**Novel non thermal food preservation technology: the science and industrial implementation of high pressure, pulsed electric fields and cold plasma.**

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Abstract

From early human developments, various methods of food preservation have been used to increase food availability and safety. Heating has become the main technology used but has many disadvantages. Research has been led into new method of physical preservation of food. This chapter first looks at three promising non-thermal methods before moving on to reviewing the factors affecting the uptake of non-thermal technology by the food industry. The three technologies are high pressure processing (HPP), pulsed electric fields (PEF) and cold plasma (CP). Their overview shows that they are all based on sound science and that each has advantages and limits of application. High pressure processing is the most mature technology with hundreds of applications and established research groups around the world, while pulsed electric fields have little application and cold plasma is at the laboratory stage. The environment influencing the application and implementation of these technologies is looked at. It shows that in addition to the scientific and academic challenges, industrial managers will need to consider many factors when implementing a promising technology. The application of new technologies such as high pressure processing spread from the USA, Japan and Europe to other parts of the world for various food categories. Ultimately, although they may be the ones with the least knowledge about the technology, consumers will be the ones leading to the acceptance or not or the new technology depending on their perception.

Keywords: Non-thermal preservation, high pressure, pulsed electric fields, cold plasma, new technology implementation.

1. Introduction

From early human developments, various methods of food preservation have been used to increase food availability and safety (Hulse, 2004). These methods include for example chilling and drying. With the rise of Napoleonic wars, a need came to preserve food for longer which led to the development of heat processing. The early 20th century saw the development of heat processing further, with the determination of heat resistances of microorganisms and development of heat processes. This has led to an excellent record in food safety and to heat processing being one of the most widespread methods of processing food.

Heat has however many disadvantages. Indeed, various organoleptic properties are modified with changes in colour, texture and flavour occurring. Also, thermal processing leads to vitamin loss and the production of chemicals that may be carcinogens. Chemicals can be added to improve preservation with a reduced heat process, but this is seen negatively by consumers. Hence, research has been led into new methods of physical preservation of food.

Some of these methods concentrated on heat and new ways of generating heat in the product. This is the case with dielectric heating (such as microwave) and ohmic heating. Although these may have positive elements such as fast heating/cooling or better processing of products with particulates, their mechanism still relies on heat and hence has the same disadvantages. This has resulted in active research in new non-thermal preservation technologies. These physical non-thermal methods include for example high pressure, irradiation, pulsed ultra violet light, ultra sound, pulsed electric fields and cold plasma technology. Many of these could lead to high quality products and hence give opportunities for increased market shares.

This chapter will first look at three promising non-thermal methods before moving on to reviewing the factors affecting the uptake of non-thermal technology by the food industry. The three technologies are high pressure processing (HPP), pulsed electric fields (PEF) and cold plasma (CP). These have been chosen as they are at various stages of development and application. High pressure is the most mature technology with hundreds of applications and established research groups around the world, while pulsed electric fields have little application and cold plasma is at the laboratory stage.

1. High pressure processing (HPP)
   1. Development

High pressure processing has been investigated as an alternative to heat processing for many years. As early as the end of the 19th century there was some work demonstrating that some foods could see their shelf life increased under pressure. Indeed, in 1899 Hite demonstrated the possibility of extending the shelf life of liquid products (Huang *et al.*, 2014; Bermúdez-Aguirre and Barbosa-Cánovas, 2011). After the demonstration that vegetative bacterial cells could be inactivated by pressure, further progress was limited by the need to develop the technical capability to reach high pressures safely (Hayashi, 1996). Once this capability was obtained, further work was carried out generating further knowledge in the baroresistance of bacteria and also enzymes. In the 80s and 90s a consortium of Japanese companies led by professor Hayashi accelerated research in high pressure processing (Hayashi, 1996). This led to the first products coming to the market in Japan in 1990 via the company Meydi ya (Hayashi, 1996; Tonello, 2011). This was followed by many other products, as pressure helped in delivering chemical free foods with a ‘fresh’ quality (Welti-Chanes *et al.*, 2004). Since 2000 the number of high pressure processers in manufacturing companies has increased exponentially (Norton and Sun, 2008) with the majority located in the United States (Tonello, 2011). In addition to microbial inactivation, high pressure has also been investigated and used for the modification of various food properties (for examples gelling or allergenic potential reduction) across a range of products (Welti-Chanes *et al.*, 2004). It is estimated that the value of high pressure processed food exceeds US$10 billion (Huang *et al.*, 2014).

