahin, 2005). According to Tewari (2007), the time required to come to target process temperature is attained within one-quarter of the time typically reached by conventional heating processes. Microwave technology is also amenable to batch processing and therefore can be used to pasteurize pre-packaged products as well as offer the flexibility of being easily turned on or off.

2.2.1 APPLICATION OF MW PROCESSING FOR PRE-PACKAGED FOODS

Microwave heating has been the most widely utilized form of electric heating. Considerable research has focused on the use of microwave heating for pasteurization and sterilization applications. Microwave sterilization operates in the temperature range of 110-130°C while pasteurization is a more gentle heat treatment occurring between 60 and 82°C (Orsat and Raghavan, 2005). Since microwave energy can heat foods effectively and rapidly, its use in food decontamination by pasteurization and sterilization has been the subject of intense study. The advantages of using microwaves for food decontamination include the rapid and homogeneous heating in certain food products. In other words, microwave heating can offer high temperature and short time processing (HTST), thereby ensuring a product of enhanced quality. Examples of packaged foods treated by microwaves include yogurt as well as pouch-packed meals (Decareau, 1985). Lau and Tang (2002) showed that microwaves, applied at a frequency of 915 MHz, were able to pasteurized asparagus pickled in jars. The process was demonstrated to achieve uniform heating for a shorter holding time, with minimal quality deterioration compared to conventional pasteurization. Canumir *et al.* (2002) previously demonstrated the suitability of microwave pasteurization to inactivate *E. coli* in pre-packaged apple juice.

Modernization of microwave technologies has resulted in equipment with a longer operating life at lower costs and therefore a greater “penetration” of microwaveable foods on the market. There are several lines of new packaged microwaveable products commercially available including the Eggology’s On-the-go 100% egg whites, and Marks and Spencer’s Steam Cuisine. The latter is a ready-to-cook product that takes ~ 6 min to cook from the raw stage using an “intelligent double pressure cooking technology” (Bertrand, 2005). Although the microwave oven is a common household appliance, microwave heating has also found increasing applications in the food industry in various processing operations.

Microwave processing has been successfully applied on a commercial scale for pasteurizing prepared meals, fresh pasta, bread, granola and milk (Giese, 1992). Microwave heating has also been used on an industrial scale to produce pre-packaged shelf-stable products, accompanied with strict temperature control to ensure predictability and reproducibility of the thermal process (Mullin and Bows, 1993). An example of a successful microwave sterilizing plant is located in Belgium and produces a line of “Ready To Heat And Eat” dishes in their "Top Cuisine" line (Bengtsson, 1998).

2.2.2 Limitations of MW for pre-packaged foods

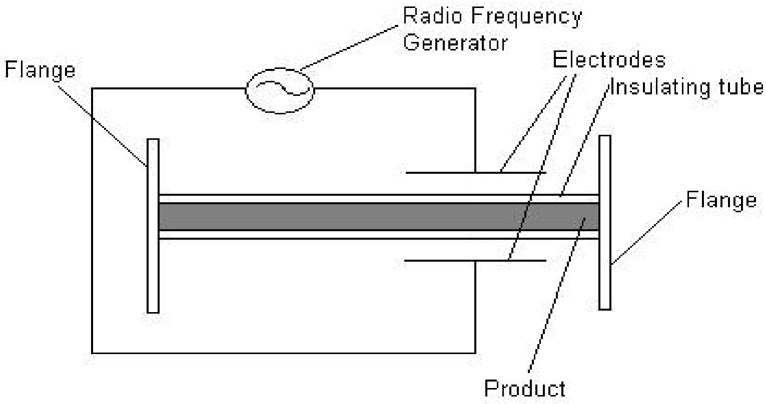
Microwave heating faces both process-related and package-related challenges. A major hurdle with microwave processing is attaining heating uniformity (Ohlsson, 1991). Prediction of temperature profiles is particularly difficult with foods of different dielectric properties, size and geometry. Temperature mapping at different locations throughout the product is thus critical in order to control the temperature at the coldest point of the product where microbial destruction is likely to be least efficient (Ahmed and Ramaswamy, 2007). This non-uniform heat distribution has made comparison of the microbial inactivation kinetics of this technology to other conventional forms of heating rather challenging due to inherent differences in the monitoring of temperature (Ahmed and Ramaswamy, 2007). As a result, the lack of reproducibility and predictability of the process lethality can lead to survival of pathogens, such as *Salmonella* and *L. monocytogenes,* in “cold spots” of the food (Schnepf and Barbeau, 1989). According to Ohlsson (1991), one way to compensate for the limitation of microwave is to use it in combination with conventional heating, using rapid volumetric heating for the final burst of 10-13°C to achieve HTST conditions.

