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Effect of high pressure processing of food characteristics: a review of quality aspect

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Abstract

To achieve the balance between food quality and safety, there is a need to optimize conventional processing techniques currently applied in food industries and to develop novel processing techniques such as high-pressure (HP) processing. HP processing is a unique technology compared to other food processing technologies as pressure can result in enhancement or retardation of chemical and biochemical reactions as well as in both desired and undesired modification of biopolymers (e.g. enzyme (in)activation, gel formation).This paper focuses specifically on the effects of HP treatment on colour, flavour and texture of foods and tries to elucidate the mechanisms behind the observed changes in quality attributes.

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Introduction

Colour, flavour and texture are important quality characteristics of fruits and vegetables and major factors affecting sensory perception and consumer acceptance of foods. High hydrostatic pressure processing (HPP) is an emerging nonthermal technology that can ensure the same level of food safety as heat pasteurization and produces fresher-tasting, minimally processed foods. This technology reportedly increases shelf life, while minimizing loss of quality. Additionally, it maintains the nutritional value and quality of food and therefore does not result in any undesirable changes associated with thermal processing (Ghasemkhani *et al*., 2014; Chiao *et al*., 2014). Various processing methods are used not only to increase the edibility and palatability of fruits and vegetables but also to prolong their shelf life. Possible impacts of HP treatments at elevated temperatures on sensory properties are highlighted since the temperature regime used for research on high pressure (HP) has been extended to elevated temperatures in order to achieve spore inactivation (e.g. HP sterilization) (Oey *et al*., 2008).

With non-thermal processing technologies, more fresh-like products can be obtained. HHP is considered to be an alternative to thermal pasteurization for fruit juices and other products when this process is used alone or in combination with traditional techniques. The major benefit of pressure is its immediate and uniform effect throughout different media, avoiding difficulties such as nonstationary conditions typical for convection and conduction processes (Ghasemkhani *et al*., 2014).

Colour, flavour and texture are important quality characteristics of fruits and vegetables and major factors affecting sensory perception and consumer acceptance of foods. HP processing could preserve nutritional value (Oey *et al*., 2007) and the delicate sensory properties of fruits and vegetables due to its limited effect on the covalent bonds of low molecular-mass compounds such as colour and flavour compounds. However, food is a complex system and the compounds responsible for sensory properties coexist with enzymes, metal ions, etc. During HP processing, different pressure and temperature combinations can be used to achieve desired effects on texture, colour and flavour of foods. Covalent bonds in food are usually less affected during HPP, because the compression energy involved is low. Pressure alters interatomic distances, acting mainly on weak interactions in which bond energy is distance-dependent, such as van der Vaals forces, electrostatic forces, hydrogen bonding and hydrophobic interactions of proteins. However, these effects on hydrogen bonding and hydrophobic interaction are complicated depending on the structural properties of the considered compounds (Ilce Gabriela *et al*., 2014). The quality of HP processed fruits and vegetables can, however, change during storage due to coexisting chemical reactions, such as oxidation, and biochemical reactions when endogenous enzymes or microorganisms are incompletely inactivated (Oey *et al*., 2008).

An overview of different publications dealing with quality considerations of fresh and processed meat products is given in Table 1.

The current article aims at giving a thorough overview of the most recent findings specifically on how HP processing affects the quality of foods.