* 1. Principles

HPP, up to 800 megapascal (MPa), have been used as a non-thermal food processing method as it can inactivate enzymes and microorganisms (Earnshaw, 1996). Several general principles apply to high pressure processing. Le Chatelier’s principle states that any phenomenon that is accompanied by a decrease in volume is enhanced by pressure (and vice versa). Hence pressure, contrary to heat, can only disrupt weak bonds, such as hydrophobic and electrostatic ones, while leaving covalent bonds unaffected (Balny *et al.*, 1997 ; Lullien-Pellerin and Balny, 2002). This has important implications as vitamin molecules are unaffected after pressure processing of plant based systems, if the temperature is moderate (Oey *et al.*, 2008) while biopolymers, such as proteins, which are stabilised by various intramolecular bonds may be modified by high pressure resulting in functional changes (Messens *et al.*, 1997). The isostatic principle (Balny *et al.,* 1997) means that there is quasi-instantaneous transmission of pressure through the product whatever its shape and size. One element to consider is the compression heat of water (3°C per 100 MPa after Norton and Sun, 2008). This may be significant and be part of the preservation process. Also, there is a small volume change occurring at high pressures (for example 10% at 300 MPa) which leads to a reversible food product deformation. Usually the food structure is maintained but food with high air content, such as strawberries, may be deformed and the technology is not considered appropriate in these cases (Rastogi *et al.*, 2007).

* 1. Technology

Usually, foods are placed pre-packed in a vessel which is then filled with water as the pressure medium (Norton and Sun, 2008). High pressure pumps then inject water to reach the working pressure. Once this is reached, no more energy is needed and pressure release can be near instantaneous through valve opening to allow water release (Nguyen and Balasubramaniam, 2011). Usual processing conditions are 300-600 MPa for 10-20 minutes (Bermúdez-Aguirre and Barbosa-Cánovas, 2011). Come-up times and pressure release times as well as initial/treatment temperature are also important parameters (Norton and Sun, 2008). Liquid foods can be processed in a vessel using a free floating piston separating it from the pressurising water and with post-processing aseptic packaging (Nguyen and Balasubramaniam, 2011).

The packaging material must be flexible in some parts to allow pressure transmission (Norton and Sun, 2008; Rastogi *et al.*, 2007). There are various manufacturers offering industrial equipment in various capacity ranges and pressure capability (Norton and Sun, 2008). These are usually horizontal to allow easy loading and unloading. Vessels can be filled to 75% capacity by using packaging that optimises vessel filling to make the process more economical (Tonello, 2011). Smaller laboratory equipment can be used for research studies (e.g. 2l capacity) (Bermúdez-Aguirre and Barbosa-Cánovas, 2011).

* 1. Microbial effects

The effect on microorganisms depends on various intrinsic and extrinsic factors such as microorganism type/physiological state, time, pressure, temperature and physico-chemical properties of environment (Rendueles, *et al.*, 2011; Huang *et al.*, 2014). Usually, Gram positive bacteria are more resistant to pressure than Gram negative ones and cells in the stationary phase are more resistant than those in the exponential phase (Rendueles *et al.*, 2011). Cocci are more resistant than bacilli (Huang *et al.*, 2014). From 50 MPa, protein synthesis in inhibited while pressures higher than 200 MPa cause protein denaturation and membrane permeabilisation. Higher pressures still (>300 MPa) results in irreversible protein and enzyme denaturation (Huang *et al.*, 2014). For yeast cells like *Saccharomyces cerevisae* pressures above 400 MPa led to organelles structures deformation and loss of intracellular material (Welti-Chanes *et al.*, 2004). HPP application must be based on an understanding of the bacterial effects of pressure during and after processing on identified pathogenic marker organisms in order to produce safe food (Huang *et al.*, 2014). Hence, in order to ensure the safety of HPP treated products, appropriate microbiological targets must be identified for the product considered, for example, *Listeria monocytogenes* for ready-to-eat meat products or *Clostridium botulinum* for low acid shelf stable foods (Rendueles *et al.*, 2011). Bacterial spores have been found to be very resistant to pressure and usually require pressures higher than 800 MPa (Norton and Sun, 2008) or 1000 MPa (Huang *et al.*, 2014) (which are not commercially feasible). Hence, no non-acid high pressure processed food without any additional treatment is available on the market (Huang *et al.*, 2014). Combinations of pressure with temperature (50-70°C) as well as initial pressure induced germination (at 50-300 MPa) and subsequent inactivation with a mild heat process have been successfully used to inactivate bacterial spores. Pressure cycling has also been considered for spore inactivation (Norton and Sun, 2008; Huang *et al.*, 2014).

* 1. Quality effects

As mentioned previously, one of the advantages of high pressure processing is that it does not affect covalent bonds. This means that sensorial and nutritional properties are minimally affected (Oey *et al.*, 2008). However, other factors could lead to changes in nutritional properties through other mechanisms such as oxidation or pressure induced chemical reactions. For example, vitamin C content is affected under pressure through oxidation in the presence of oxygen (Oey *et al.*, 2008). For juice processing, there usually is still better retention than with heat treatment and closer values to the fresh product (Sánchez-Moreno *et al.*, 2011). There is however some evidence that advantages obtained through high pressure processing in terms of nutritional value and sensory quality, when compared to heat treatments, could be lost during subsequent refrigerated storage (García-Parra *et al.*, 2011). When the adiabatic heat of pressure is used to assist pressure sterilisation, the quality of products is higher than when using heat alone. For example, enhanced flavour retention of herbs and texture retention of vegetables have been observed (Matser *et al.*, 2004).