Certain packaging materials such as glass and several types of plastics can be problematic for microwave heating. Although glass is an acceptable microwaveable material, it has a relatively higher cost, higher shipping weight, greater breakability and has the tendency to gain thermal energy from the surrounding food. Their tall cylindrical geometry can sometime lead to focused interior heating (Schiffmann and Sacharow, 1992). Moreover, glass may also break during microwaving especially if there is a sharp temperature differential between the internal and external temperature. In addition, tall glass jars can also cause overflow or eruption of the product, especially for particulate foods (Schiffmann, 1988). Plastics are also prominent packaging materials for microwaveable foods. However, a caveat with the use of plastic pouches for packaging fatty foods is that fat separation can occur, causing the lipid layer to stick to the pouches (Schiffmann, 2001). During microwaving, this interfacial fat can rapidly gain heat and can cause the pouch to melt. Thus, product formulation to avoid fat separation as well as design of stand-up pouches to allow venting should be ensured to maintain package integrity and to avoid pressure build-up.

In addition, the use of microwave heating does not always necessarily guarantee a better retention of quality of the food products. The rate of deterioration and thermal degradation of the sensorial and nutritional attributes depend on several intrinsic (product-related) factors, as well as processing factors related to the design and dielectric properties of the microwave process. Sumnu and Sahin (2005) mentioned that microwave heating can lead to the development of quality problems in microwave-processed foods due to the occurrence of hot spots at the corner and edges of the product (Sumnu and Sahin, 2005). In addition, quality could also be compromised due to insufficient time for some biochemical reactions to occur. However, modernization in the design of microwaves equipment to include features such as phase control heating, variable frequency or the combination of microwave energy with other thermal methods may improve the performance of MW food processing (Sumnu and Sahin, 2005). Advances in process development and controls also need to be accompanied with innovations in the area of packaging research and design.

2.3 Infrared (IR) and Radiofrequency (RF) heating

Another processing method involving dielectric heating is RF heating which has the potential for the rapid heating of solid and semi-solid foods. RF heating refers to the heating of dielectric materials with electromagnetic energy at frequencies between 1 to 300 MHz (Orfeuil, 1987). Research and application of RF sterilization of packaged foods has been fairly limited. Previously, researchers at Washington State University, in conjunction with laboratories at Strayfield UK, the U.S. Army Natick Soldier Center and the U.S. Army Combat Ration Network have designed and created a prototype 27-MHz RF sterilization system to process foods pre-packaged in a polymeric tray or a multi-tray system to mimic large-scale industrial production systems (Ramaswamy and Tang, 2008). The research group demonstrated the efficacy of RF energy to inactivate heat-resistant spores to produce shelf-stable pre-packed foods such as RF-processed eggs, pasta and meats. In addition, research work undertaken by the group also involved the development of computer models to predict RF energy generation in packaged foods; as well as, improvement in the design of RF sterilization systems (Ramaswamy and Tang, 2008). Figure 3 is a schematic diagram of a generic RF dielectric heating unit adapted from Zhao and others (2000).



IR uses electromagnetic radiation generated from a hot source (quartz lamp, quartz tube or metal rod) resulting from the vibrational and rotational energy of molecules. Thermal energy is thus generated following the absorption of radiating energy. Although IR is an emerging technology for the food industry, research on its application to process food has been conducted on an experimental or pilot-scale. IR provides instant heating, thereby cutting down on the need for heat build-up. In addition, compared to conventional heating equipment, the operating and maintenance costs are lower and it is a safer and cleaner process.

2.3.1 APPLICATION OF IR AND RF PROCESSING FOR PRE-PACKAGED FOODS

Short (1 µm) and intermediate (5 µm) wave IR heating have gained wide acceptance and have been applied for the rapid baking, drying and cooking of foods of even geometry and modest thickness (Tewari, 2007). Short-wave IR has a penetration depth of several mm in many foods. In addition, it is not absorbed by transparent plastic packaging and therefore has been successfully applied for the surface pasteurization of packaged bakery products (Tewari, 2007). Long-wave IR (30 µm) has been in use for industrial cooking and drying applications, achieving shorter processing times when compared to convective heating. Various materials have been used to package foods for processing by RF including waxed paper (Cathcart *et al.*, 1947), cellophane (Cathcart *et al.*, 1947), Cryovac tubings (Bengtsson and Green, 1970) or even tubes made of glass (Houben *et al.*, 1991). Advances in packaging research and design for RF-heated foods, such as the development of high-barrier plastic films through the application of EVOH or silicon oxide (SiOx) surface coatings have also been reported (Tewari, 2007). Table 1 highlights examples of studies evaluating the efficacy of the aforementioned thermal interventions used to enhance the safety of packaged foods.