The effect of HP processing on flavour

Any changes in the compounds responsible for the sourness, sweetness, bitterness or odour of fruits and vegetables may result in changes in their flavour. Flavour is the sensory impression of a food that is determined mainly by the chemical senses of taste and smell. Chiao *et al*., (2014) evaluated the effects of high-pressure treatment on microbial growth and production of off-flavor compounds in raw octopus during 16 days of refrigerated storage. Chopped raw octopus samples were treated at 150, 300, 450, and 600 MPa for 6 min using high-pressure laboratory food processing equipment. The number of psychrotrophic bacteria on day 16 was reduced by 0.1, 0.5, 1.3, and 2.8 CFU/g after pressure treatment at 150, 300, 450, and 600 MPa, respectively, as compared with control group. The amounts of trimethylamine (TMA) and dimethylamine (DMA) produced in the chopped raw octopus treated at 600 MPa was significantly reduced as compared to the levels in the control. The production of biogenic amines (BAs) increased up to 1.82 mg/g in the control after 12 days of refrigerated storage, while the BA levels in the 450 MPa- and 600 MPa-treated octopus were 1.40 and 1.35 mg/g, respectively. High-pressure treatment is a promising alternative technology for extending the shelf life of raw octopus.

Table 1. Compilation of studies on the effect of HPP on the quality characteristics of meat and meat products (Bajo *et al.*, 2012).

Product	Processing conditions	Main effects
Fresh meat		
Chicken breast fillet	300, 450 and 600 MPa, 5 min, 15 °C	600 MPa inactivated *E. coli*, *S. typhimurium* and *L. monocytogenes* below detectable levels. Increased pressure levels increased the cooking loss and the colour by increasing L*, a*, b* values. Increased pressure increased hardness, cohesiveness, gumminess and chewiness. Pressure level at 450 MPa induced lipid oxidation. Volatile basic nitrogen values (VBN) were significantly reduced. A semi-trained sensory panel found that chicken breast treated with 450 MPa gave the lowest aroma strength.
Chicken breast fillet	300 MPa, 5 min, 20 °C in combination with liquid antimicrobial edible coating and MAP packaging.	The combination of antimicrobial coating and HPP in MAP packaging exhibit a strongly synergistic interaction extending the shelf-life up to 28 days. The sensory attributes, color, tenderness and overall acceptability were maintained during storage.
Turkey breast	50-300 MPa, for 0.1 s and 1, 2, 3, 5, 10 and 15 min at 25 °C.	HPP could be used as a processing aid in enhancing salt diffusion into turkey breast. Diffusion coefficient of NaCl infusing into the meat was maximum at 150 MPa. Treatment at 150 MPa resulted in turkey breast with minimum hardness, gumminess and chewiness.
Pork (*M. longissimus dorsi*), and chicken and turkey (pieces of meat)	0.1 MPa-600 MPa, for 1 min at 5 °C,	Increasing cohesiveness with increasing pressure was observed, reaching maximum at 400 MPa. Further increase in pressure resulted in declining cohesiveness at 500 and 600 MPa. Minimum color changes were observed till 200 MPa. With increasing pressure, L*-values decreased. Changes in color were more depending on the applied pressure than on the holding time.
Beef (*M. pectoralis profundus*)	200, 300 and 400 MPa, for 20 min at 20 and 40 °C,	Lower pressure levels of 200 MPa minimally affect meat quality parameters. Increasing the pressure level and temperature level increased the cook loss, lipid oxidation and alter the color. Pressure did not alter the ratio of polyunsaturated/saturated fatty acid (PUFA/SFA), but increasing the temperature affected the sum higher saturated, monounsaturated and polyunsaturated fatty acids.
Beef	500-600 MPa, for 20-300 s, at 10 °C	HPP treatment resulted in a 1 week delay of microbial growth (520 MPa, 260 s). Pressure intensity was more significant than holding time for redness, total color difference and metmyoglobin content. Pressure higher than 300 MPa induces modifications of meat color parameters.
Pork (pre-rigor)	215 MPa, 15 s, at 33 °C	HPP partially inhibited post mortem metabolism, resulting in improved cook and drip loss compared to non-treated meat. HPP increased the lipid oxidation slightly and HPP treatment caused lighter products. Tenderness was improved. Myofibrillar solubility was decreased resulting in decreased functionality relying on protein- protein bind in further processed pork products produced with the HPP treated meat compared to the untreated.
Turkey meat (PSE-like)	50, 100, 150 and 200 MPa, for 5 min at 4 °C	HPP treatment with 50 and 100 MPa increased the water holding capacity (WHC) close to the level of normal meat. Low pressure levels of 50 and 100 MPa increased the total protein solubility of low and normal pH meat and showed better gel forming ability.
Chicken breast	600 MPa, for 2 min at 20 °C	HPP treatment alone gave a <3.3 log reduction of *L. monocytogenes* in cooked chicken. 2% Na lactate + HPP kept *Listeria* numbers below 50 CFU g^{-1} throughout storage.
Processed meat		
Cooked ham	400 MPa or 600 MPa, for 10 min at 22 °C	HPP inhibit the major bacterial populations in vacuum -packed cooked ham over a storage time of 90 days. *Weissella viridescens* and