* 1. Applications and future work

High pressure is a technology that is now widely available throughout the world (Norton and Sun, 2008). Pressure treated products include oysters (which are chuckled as well as being made safer through viral inactivation), avocado products (for which browning is reduced due to enzyme inactivation) and many others (Tonello, 2011). The technology however remains expensive and the problem of spore resistance limits potentially wider application. Other possible opportunities to use high pressure at low temperature include, pressure shift freezing and pressure assisted thawing which can lead to higher quality products (Norton and Sun, 2008).

1. Pulsed electric field (PEF)
   1. Development

Initial research in the use of electricity to preserve food dates back to the beginning of the 20th century. By the middle of the 20th century, electrical fields were used to permeabilise fruits to increase juice extraction (Martín-Belloso and Soliva-Fortuny, 2011). Initially, the microbial inactivation was thought to be due to thermal effects but the question of whether the electric current itself had a bactericidal effect started being investigated and was demonstrated in the 1960s. Since then, more work was carried out, especially in the 1990s, defining the parameters and the inactivation effect on various microorganisms (Martín-Belloso and Soliva-Fortuny, 2011). In 1995, The Food and Drug Administration accepted a pulsed electric fields process for antimicrobial treatment of food (Barbosa-Cánovas and Sepúlveda, 2004). Because of its effect on the membrane, PEF can also be used to increase extraction yields or drying rates for example (Muthukumaran *et al.*, 2009).

* 1. Principles

Two electrodes between which the product is placed, or flows, are mounted on nonconductive material to form a chamber. A high-intensity electric pulse is produced in the chamber containing the food product when a high voltage pulse is applied to the electrodes (Martín-Belloso and Soliva-Fortuny, 2011). The mechanism of action on microorganisms is postulated to be due to membrane electroporation leading to loss of ability to maintain homeostasis by the cell. Charges on either side of the membrane apply pressure, as they seek equilibrium, and at a transmembrane potential of 1V the microbial membrane is disrupted (Martín-Belloso and Soliva-Fortuny, 2011). The cell cannot interact with its environment anymore, loses intra-cellular material and dies. The effect on membranes was for example shown by Wooters *et al.* (2001) who observed propidium iodide uptake by cells after PEF treatment. There is little effect on the product quality but there may be problems with electrode material leading to medium electrolysis, deposits or corrosion and transfer into the treated product when stainless steel is used (Martín-Belloso and Soliva-Fortuny, 2011). Alternative materials such as carbon and titanium could therefore be used for the electrode with similar or increased efficiency (Toepfl *et al.*, 2007; Toepfl, 2011).

* 1. Technology

A treatment unit is made of a high voltage pulse generator and a treatment chamber (Wan *et al.*, 2009). Treatment can be batch or continuous depending on the treatment chamber design. Barbosa-Cánovas and Sepúlveda (2004) outline the various considerations needed when designing treatment chambers and PEF systems. The process is however limited to pumpable food. Typical process parameters are field strength (15-50 kV. cm-1), pulse frequency (200-400 Hz), pulse length (2-20sec) and temperature. The pulse characteristics are important for the inactivation of bacteria (Martín-Belloso and Soliva-Fortuny, 2011). After initial pore formation the pulse duration allows the pore expansion and death. Square or exponentially decaying pulses can be used and usually the former are more effective as the intensity level remains high throughout the pulse (Wan *et al.*, 2009). Alternative positive and negative pulses can also be used for both types of pulses. Usually, these are referred to as bi-polar and are more effective in inducing microbial inactivation.

PEF has a thermal effect, so the temperature should be limited to prevent sensory and nutritional changes (Martín-Belloso and Soliva-Fortuny, 2011). Some cells have built in heat exchangers but, as the heat due to PEF is throughout the volume, it is difficult to cool efficiently in practice.

* 1. Microbial effects

The effects on bacteria are limited to vegetative cells. Usually, larger cell like yeasts are more sensitive and for bacteria, Gram-negative species are more sensitive (Wan *et al.*, 2009; Toepfl *et al.*, 2007). Bacteria are also usually more sensitive in the exponential phase of growth. It has also been shown that sub-lethal injury could occur during PEF treatment of apple juice, leading to inactivation during subsequent storage because of the food’s low pH (Garcia *et al.*, 2005). Bacterial spores are resistant and hence, this technology is more applicable to products normally heat pasteurised (acid products or those with low water activity) or for higher pH products with limited refrigerated shelf life (Wouters *et al.*, 2001). Various intrinsic food properties affect the efficiency of PEF (Martín-Belloso and Soliva-Fortuny, 2011). As with other methods, properties like pH or antimicrobial presence influence the inactivation level (Wooters *et al.*, 2001). Physical properties also affect PEF’s effectiveness. For example, low food conductivity increases the level of microbial inactivation (Wouters et al, 2001; Wan et al, 2009). Electric field intensity (as well as treatment time) is one of the most important parameter for microbial inactivation (Martín-Belloso and Soliva-Fortuny, 2011), however it should not be too high as it could lead to dielectric breakdown of the food being processed.