Table 1.

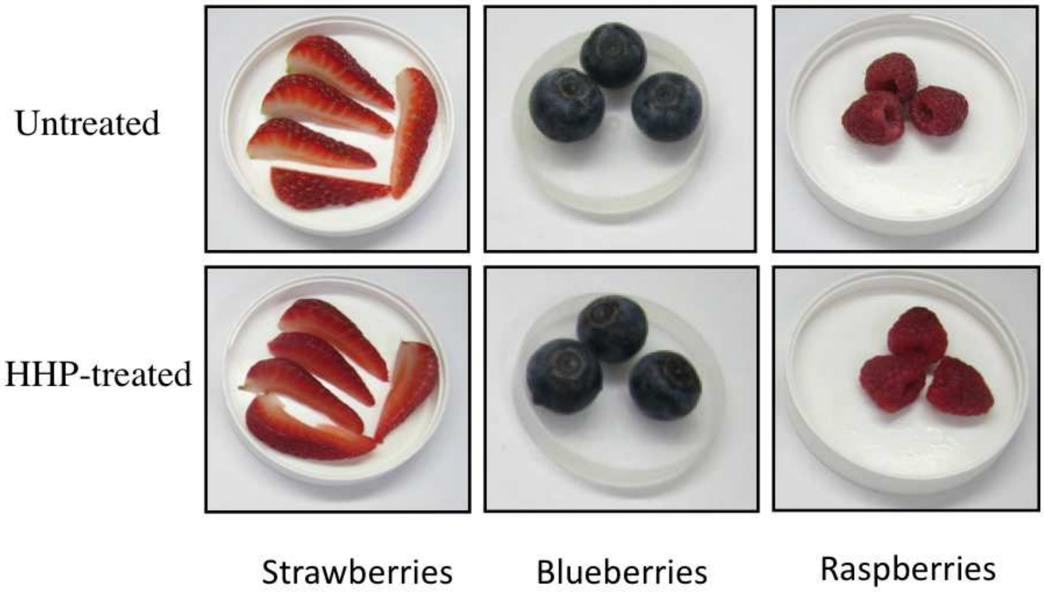
Technology	Food matrix	Target microorganism(s)	Outcome	Reference
Sous-vide/cook-chill	Fish cakes	Total Viable Counts	Eight-fold increase in shelf-life	Shakila *et al*. (2009)
Sous-vide cooking	Turkey	*Clostridium perfringens*	No outgrowth	Juneja and Marmer (1996)
Sous-vide cooking	Salmon slices	*Staphylococcus aureus, Bacillus cereus, Listeria monocytogenes*	Undetectable counts	Gonzales-Fandos *et al*. (2003)
Microwave heating	Beef frankfurters	*Listeria monocytogenes*	> 7 LR	Huang and Sites (2007)
Microwave heating	Frankfurters	*Listeria monocytogenes*	1.5 - 5.9 LR	Rodriguez-Marval *et al*. (2009)
Radio-frequency heating	Mashed potatoes	*Clostridium sporogenes* (PA 3679)	> 7 LR	Luechapattanaporn *et al*. (2006)
Infrared heating	Almonds	*Salmonella* Enteritidis	> 7.5 LR	Brandl *et al*. (2008)
Infrared heating + submerged pasteurization	RTE meat products	*Listeria monocytogenes*	< 3.5 LR	Gande and Muriana (2003)

Definition of abbreviations used in table: RTE = Ready-to-eat, LR = Log reduction

3 INNOVATIVE NON-THERMAL PROCESSING FOR PRE-PACKAGED FOODS

3.1 HIGH HYDROSTATIC PRESSURE (HHP)

Among the array of non-thermal processing technologies, HHP has garnered the most attention since the early 1990s. For the last 20 years, HHP has been explored quite intensively by food research institutions as well as the food industry with the goal to enhance the safety, quality, nutritional and functional properties of a wide variety of packaged foods with minimal deleterious effects on their nutritional and organoleptic characteristics (Welti-Chanes *et al*., 2005). Figure 4 visually compares untreated and pressure-treated (350 MPa/ 2min/ 4°C) strawberries, blueberries and raspberries. HHP-treated blueberries and strawberries did not undergo extensive quality deterioration although raspberries became noticeably softer.