The human tongue can distinguish only among five distinct qualities of taste, of which sourness, sweetness and bitterness are the most important ones regarding the flavour of fruits and vegetables. The human nose, on the other hand, can distinguish among a vast number of volatile compounds, even in minute quantities.

Table 1. (continued) (Bajo *et al.*, 2012).

Product	Processing conditions	Main effects
		Leuconostoc mesenteroides survived HPP treatment and were responsible for the final spoilage.
Dry cured ham	600 MPa, for 5 min at 15 °C and addition of nisin	Depending on the type of dry cured ham inactivation from 1.82 – 3.85 log units for *L. monocytogenes* by HPP was achieved. *L. monocytogenes* was more resistant to HPP treatment at low a_w. Nisin enhanced the high pressure inactivation.
Marinated beef, cooked ham, dry cured ham	600 MPa, for 6 min at 31 °C	HPP treatment at 600 MPa effectively inactivated *L. monocytogenes*, *S. enteritica*, *S. aureus* *Y. entreocolitica* and *Debaryomyces hansenii*. During storage at 4 °C, most of the microorganisms maintained below the detection limit during the storage (4 °C, 120 days).
Genoa salami and pig masseter	483 and 600 MPa 0.5–5 min or 1–12 min, 4.4–35 °C	HPP inactivated *T. spiralis* larvae either at 483 or 600 MPa in infected pig masseter muscle. HPP was effective to control *Listeria monocytogenes*, *E. coli* O157:H7 and *Salmonella* sp. in combination with fermentation and drying in Genoa salami reaching a 5.0 log reduction
Cooked ham	100–700 MPa, include processing time for 10 min at 5–40 °C, with and without addition of caprylic acid and lactate-diacetate	5 log reduction in MAP packed cooked ham could be achieved with ≥ 600 MPa at ≥ 25 °C. HPP treatment delayed the microbial growth to 59 days whereas in combination with antimicrobials it was extended to a minimum of 84 days. HPP treatment had no or little effect on color and sensorial evaluation but increased the drip loss over storage. A negative influence from the antimicrobials on taste was detected.
Dry cured ham	600 MPa, for 6 min at 15 °C	HPP at 600 MPa modified the color of dry cured ham increasing the L*-value. Sensory attributes resulting in an increase in hardness, chewiness, brightness, odor intensity and saltiness. Higher nitrite content was found in pressurized ham during light storage indicating a lower effect of the light as pro-oxidant during 50 days refrigerated storage in HPP treated cured ham.
Cooked ham	400 MPa for 10 min at 17 °C, and in combination with alginate films containing antimicrobials	Use of HPP resulted in the reduction of 3.4 log units of *L. monocytogenes*. Combining antimicrobial films with HPP was effective to achieve a shelf-life of 60 days.
Fermented sausages (low-acid)	400 MPa, 10 min, 17 °C	HPP treatment after fermentation and drying resulted in minor changes in color for chorizo as assessed by a trained panel. No difference for lipid oxidation was found. Increased cohesiveness, chewiness and springiness for HPP treated samples were observed.
Pork Sausages with carrot fibre	500 and 600 MPa, for 1 s, 3, 6 and 9 min at 40, 50 and 60 °C	Addition of carrot fiber improved the emulsion strength and firmness of HPP treated pork sausages. Increase in L* and decrease in a* were reported with increasing pressure level and temperature level.