Temperature is also an important parameter influencing PEF effectiveness. Amongst other authors, Toepfl *et al.*, (2007) have shown an increase of *Escherichia coli* sensitivity to PEF’s action from 35˚C to 55˚C. PEF treatment at 60°C and 30kV/cm has been show to allow a 5 log reduction in pathogen in orange juice as required by the US FDA (Sampedro at al., 2013). Above 60°C for a few seconds, the intrinsic PEF thermal effect is the more important element and non-thermal advantages of the treatment are reduced. For example, sensory changes of oranges treated with PEF started when an initial temperature of 61˚C was used (Toepfl, 2011).

* 1. Quality effects

PEF affects protein structure and this can lead to denaturation and changes in functional properties such as foaming capacity and emulsibility, for example (Martín-Belloso and Soliva-Fortuny, 2011). The effects of PEF on enzymes can be as irreversible as those of heat processing even if some are very resistant (Martín-Belloso and Soliva-Fortuny, 2011).

PEF treatment has been shown to be able to inactivate the microflora of orange juice and other products without significant change in sensory properties. In some cases properties such as colour, pH, flavour and vitamin C content were better preserved than with heat processing (Martín-Belloso and Soliva-Fortuny, 2011). PEF treatment of pomegranate juice also led to a similar shelf life as pasteurisation through microbial inactivation and demonstrated good bioactive compound retention (Guo *et al.*, 2014). In terms of sensory properties, the product had the same consumer satisfaction level as unprocessed pomegranate juice and a higher one compared to heat treated juice (Guo *et al.*, 2014). There is evidence that vitamins and other important health related compounds are little affected by PEF (Sánchez Moreno *et al.*, 2011). Hence vitamin C content for example is less reduced than with heat treatment. This advantage is also kept during refrigerated storage post processing. PEF processing has also been shown to increase the bioavailability of lycopene and flavonoids in plants as it permeates membranes ((Sánchez Moreno *et al.*, 2011).

As PEF affects the membrane, there are textural changes, even under conditions insufficient to inactivate microorganisms, which make it not applicable to the preservation of solid products like fish or meat (Martín-Belloso and Soliva-Fortuny, 2011; Toepfl et al, 2006). This effect can however be useful if PEF is used as a pre-treatment in order to enhance other processes’ efficiency such as drying or the extraction of valuable molecules (Martín-Belloso and Soliva-Fortuny, 2011).

* 1. Applications and future work

The first application for fruit juice happened in 2006 in the USA and it is likely that in the future other countries will follow even if that initial application was later closed down due to lack of funds to support wider distribution and the building of a market (Barbosa-Cánovas and Bermúdez-Aguirre, 2011 ; Dunne, 2011). Work is carried out to try and preserve solid food but this technology is mainly used for pumpable foods. Also, more work is needed on scale up of experimental system in order to get reliable data (Martín-Belloso and Soliva-Fortuny, 2011; Toepfl, 2011). In addition, industrial scale applications need validation of the specific equipment used on the specific target microorganism in the food of interest (Wan *et al.*, 2009).

1. Cold plasma (CP)
   1. Development

This is one on the latest novel non-thermal technology being studied in food science laboratories although plasma has been studied for its sterilising properties since the 60s (Misra *et al.*, 2011). Plasma is a neutral ionised gas made of photons, electrons, atoms, free radicals, positive and negative ions that are permanently in interaction (Moreau *et al.*, 2008). A common form of artificially produced plasma is fluorescent or neon light (Wan *et al.*, 2009). Cold plasmas are created at atmospheric or low pressure contrary to thermal plasmas which require high pressures and also higher powers (Misra *et al.*, 2011). Even at its low temperature CP has antimicrobial effect on surfaces and has been used to disinfect medical devices (Niemira and Gutsol, 2011).

* 1. Principles

Energy through various forms (thermal, electric or electromagnetic) can be applied to a gas to convert it to plasma. Plasma is a state of matter distinct from solid, liquid and gas. In this state, collision between gas particles lead to the creation of a high number of electrically charged particles as atoms lose electrons and get positively charged. This leads to a mix of positive and negative charges in the medium (Hati *et al.*, 2012). Free radicals are also produced and this leads to a mix of particles with strong oxidising power that can decompose various compounds (Chen *et al.*, 2010). UV radiation is also produced during the process.