During HHP, pre-packaged foods are exposed to pressures of the order of 200–600 MPa for a few minutes. Process temperatures during treatment can vary from subzero temperatures to above boiling point of water (100°C) (Caner *et al.*, 2004a). Because HHP is performed on packaged foods, cost-intensive aseptic package sterilization can be avoided (Rastogi *et al.*, 2007).

3.1.1 MECHANISMS OF MICROBIAL CONTROL OF HHP

The mechanism of microbial control and inactivation lies in a combination of processes including the breakdown of non-covalent bonds in large macromolecules, as well as the disruption and permeabilization of the cell membrane (Rastogi *et al.*, 2007; Welti-Chanes *et al.*, 2005). Food microorganisms, such as vegetative bacteria, human infectious viruses, fungi, protozoa and parasites, can significantly be reduced when subjected to high pressure. The mechanism of microbial control and inactivation lies in a combination of processes such as the breakdown of non-covalent bonds in large macromolecules, biochemical effects, effects on the genetic mechanisms of cells, morphological changes as well as the disruption and permeabilization of the cell membrane (Patterson, 2005). A range of barotolerances exists among the different microbial groups and even among the different strains of the same species (Patterson, 2005).

3.1.2 APPLICATION OF HHP PROCESSING FOR PRE-PACKAGED FOODS

HHP is applied today at a wide range of temperatures in order to pasteurize foods in their packaging while preserving their organoleptic and nutritional qualities. The food and the package are treated together so that post-processing contamination can be prevented. Several researchers have investigated the efficacy of HHP to inactivate foodborne pathogens *L. monocytogenes*, *S. aureus* and *Salmonella* on vacuum-packaged RTE meat and poultry products to enhance their microbiological safety (Garriga and Aymerich, 2009). Similarly, the commercial use of Safe Pac™ high pressure pasteurization to inactivate microorganisms and extend the shelf-life of pre-packaged RTE products including meats, soups, wet salads, sauces, fruit smoothies, shellfish and seafood by 200-300% has also been reported (Safe Pac LLC, 2010). Jofré *et* *al.* (2008a, b) and Marcos *et al.* (2008) demonstrated the synergistic effect of HHP and antimicrobial packaging incorporating natural antimicrobials to control *Salmonella* on sliced cooked ham. Jofré *et al.* (2008b) also demonstrated that antimicrobial packaging, HHP and refrigerated storage acted as an effective triple combination of hurdles to inhibit *Salmonella* sp., *L. monocytogenes* and

S. aureus in cooked ham. Another innovative example of “hurdle technology” involves the use of HHP at 300 to 800 MPa to treat foods in contact with an antimicrobial packaging material to ensure a delayed release of the antibacterial compound, allyl isothiocyanate (AIT). AIT is encapsulated within cyclodextrins inside a polylactic acid (PLA) matrix to ensure a controlled release of the agent during ambient temperature storage (INRA, 2010).

3.1.3 LIMITATIONS OF HHP PROCESSING FOR PRE-PACKAGED FOODS

Although various flexible packaging systems have been used for HHP products, other forms of packaging including metal cans, glass bottles and paperboard-based packages are inappropriate (Min and Zhang, 2007). Moreover, the presence of metals such as aluminum in multilayered packaging was also affected during HHP processing (Caner *et al.*, 2004a). The researcher attributed it to the differential elasticity of the different components of the package, resulting in rupture of the aluminum layer given its rigidity. Other authors have reported that HHP also affected the barrier, mechanical and mass transfer properties of the package. In some instances, the general integrity of the material was compromised after pressure treatment. Delamination of the package due to the type or quality of the materials and adhesive has also been reported (Schauwecker *et al.*, 2002).

Since bacterial spores are quite baro-resistant and difficult to inactivate using pressure, HHP has greater commercial relevance for pasteurization rather than sterilization applications. Pressure-pasteurized foods need low temperature storage and distribution to retain their sensory and nutritional qualities. Hence, the potential for temperature abuse to occur during refrigerated storage and distribution has to be carefully monitored and minimized. In addition, because of the high capital cost and costs associated with operations and service of the high-pressure equipment, the use of HHP in food processing is limited to certain niche products. HHP also has limited application for foods with a large number of air spaces such as plant-derived foods (Michel and Autio, 2001). Air within the package of the food can be detrimental to quality. Therefore, headspace must be limited to maximize efficient utilization of the chamber space and the package space (Rastogi *et al.*, 2007). Removal of air from the package also considerably reduces the time to reach target pressure and thus cuts down costs (Hogan *et al.*, 2005). With regard to the regulatory aspects, establishment of microbiological criteria for HHP-processed foods (Rastogi *et al.*, 2007), and adherence to Good Manufacturing Practices (GMP) and Hazard Analysis Critical Control Point (HACCP) are also critical.