It is generally assumed that the fresh flavour of fruits and vegetables is not altered by high-pressure processing, since the structure of small molecular flavour compounds is not directly affected by high pressure (Oey *et al.*, 2008). As HP processing can enhance and retard enzymatic and chemical reactions, it could indirectly alter the content of some flavour compounds and disturb the whole balance of flavour composition in fruits and vegetables. As a consequence, HP processing could result in undesired changes in flavour. Hexanal is a volatile compound associated with the smell of foliage and grass. Gas chromatographic studies showed changes in the hexanal content of fruits and vegetables as a result of HP processing. At concentrations lower than about 1.2 mg kg^{-1}, n-hexanal contributes to the typical fresh flavour of tomatoes. Higher concentrations impart a rancid flavour. The increased concentration of n-hexanal was considered to be a result of HP-induced oxidation of free fatty acids, such as linoleic and linolenic acid.

Kyung *et al.*, (2014) investigated the characterization of flavor, physicochemical properties and biological activities of garlic extracts prepared by high hydrostatic pressure (HHP) treatment (500 MPa) was conducted at various HHP reaction times and pH conditions. The evaluation of flavor revealed that HHP treated garlic samples in acidic condition (pH 1.8-3) were most effective to reduce the pungent flavor of garlic among all conditions.The antioxidative, antimicrobial and antitumor activities of HHP treated garlic samples were decreased compared with control. A rapid decrease in antimicrobial and antioxidative activities was observed over 3 min HHP reaction time. No antitumor activities were observed after 3 min HHP reaction time. Up to 56 s HHP reaction time, the alliinase activity was not changed significantly but it was dramatically decreased at a longer HHP reaction time compared with control (P < 0.05), showing higher stability in acidic condition than alkaline condition.

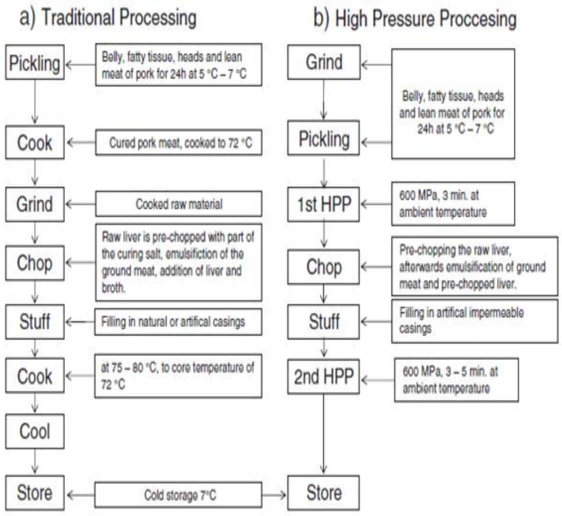

Fig. 1. Comparison of the traditional process (a) and the novel high pressure processing (b) for the production of German liver sausages (Bajo *et al.*, 2012).

Lipoxygenase and hydroperoxide lyase, which are naturally present in tomato, are partly responsible for the development of the rancid taste as they catalyse the oxidation of poly unsaturated fatty acids. At pressures lower than 500 MPa (20 ºC), tomato hydroperoxide lyase is more labile than tomato lipoxygenase, while their stabilities are opposite at pressure 500 MPa (Rodrigo *et al.*, 2007). In diced tomatoes, lipoxygenase activity was reduced by almost 50% as a result of HP treatment at 400 MPa (25 or 45 ºC/1-5 min) and it was very low after treatment at 800 MPa (25 or 45 ºC/1 min) (Shook *et al.*, 2001). Regarding strawberry based food products, HP processing at 800 MPa (20 ºC/20 min) modified the flavour profile of strawberry pure´e (Lambert *et al.*, 1999). Some new compounds were formed, e.g. g-lactone, which correlates with the flavour of peach. The concentration of many volatile compounds contributing to fresh strawberry flavour, such as nerolidol, furaneol, linalool and some ester compounds was significantly lower in the strawberry pure´e processed at 800 MPa (20 ºC/20 min) than in the unprocessed pure´e.