* 1. Technology

There are various ways of creating CP, usually food applications use an electric field. It has been found that the microbial inactivation depended on the applied voltage, flow rate and treatment time. The type of gas being used and pressure has also an impact (Wan *et al.*, 2009). The cold plasma is usually generated at atmospheric pressure but this has a thermal effect. This heat effect can be avoided, and a temperature close to room temperature maintained, by using short pulses (nanoseconds) or low pressures (10 Pa) to reduce the gas density and hence probability of particle collision and hence thermal effects (Wan *et al.*, 2009). There are distinctions made whether the plasma is remotely generated and then guided onto the surface to treat, generated close to the surface to treat or whether the surface to treat is in close contact with one of the electrodes (Niemira and Gutsol, 2011).

* 1. Microbial effects

The comparison between different studies is difficult as various equipment designs and ways of creating the plasma are used (Wan *et al.*, 2009). However, there is evidence that CP can inactivate both vegetative cells and spores. Log reductions of 1-7 have been reported in the literature with treatment times usually less than 1 minute. For example, *Escherichia coli* was destroyed by 5 Log in 30 seconds (Niemira and Gutsol, 2011). Gram positive bacteria are usually more resistant than Gram negative ones (Ziuzina *et al.*, 2014). Microbial inactivation occurs through chemical reactions of cell membrane with reactive particles in the plasma and the effect of the parallel UV radiation generation which affects membranes, cellular constituents and DNA (Niemira and Gutsol, 2011). Usually, oxygen plasmas lead to more inactivation and the direct methods are also more effective (Misra *et al.*, 2011). Various products have been treated successfully although this is very product dependent. For example, various pathogens have been inactivated on the surface of tomatoes and strawberries, but the process was less efficient for strawberries because of their irregular surface providing protection against the treatment (Ziuzina *et al.*, 2014). For ready to eat meat, the inactivation of *Listeria innocua* was most successful in products with low water content (Rød *et al.*, 2012).

* 1. Quality effects

The effects on nutritional content and sensory properties need to be investigated further (Misra *et al.*, 2011). For irregular surfaces, such as apples, browning could occur depending on treatment time and intensity (Niemira and Gutsol, 2011). The colour of ready to eat meat was not affected by plasma treatment (Rød *et al.*, 2012). Food with high lipids content will be subject to oxidation potentially leading to odours and off-flavour (Misra *et al.*, 2011).

* 1. Applications and future work

Various food products can be processed. For example, almonds have been treated successfully with little effect on quality. Potential applications also exist for surface equipment, egg surfaces, packaging and water decontamination (Misra *et al.*, 2011).

This technology is still at the laboratory development stage and future work should concentrate on defining better the factors affecting the inactivation of microorganisms and product quality. Synergistic effects with pulsed light could be a possibility for future applications (Misra *et al.*, 2011).

1. New technology dissemination

Among the novel technologies covered in this chapter, several stages of development and application are apparent. High pressure processing has seen new products coming to the market, while PEF still has to demonstrate commercial success even if industrial equipment is available. CP is still at the research stage and will probably not reach industrial food applications for many years. Even when the research in a new technology is mature, the advantages it offers do not necessarily translate in a successful product in the market-place (Nielsen *et al.*, 2009). The following sections will look at non-thermal technology from an academic, industrial manager and consumer point of view. Emphasis will be given to the non-thermal technologies included in this chapter where data are available. A global perspective will be adopted and differences in views of the technologies from different countries will be highlighted throughout where possible.

* 1. Academic perspective

Food scientists are excited by the progress of science and by the development of new technologies. Academic research in new methods of preservation is as exciting as it is multidisciplinary. These disciplines include for example microbiology, chemistry, physics, sensory analysis and human nutrition as well as mathematics, unsurprisingly attracting the attention of scientists. However, just being interesting is not sufficient for research to start in a given technology. Research and development in new technology is expensive and is mainly carried out by universities through government funding or funding via major manufacturers in developed countries. In countries such as the UK and Australia, research institutes are also part of the landscape. Hence research projects can involve Campden BRI or Leatherhead Food International in the UK or Food Science Australia in Australia with scientists from universities and companies (Yannakou, 2011). However, the new technologies rapidly spread through the globe as their scientific and technical base become more defined and equipment costs are reduced.

A search on the web of science searching for “high pressure processing” in the article title for the period 1995-2000 gave 34 records with the top 10 being the USA, England, Germany, Belgium, Canada, Spain and Australia, France, Italy and the Netherlands. The same search criteria applied for 2010-2015 gave 200 results. The top 10 countries were Spain, the USA, China, Korea, Australia, New Zealand, Mexico, Portugal, Canada and Ireland. This search keyword underestimates the papers published but clearly demonstrates how the number of publications has increased recently as has the geographical spread of the research locations. Initial research mainly being located in developed countries, spreading more globally with time.

A similar result is found for PEF, although a little less noticeable. A search for “pulsed electric field food” yielded 25 results for 2010-2015. The locations were, from top to bottom: Canada, China, Germany, Spain, USA, England, France, Japan, United Arab Emirate and Australia. The same search for 1995-2000 found 20 results from the USA, France, Canada, Netherlands, England, Spain and the Ukraine.