The comparison of experimental results produced in different laboratories is also challenging due to insufficient description of methodologies used and differences in sample preparation and packaging procedures, as well as differences in the strains of inocula used. Furthermore, the HHP equipment used has different designs and configurations (Rastogi *et al.*, 2007). It is thus necessary to provide an adequate description of the HHP equipment such as chamber size, material of construction, wall thickness, pressure-transmitting medium, packaging material, heating and cooling systems, power specification, data acquisition system and any other relevant information (Rastogi *et al.*, 2007). HHP treatments are also dependent on the dual effect of pressure and temperature. Documentation of the temperature of the pressure vessel and pressure-transmitting fluid, and the temperature history of the packaged product under pressure is essential for the optimization and design of industrial processes (Denys *et al.*, 1997).

3.2 IRRADIATION

Food irradiation is a process involving the exposure of food to ionizing radiations, such as gamma rays emitted from the radioisotopes cobalt–60 and cesium–137, and high-energy electrons and X-rays produced by machine sources (Ohlsson, 2002). Ionizing radiation can be applied to decontaminate pre-packaged food. Since food and packaging materials are irradiated concurrently, the radiation stability of the packaging material is of paramount importance if the technology is to be implemented successfully.

3.2.1 MECHANISMS OF MICROBIAL CONTROL USING IRRADIATION

During irradiation, molecules absorb energy to form highly labile and reactive ions or free radicals that result in breakage of a small percentage of chemical bonds (Ohlsson, 2002). High-energy electrons fracture molecules (typically water molecules) into highly reactive species such as radicals, which can disrupt other cellular macromolecules such as DNA, proteins or structures such as cell membranes (Fellows, 2000).

3.2.2 APPLICATION OF IRRADIATION TREATMENT FOR PRE-PACKAGED FOODS

Various studies have demonstrated the ability of irradiation to destroy foodborne pathogens and spoilage microbiota on various pre-packaged meats and plant-derived products. Fan and Sokorai (2005) investigated the effects of various doses of irradiation on the quality of fresh-cut iceberg lettuce packaged in film bags and determined that 1-2 kGy was the optimum dose to ensure satisfactory inactivation of spoilage bacteria while minimizing sensorial changes. Lamb *et al.* (2002) showed that low-dose gamma irradiation effectively reduced *S. aureus* in ready-to-eat ham-and-cheese sandwiches and proved to be more effective than refrigeration alone. The integrity of the post-irradiated packaging material was not significantly changed. Other authors also showed the feasibility of irradiation at 2-2.5 kGy to reduce the population of aerobic bacteria (Niemand *et al.*, 1983) and bacterial members of the Enterobacteriaceae (Farkas *et al.*, 1997) on vacuum-packaged chilled meat products for shelf-life extension.

In addition to the application of irradiation alone, combined application of ionizing radiation and modified atmosphere packaging (MAP) have also been investigated. Fan *et al.* (2003) demonstrated enhanced safety and improved quality of fresh-cut lettuce irradiated in MAP at doses of 1-2 kGy. Lambert *et al.* (2000) showed that the combination of irradiation (1 kGy) and MAP (10–20% O_2, balance N_2) significantly reduced the microbial populations of fresh pork although to the detriment of organoleptic quality. Similarly, Przybylski *et al.* (1989) showed that application of low-dose irradiation and MAP brought about a four- to five fold extension in the shelf-life of fresh catfish fillets

3.2.3 LIMITATIONS OF IRRADIATION FOR PRE-PACKAGED FOODS

Compared to other processing technologies, irradiation has relatively low operating costs due to its low energy requirements; however, the high investment costs, the requirement for a critical minimum capacity and product volume for economically feasible operation (Rahman, 2007), and the complexity of regulatory actions have been obstacles to the successful implementation of this technology (Arvanitoyannis and Tserkezou, 2010). Irradiation of food can also result in nutritional degradation and undesirable organoleptic changes with concomitant off-flavor development (Arvanitoyannis and Tserkezou, 2010). Factors affecting the kinetics of nutrient degradation that need to be carefully monitored include the radiation dose, treatment temperature, oxygen availability and product composition. Irradiated foods should also be properly handled, stored and distributed to prevent chemical and biochemical deterioration, spoilage or further loss of nutritive value (Sommers, 2006; Thayer, 1994). Moreover, although irradiated foods have been declared as safe and wholesome, consumer attitude towards this technology still remains one of the major factors hindering wide application of this technology. Griffith (1992) attributed the poor growth and acceptance of food irradiation to lack of consumer education and consultation with customers.