After cold storage (1 day, 4 _C), the concentrations of acids (butanoic acid, 2-methyl-butanoic acid and hexanoic acid) and the ketone compound 2,4,6-heptanetrione of HPtreated (200, 400, 600 or 800 MPa/18-22 ºC/15 min) strawberries were lower than in the untreated strawberries (Zabetakis *et al.*, 2000). The concentration of the alcohol 1,6,10-dodecatrien-3-ol increased in strawberries treated at 800 MPa. Ester compounds belong to the most important flavor compounds in strawberries but the stability of ester compounds during pressure is still under discussion. HP-treated strawberry pure´e differed from heat-treated and unprocessed strawberry pure´e. Cross validation of the electronic nose data showed that heat treatment changed volatile compounds more than high-pressure processing. Corresponding results were reported for similarly processed raspberry and black currant pure´es (Dalmadi *et al.*, 2007).

Baxter *et al.*, (2005) observed no differences in the concentration of volatile flavour compounds between freshly frozen, heat-treated (85 ºC/25 s) or high-pressure-treated (600 MPa/18e20 ºC/60 s) orange juice. The results of the chemical analysis were supported by the results of a trained sensory panel and a consumer panel, which did not remark any differences in odour or flavor between the differently treated orange juices.

Navarro *et al.* (2002) reported that when HP-treated (400 MPa/ambient temperature/ 20 min) strawberry pure´e was stored for 30 days at 4 ºC, increases in the contents of methyl butyrate, mesifurane, 2-methyl-butyric acid, hexanoic acid, ethyl butyrate, ethyl hexanoate, 1-hexanol and linalool were observed.

The flavour of HP-treated basil (two pulses/ 860 MPa/75 ºC and two pulses/700 MPa/85 ºC) was more intense than the aroma of conventionally heat-sterilized, frozen or dried basil. A significant volume of important flavour compounds accumulate in many fruits as non-volatile and flavourless glycoconjugates, which are known as glycosidic aroma precursors.These glycosides can be hydrolysed to volatile aglycones by the action of b-glucosidases, enzymes naturally present in many plants (Pogorzelski and Wilkowska, 2007).

HP processing is a promising preservation method of fruits and vegetables, even though the original fresh sensory properties are not always fully retained. The sensory properties of many HP-treated fruit and vegetable products are still superior to those of products preserved in the traditional way by heat treatment. Regarding flavour, it is difficult to evaluate how HP-induced changes in volatile compounds affect the overall flavour of fruits and vegetables.

Effect of HPP on the inactivation of microorganisms

The basic principles of HPP microbial inactivation are based on protein denaturation which results in enzyme inactivation, and the agglomeration of cellular proteins (Bajo *et al.*, 2012). Moderate level of pressure (10–50 MPa) decreases the rate of growth and reproduction, whereas higher level of pressure causes inactivation (Rademacher, 2006). The cell membrane is constructed as a bi-layer of phospholipids and high pressure causes a phase transition and as a consequence the membrane is destabilized and the permeability is negatively affected. Further, the inactivation could be linked to protein denaturation resulting in the dissolution of membrane bound enzymes. The partial inactivation of enzyme systems by high pressure leads to a breakdown of metabolic actions in biological systems.The protein denaturation depends on such external factors as pH, salt content,water activity (aw) and the presence of other ingredients like sugars (Bajo *et al.*, 2010). Aside from the product parameters, the processing conditions: pressure (P), temperature (T) and time (t) have a decisive importance on the inactivation of living cells. In the high temperature domain, it is generally accepted that pressure and temperature act synergistically on the inactivation of vegetative bacteria (Heinz and Buckow, 2010). For the majority of microorganisms, the highest pressure tolerance is found between 20 and 30 °C. In the case that lower temperatures are applied the stability is decreased (Buckow and Heinz, 2008). Inactivation depends on a number of factors related to the Gram type, physiological state and strain particularities (Jofré *et al.*, 2010). Synergistic effects with HPP have been described with antimicrobials, low pH, carbon dioxide, vacuum packaging and chilled storage (Garriga and Aymerich, 2009).