* 1. Managerial perspective

In theory, a technology that increases food quality and hence gives potential for increased market share and high added value products would be welcome by managers in food companies. However, in practice there is usually a long gap between the development of new processing methods and their wider application in the food industry. It took 100 years for HPP and 46 years for PEF for example (Lelieveld, 2011). The food industry is subject to day to day production pressures and the commercial adoption of new technology can be risky and disruptive (Yannakou, 2011). Industrial scientists have the additional job to convince managers to implement the new technologies. Lelieveld (2011) gives advice on how industrial scientists can help themselves in influencing new technology uptake by managers and the following section looks at the key aspects that managers need to understand when considering introducing new technology.

* + 1. Safety and quality

It is rare that a company can implement a technology directly as there may be incomplete data in the published literature. The effects on quality and safety being product specific, the company may have to do specific reviews or additional work to identify knowledge gaps that will allow making the decision of whether or not to implement the technology (Lelieveld, 2011).

The safety aspect cannot be overemphasised and care must be taken when designing new processes as the main aim is to end with a product as safe as when produced through known technology. Hence, work must be carried out to ensure the microorganism needing inactivation is known as this target may be different to traditional processes (Spinak and Larkin, 2011). New potential hazard implication involving the new technology must be anticipated and the technology’s limitations need to be understood. The manufacturer must demonstrate the safety for all units of food produced and show a deep understanding of the technology so that the implication of changes (process, ingredients, maintenance, aging of equipment) are clearly understood (Spinak and Larkin, 2011).

The same scientific approach must be adopted in terms of quality. Even if non-thermal technologies usually impart minimum energy to the food, there is bound to be an effect on various aspects of the foods nutritional and organoleptic quality if the energy was high enough to inactivate microorganisms (Lelieveld, 2011). These must be adequately identified and process optimisation considered to minimise them. For PEF for example, this could be a reduction in pulse frequency and length to minimise effects on quality while still inactivating microorganisms.

* + 1. Scale up

Data must be available to prove that laboratory data can be translated to commercial processes to support scale up. This should be feasible in terms of the science base, costing and timing. Parameters allowing microbial inactivation in a laboratory setting should be demonstrated in larger equipment and equivalent processes defined. For example, PEF treatments translation from laboratory to industrial processing needs a scale up of average power from a few kW to >100 kW and also an increase in product flow rate (Toepfl, 2011). For HPP, the use of silicone oil in laboratory HPP equipment could overestimate the microbial inactivation because of adiabatic heating which is much less important in industrial equipment which uses water as the pressurising medium. Indeed, the heat of compression of water is 3°C/100MPa while it is 20°C/100MPa for silicone oil. This thermal effect could lead to an over-estimation of microbial inactivation in laboratory equipment (Nguyen and Balasubramaniam, 2011).

Costing could increase greatly when translating technology to larger equipment as is the case with high pressure vessels which sees their cost increase with the treated volume. Also, timing of implementation is important. If the market has been identified as ready, any delays of implementation, because of poor scientific understanding of the principles or prohibitive unexpected costs, could lead to delays and failure or to the company giving up implementation (Lelevield, 2011). In addition, there may be other changes required as a consequence of adopting the new technology. These could include new packaging material or an aseptic packing line post-processing (Lelieveld, 2011).

* + 1. Cost

Once a technology is ready to be applied commercially, implementation costs will need to be justified and the business profitability ensured (Lelieveld, 2011).

High pressure processing requires high capital investment which is usually one of the main barriers to its implementation. Also, the running cost will depend on processing pressure/time, product geometry, energy and labour costs. Hence oyster processing at 200-400 MPa requires less costly equipment than guacamole production, for example, which requires 600 MPa (Torres and Velasquez, 2005). Depending on the size of the vessel and on the application, capital costs can be in the range 5000-10000€/L while operating cost are 0.104-0205€/kg (Tonello, 2011).

For PEF, the investment cost is 2-3 million US $ for industrial systems at 5t/h (Toepfl *et al.*, 2006) and the operating cost of liquid product preservation is estimated at 0.01-0.02 €/t (Toepfl, 2011).

Other authors have compared new non-thermal technologies and thermal processing. Capital cost has been estimated for a liquid food at 0.08 ¢/l for thermal pasteurisation, 3.1 ¢/l for HPP (Sampedro *et al.*, 2014) and 1.3 ¢/l for PEF (Sampedro *et al.*, 2013). The cost of production of 1l of orange juice has been estimated at 1.5 ¢ for thermal pasteurisation, 10.7 ¢ for HPP and 3.7 ¢ for PEF ((Sampedro *et al.*, 2013; Sampedro *et al.*, 2014). These new technologies are therefore probably more suitable for high added value products.

Some authors have suggested that CP is more cost effective than chemical sterilisation for medical devices but food applications still need evaluating (Niemira and Gutsol, 2011).

For some new technologies, energy saving may lead to reduced operating costs. Both PEF and HPP can potentially save energy when compared to heat sterilisation as they reduce the cooling energy required (Pereira and Vicente, 2010). Also, HPP requires less water than conventional heat processing (Pardo and Zufía, 2012).