3.3 PULSED LIGHT TECHNOLOGY (PL)

PL technology is an innovative method for the decontamination and sterilization of foods using very high power and very short duration pulses of light emitted by inert gas flashlamps (Palmieri and Cacacea, 2005). The high power pulses of radiation can be in the spectra of UV, visible (VL) and IR light. PL, in addition to being used for the sterilization of packaging materials and online sterilization of transparent fluids, has also been successfully used for the surface decontamination of foods in plastic packaging. This process has shorter treatment times with concomitantly higher throughput, rendering the process very efficient.

3.3.1 MECHANISMS OF MICROBIAL CONTROL OF PL

UV light exhibits germicidal properties in the wavelength range of 100-280 nm (UV-C region). UV-light energy is thought to have a photochemical, photothermal and/or photophysical impact on microorganisms. Wekhof (2000) summarized that the lethal effect of pulsed UV light is a combination of the germicidal nature of UV-light (photochemical) and cellular disruption caused by local heating (photothermal). It is thought that the constant disturbance caused by the high-energy pulses also induces morphological damages to bacterial cells, ultimately leading to cell wall damage, cytoplasmic membrane shrinkage, cell content leakage, mesosome rupture, and genetic material leakage (Krishnamurthy *et al.* (2010).

3.3.2 APPLICATION OF PL TECHNOLOGY FOR PRE-PACKAGED FOODS

Dunn *et al.* (1995) reported that microbial log reductions of pathogens achieved by PL on relatively simple surfaces are considerably higher than in foods with more complex surface aspects. Indeed, efficient light absorption depends on the distance through which light is passing, the thickness of the product and the thickness of the package. Hillegas and Demirci (2003) demonstrated the effect of product thickness on PL-induced microbial inactivation and showed a significant increase in reduction of *C. sporogenes* spores in clover honey in samples of 2-mm thickness as compared to samples that were four-fold thicker. Similarly, Haughton *et al.* (2011) demonstrated the efficacy of PL to inactivate *Campylobacter* on packaged chicken and also showed an inverse correlation between the microbial reduction and film thickness. Keklik *et al.* (2010) demonstrated the optimal efficacy of pulsed UV light to decontaminate vacuum-packaged boneless chicken breasts for 15 s when placed at a distance of 5 cm from the quartz window in the pulsed UV light chamber. The author reported that the treatment resulted in approximately 2 log reduction in the population of *Salmonella* Typhimurium, with minimal impact on the quality and color of the sample tested. The same author demonstrated that PL was effective in reducing the population of *L. monocytogenes* on vacuum-packaged chicken frankfurters by 1.9 log, although the treatment significantly affected the color parameters of the samples (Keklik *et al.*, 2009). Moreover, the applicability of PL to pasteurize bottled beer has also been demonstrated previously (Palmieri and Cacacea, 2005).

The use of PL to enhance the microbiological quality and extend the shelf-life of foods has also been examined. Shuwaish *et al.* (2000) showed that the application of PL to high-density polyethylene (HDPE) pre-packaged catfish fillets led to a decrease in coliform and psychrotrophic bacterial counts. Dunn *et al.* (1991) previously showed that the application of PL to freshly baked cakes packaged in clear plastic containers resulted in non-detectable molds when stored at ambient temperature for eleven days while their untreated counterparts produced visible molds. Rice (1994) similarly showed that PL can be used to inactivate mold spores and consequently extend the shelf-life of foods, such as packaged sliced white bread and cakes, from a few days to over two weeks. The shelf life of cakes, pizza and bagels wrapped in clear plastic films was also extended to 11 days during storage at ambient temperature following PL treatment (Ohlsson, 2002). Djenane *et al.* (2003) reported that UV irradiated beef steak packaged in PE pouches with modified atmosphere followed by chilled storage at 1°C had an extended shelf-life of 16 days.