* + 1. Legislation

The regulatory attitude towards the commercial application of the technology is an important factor which managers must consider. For example, various countries have a different stance on HPP products and, after Tonello (2011), this could explain why the United States have 60% of the world’s HPP equipment while Europe has 22%. Indeed, there is no specific regulation for high pressure processed food in the USA. However, the U.S. National advisory Committee on Microbiological Criteria for Foods list HPP as a technology equivalent to heat pasteurisation and the U.S. Food and Drug Administration and U.S. Department of Agriculture have approved the use of high pressure for food (Huang *et al.*, 2014). Meanwhile in Europe, regulations are in place to control these types of products through the novel food regulation (Rendueles *et al.*, 2011; Tonello, 2011; Norton and Sun, 2008). Through this legislation, the manufacturer must not only prove the microbiological safety of the HPP product but also toxicological and allergenic safety. In addition it must prove that there are no negative effects on sensory and nutritional properties and that it is not misleading consumers on perceived value (Tonello, 2011). This is a stringent requirement even for large companies and could limit the technology’s uptake. Even within Europe, these requirements differ as the UK adopts a stance closer to the one in the USA (Tonello, 2011). PEF has had just one application and this followed the U.S. Food and Drug Administration rule stating that new processes for juice pasteurisation must ensure a 5 log reduction of the pathogen of concern (Sampedro et al, 2013).

Consumers are ready to accept risk from products processed through new technology if they are given clear information through the label (Rollin et al., 2011). Irradiated food (and ingredients) in Europe must be labelled hence giving a sense of control to consumers (although some will consider this as a warning). For HPP there is also the difficulty of words choice used. Hence the use of “raw” and “fresh” food, which is not legally defined (Spinner, 2014), may be misleading as the shelf life is increased and the product has clearly been processed. Processors will usually add information on the label regarding the new technology to educate customers.

* + 1. Markets

It is important to identify areas where the probability of success is highest (Yannakou, 2011). In terms of products, HPP has been successful with fruit juices, vegetables, ready-to-eat meat products and seafood (Tonello, 2011). For example, there is a successful operation in the USA with the HPP treatment of oysters which led to microbial safety while also shucking the oyster hence leading to a safe, attractive product with less knife injuries (Torres and Velasquez, 2005). Similarly, the same technology found niche application in guacamole production (Torres and Velasquez, 2005). There is also a move to functional food such as HPP bovine colostrum in New Zealand.

As we saw earlier with the analysis of published literature, the research in these new methods is expanding through the world and will certainly lead to a global application. The geographical spread of new non-thermal technology and its industrial application has usually started close to where the research has been carried out. Also, these processes are of higher cost and hence initially predominantly present in the developed world in Europe, North America and Australia. The application of PEF started in the USA as this is where the technology was first developed. It is perhaps surprising therefore that while the first HPP product appeared in Japan where academic research was revitalised in the 80s, the Japanese government is yet to approve HPP as a pasteurisation method (Spinner, 2014). North America has led the way for major HPP implementation followed by Europe (France with fruit juice, and Spain with sliced cooked ham). Today, many more products have appeared in these locations and more are now present in Asia and South America where ready-to eat-meat HPP are strong (Spinner, 2014). China is also developing fast and there remains scope for development even in Europe for example where the German market is probably underdeveloped (Spinner, 2014).

* 1. Consumer perspective

Even if all the elements looked in the previous section are favourable, consumers will ultimately decide whether the new product (and hence process) is successful. Consumers must trust the technology in delivering food that is safe with good organoleptic and nutritional quality. Such trust must be based on the science provided clearly to the public by trusted independent scientists (Bruhn 2011; Siegrist, 2008). Clear labelling must be used as people will be more likely to accept the risk associated with a new technology (Rollin *et al.*, 2011), although it may also be interpreted as a warning signal and may have a negative impact on the food choice (Siegrist, 2008).

Cold plasma is a very new technology for food preservation with little public awareness presently. PEF and HPP are probably the less controversial new technologies especially when compared to irradiation or genetic modification although public awareness may also be low (Frewer *et al.*, 2011). Siegrist (2008) suggests that the main factors affecting new food technology acceptance are perceived risks, perceived benefits and perceived naturalness.

* + 1. Perceived risks

Consumers may be influenced by a positive or negative perception of the technology (Lelieveld, 2004) and the risk perception that is associated (Bruhn, 2011). Cardello *et al.* (2007) found that when consumers considered new technology, perceived risks were of greatest importance while cost was of least importance. In that study with US military personal, laboratory employees and mall shoppers, PEF and HPP were positively regarded while irradiation and genetic modification had the most negative perception (Cardello *et al.*, 2007). There seems to be a more positive attitude to HPP than to PEF because of the technology’s name (Frewer *et al.*, 2011). However, a study with Chinese consumers found that both HPP and PEF were perceived as too complicated and there were especially negative feelings about PEF (Lee et al., 2015). In one study with Northern and Easter European consumers, PEF was perceived more negatively due to its association with irradiation and electricity (Nielsen *et al.*, 2009). In another European study, it was found that the use of an alternative name such as micropulse treatment instead of PEF had a positive impact on consumers’ perception of the technology (Jaeger et al., 2014). HPP was however still judged more positively than both micropulse and PEF. In a study in the USA, HPP was also well perceived by consumers and was not considered different to heat pasteurisation (Cardello *et al.*, 2007).

Lack of knowledge will constitute a barrier to a given technology’s acceptance although increased knowledge does not necessarily increase positive attitudes towards it (Rollin *et al.*, 2011). Irradiation has been shown to be safe and effective but consumer perception has prevented the technology from being widely used as a method of food preservation (Rollin *et al.*, 2011). However, it has been shown that irradiated foods were well accepted when consumers were given information about the benefits and the technology (Bruhn, 2011; Rollin *et al.*, 2011). The level of information needed could vary as Chinese customers required more information compared to Europeans for HPP and PEF (Lee et al., 2015).

* + 1. Perceived benefits

Consumers will develop preferences on complex processing technologies even though they have limited knowledge of these (Nielsen *et al.*, 2009). They may reject technologies perceived to give little personal benefit while having a high degree of uncertainty like irradiation or GM foods (Frewer *et al.*, 2011). This is especially true if the benefits are mainly considered to be on the manufacturer’s side (Nielsen *et al.*, 2009). The main product benefit leading to the acceptance of a new technology is flavour (Bruhn, 2011; Cardello *et al.*, 2007). The vitamin content and high nutritional value of PEF and HPP products have also been identified as positive elements (Cardello *et al.*, 2007; Nielsen *et al.*, 2009). However, although consumers will put nutrition and health as an important factor in leading to the acceptance of a product, repeat purchases will only occur for products that also have good taste (Bruhn, 2011). This can be geographically dependent. For example, French consumer’s drive for purchasing high pressure processed foods is taste while it is health related for German consumers (Bruhn, 2011). Other customers may value other advantages. Chinese consumers who initially chose heat treatment as their preferred option changed to HPP or PEF when detailed information about the technologies was given and they realised no chemical additives were present (Lee et al., 2015).

Consumers seem to be ready to pay more for increased convenience and higher quality, making the initial investment worthwhile and sustainable (Norton and Sun DATE). Chinese consumers have been shown to be ready to pay a higher price hence indicating that they perceived the products as being value-added (Lee et al., 2015). This has also been shown for PEF and HPP treated baby food for which European consumers were ready to pay a high price as this was linked to higher quality (Nielsen *et al.*, 2009). However, this is product dependent as the same studies found that the high cost of PEF and HPP treated juices had a negative effect (Nielsen *et al.*, 2009).

Sampedro *et al.* (2014) found that both PEF and HPP generated more equivalent CO2 emissions than heat pasteurisation because of the higher electricity consumption. However, novel technologies such as HPP and PEF also have the potential to decrease energy use and waste production. This can be a positive element for consumers (Toepfl *et al.*, 2006) as environmental friendliness has been identified as an important positive element by focus groups studies for example (Nielsen *et al.*, 2009). Trust in the technology and information must be present though. For example in Europe, North European seem more sceptical of HHP and PEF environmental benefits than Eastern Europeans (Nielsen et al., 2009).

* + 1. Perceived naturalness

All these technologies are physical transformations and it is thought consumers rate products processed this way as having their natural characteristic less reduced than when subjected to chemical transformation (Siegrist, 2008). However, even with physical processing consumers will view the product negatively if it appears over processed. Lee et al. (2015) found that Chinese consumers made negative links between processing and product’s freshness and naturalness. In Europe, the extended shelf life of HPP and PEF treated juice was seen negatively by northern European consumers as this gives the idea of a highly processed food (Nielsen *et al.*, 2009). The same study found that this did not worry Eastern European consumers as much, probably because they are used to long shelf lives.

Scientists and manufacturers usually refer to these new non-thermal processed products as “minimally processed” referring to the fact that the product is closer to its natural state and has retained nutritional and sensory characteristics. However, even this denomination, considered by the manufacturer as positive, can be perceived negatively if this implies for the consumer that the food hasn’t been processed enough and may pose a safety concern (Cardello *et al.*, 2007).

1. Concluding remarks

There are many new non-thermal technologies and this chapter has looked at three in particular. The three technologies looked at are based on sound technical and scientific knowledge but we have seen that each present limitations in their safety and quality effects on the product. This limits their application and in addition other barriers at the manufacturer and consumer level can prevent the technologies from reaching an industrial application. Hence, the implementation of most of these technologies will probably remain niche and product specific in the future. Future work will look at understanding more these technologies and at finding more applications. There are also opportunities to combine various non-thermal technologies in order to solve drawbacks from the use of a single technology. These hurdle methods could lead to new high quality high added value products that will increase consumer choice.

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