3.3.3 LIMITATIONS OF PL TREATMENT FOR PRE-PACKAGED FOODS

The efficiency of PL depends on the degree of exposure and susceptibility of microbes to the treatment. The sterilization of foods is possible as long as the packaging and packaged content is UV transparent; however, because of the opacity and irregular surface topography of most foods, PL is mostly effective for surface decontamination. Microorganisms penetrating into the deep crevices or surface irregularities of food are thus protected from the effects of PL due to the "shadow effect" (Elmnasser *et al.*, 2007). Haughton *et al.* (2010) reported that this "shadowing effect" can be exacerbated with the use of certain packaging materials such as Polyethylene-Polypropylene (PET-PP) and polystyrene (PS). The author mentioned that the porous nature of the polymers can enable bacteria to hide in the package "sub-surface", thereby shielding from UV light. In addition, the efficacy of PL is also limited by the thickness of the film (Haughton *et al.*, 2011). Furthermore, PL also has diminished efficacy on heavily contaminated foods, *i.e.,* products with a high initial load of the target microorganisms due to the shadow effect on the underlying layer of cells (Wuytack *et al.*, 2003).

In addition, researchers have also demonstrated that UV light can interact with the packaging materials yielding undesirable products. UV can cause the package constituents to undergo certain chemical reactions. Materials made of PET are strong UV absorbers and undergo extensive oxidation following UV exposure (Ozen and Floros, 2001). Examples of surface oxidation products formed after treatment of certain plastics include carbonyls, carboxylic acids and hydroperoxides (Peeling and Clark, 1983). Researchers showed that a food solution containing d-limonene had a higher detectable level of oxidation products following contact with a UV-treated PET film. UV-treated LDPE also resulted in detectable amounts of oxidation products in the tested food solution albeit to a lesser extent (Berends, 1996). The higher abundance of oxidation products observed in samples contacted with PET may be attributed to the polar nature of PET, thought to accelerate the oxidation of the film surface during UV-treatment (Berends, 1996). In addition, exposure of a model food solution containing linoleic acid to UV-light-treated PET resulted in significant accumulation of a major oxidation product, hexanal, over time. UV-treated LDPE produced lower amounts of oxidation products compared to PET; although oxidation was still significantly higher than of the samples contacted with untreated LDPE (Peeling and Clark, 1983). These observations are therefore a testament to the need to choose an optimal packaging material to assure the safety and lack of toxicity of the "in-package" UV-treated food. In addition to the effect of UV on the migration properties of plastic films, the mechanical properties of films were also affected after UV treatment. Berends (1996) observed extensive crystallinity in PET film after UV exposure compared to LDPE, which presented limited structural modifications. Polypropylene is a fairly UV-light transmissible polymer, however, it has been reported to be quite sensitive to ultraviolet degradation (Guillard et al., 2010). UV aging caused embrittlement of polypropylene and also negatively affected the mechanical properties of the polymer, including its yield strength and percent elongation.

Another limitation is that local sample heating could be a concern for extended PL treatments lasting longer than 5s (Krishnamurthy *et al.*, 2010). Heat can originate from absorption of light by the food or by the lamp itself. For example when studying the inactivation of *A. niger* spores on corn meal under certain settings, sample temperatures peaked to as high as 120°C, potentially burning the products (Jun *et al.*, 2003). In addition, since UV-treatment can interact with packaging materials and result in the formation of certain oxidation products, foods rich in proteins and lipids are not suitable for decontamination by PL (Elmnasser *et al.*, 2007). Discoloration of the product (Djenane *et al.*, 2003) and/or the packaging material could also occur and should be minimized. Table 2 highlights examples of studies evaluating the efficacy of HHP, irradiation and PL technologies to enhance the safety of packaged foods.

Table 2 Studies investigating the efficacy of nonthermal interventions to improve the safety of packaged foods

Technology	Food matrix	Target microorganism(s)	Outcome	Reference
HHP	Sausage	*Listeria monocytogenes*	6-7 LR	Chung et al. (2005)
HHP	Turkey meat	*Listeria monocytogenes*	3.8 LR	Chen (2007)
HHP	Strained chicken baby food	*Salmonella* Senftenberg 775W	< 2 LR	Metrick et al., (1989)
Irradiation	Minced meat	*Enterobacteriaceae*	4 LR	Farkas and Andrassy (1993)
Irradiation	Fresh catfish fillets	Background microflora	4-fold increase in shelf-life	Przybylski et al. (1989)
Irradiation	Fresh pork	Background microflora	> 2 LR	Lambert et al. (1992)
Irradiation	RTE ham and cheese sandwich	*Staphylococcus aureus*	6.2 LR	Lamb et al. (2002)
Irradiation/antimicrobials	Beef product	*Clostridium botulinum*	> 4.4 LR	Suarez Rebollo et al. (1997)
PL	Raw poultry	*Campylobacter jejuni*	< 4.6 LR	Haughton et al. (2010)
Pulsed UV Light	Chicken breast	*Salmonella* Typhimurium	< 2.4 LR	Keklik et al. (2010)

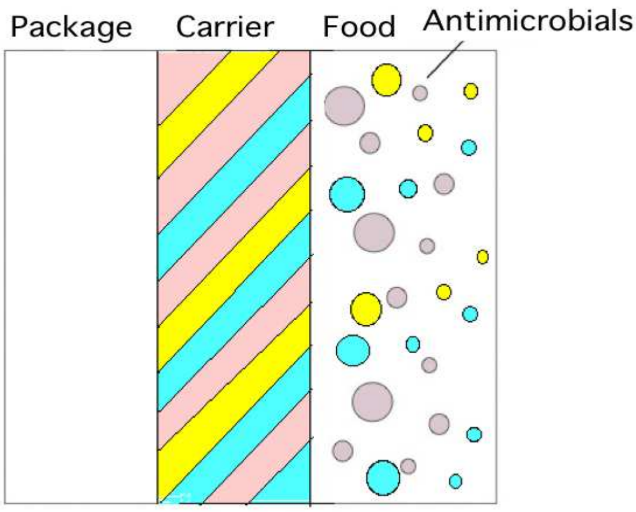
Definition of abbreviations used in table: RTE = Ready-to-eat, LR = Log Reduction

3.4 ACTIVE PACKAGING

Conventional mainstream packaging acts as straightforward food containers to protect, transport and sell the products. Active packaging is more dynamic and is able to sense changes in the environments in the interior and exterior of a package by adjusting properties of the package (Han, 2007).

3.4.1 MECHANISMS OF MICROBIAL CONTROL OF ACTIVE PACKAGING

Active packaging serves as an effective intervention or hurdle to reduce or prevent microbial growth during food storage. This is achieved by: (i) actively or constantly changing permeation properties or the gas composition in the package headspace during storage, or (ii) actively releasing minute concentrations of antimicrobial agents, incorporated or impregnated into the packaging materials, overtime (Hurme *et al.*, 2003). Figure 5, adapted from Han (2003), depicts the structure of a generic antimicrobial package, consisting of a base such as a plastic film coated with a carrier such as methylcellulose into which antimicrobials such as nisin, lyzozyme etc. can be incorporated.



3.4.2 LIMITATIONS OF ACTIVE PACKAGING

Addition of agents to packaging materials may negatively alter the chemical and physical properties of polymers. Critical properties of polymers such as permeability, mechanical strength, color, appearance and gloss, can deteriorate (Han *et al.*, 2004). The incorporation of certain components in the polymer film can also lead to their undesirable migration into food (Lopez-Rubio *et al.*, 2004). Moreover, the use of antimicrobials or other active agents should follow the guidelines of regulatory agencies. Active agents and packaging materials are regarded as food contact substances or food additives and require clear classification prior to commercialization. In addition, consumers may have health-related concerns about active packaging due to the possible interaction between the packaging and the food (Meroni, 2000). Han and Floros (2007) also mentioned that the manufacturing of new packaging systems require procedures of processing different from traditional packaging, which in turn may increase installation costs for establishing new systems, as well as add manufacturing costs to these novel materials.

One of the main drawbacks of MAP is that the resulting shelf-life extension and microbiota suppression may provide ample opportunity for pathogens to grow (Phillips, 1996). Careful monitoring of parameters such as the food matrix and formulation, the pathogen load, and the packaging material itself, as well as storage parameters such as gas composition and storage temperatures are therefore vital. Moreover, to maximize the efficacy of MAP, it is important to use high quality raw materials in conjunction with processing, packaging and distribution under good sanitary and hygienic practices to minimize cross-contamination. A quality assurance system through the implementation of HACCP throughout the production line needs to be established to ensure safety of MAP foods (Sivertsvik *et al*., 2002).

4 CONCLUDING REMARKS

Recalls, largely caused by the transference of pathogens such as *L. monocytogenes* into food products between the final processing step and packaging of perishable foods, have spurred interest in post-packaging decontamination. Improvements to existing designs and development of new technologies for thermal post-packaging applications have included sous-vide processing, microwaving, and RF heating. Non-thermal post-packaging decontamination systems can include high hydrostatic pressure, irradiation, pulsed light technology and active packaging. One can expect continuing research of these technologies in tandem with advances in food packaging materials, given increasing consumer awareness of product safety linked to human health and the potential of economic losses associated with contaminated products. Since non-thermal methods do not incorporate additional exposure of packaged products to elevated temperatures which can further degrade sensory quality and nutrient content, one can easily envision post-packaging decontamination using a non-thermal method, such as HHP, becoming more commonplace in the food industry in order to assure enhanced food safety at a moderate cost.

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