Katharina *et al.*, (2014) produced a new fermented fish sausage product, based on monkfish. To evaluate food safety, a challenge test was performed, in which the raw materials were inoculated with low levels of Listeria monocytogenes and Salmonella enteric.The product was manufactured, fermented, QDS dried, and half of the samples were pressurized (600 MPa, 5 min, 13 ºC). They monitored pathogens, technological microbiota, spoilage indicator bacteria from fish (hydrogen sulphite producing bacteria, coliforms and Escherichia coli) and physicochemical parameters during manufacturing and after 6, 13, 20 and 27 days of refrigerated storage at 4 and 8 ºC. Their results showed that in the finished product, pathogens and spoilage indicator bacteria could not grow but decreased and E. coli was not detected during storage. Pressurization had an important reducing effect on technological microbiota, and eliminated L. monocytogenes, S. enterica, hydrogen sulphite producing bacteria and coliforms immediately after production and during refrigerated storage.

The effect of HP processing on texture

Due to cell disruption, HP processing facilitates the occurrence of enzymatic and non-enzymatic reactions. Texture changes in fruits and vegetables can be related to transformations in cell wall polymers due to enzymatic and non-enzymatic reactions (Sila *et al.*, 2007). Substrates, ions and enzymes which are located in different compartments in the cells can be liberated and interact with each other during HP treatment. At the same time, pressure can enhance the action of pectin methyl esterase (PME), lower the poly galacturonase (PG) activity (occurring mostly at moderate temperature), and retard b elimination [a reaction where loss of two substituents from adjacent atoms (such as carbon, nitrogen, oxygen) results in the formation of new unsaturated bond] (possibly occurred at elevated temperatures). Different pressure and temperature combinations can be used to activate or inactivate some specific pectinases during processing to create textures, which cannot be formed by thermal processing. Moreover, the use of HP processing can be combined with pretreatments such as infusion of exogenous pectinases (Duvetter *et al.*, 2005) and/ or soaking in calcium chloride solutions (Sila *et al.*, 2006), which can result in increased firmness of the processed fruits and vegetables. HP treatment can disturb the cell permeability of fruits and vegetables, which enables movement of water and metabolites in the cell. The degree of cell disruption is not only dependent on the applied pressure level but also on the type of plant cell. HP processing affects the organization of the parenchyma cells. The plant cells disintegrate and the intercellular spaces are no longer filled with gas (for example in spinach leaf). After HP treatment, cavity formation occurs and a firm texture and a soaked appearance (e.g. cauliflower) are noticed after HP processing. Concerning HP effects on texture of (solid) fruits and vegetables, hardness or firmness is mostly used as a parameter.

Besides increase in hardness, fruits and vegetables such as apple, pear, orange, pineapple, carrot, celery, green pepper and red pepper experienced softening at pressures above 200 MPa (room temperature/5- 60 min) (Basak and Ramaswamy, 1998). At 100 MPa, pear was the most pressure sensitive fruit followed by apple, pineapple and orange, while at 200 MPa, apple was more sensitive than pear. Softening under pressure was also observed for cherry tomatoes (Tangwongchai *et al.*, 2000). Pressures from 200 to 400 MPa (20 °C/20 min) resulted in increased texture damage while pressures greater than 400 MPa (500 and 600 MPa/20 °C/20 min) led to less apparent damage. The softening of cherry tomatoes HP treated at 200-400 MPa may be a result of simultaneous activity of PME and PG, since PG is able to depolymerize pectin that has been demethylated by PME. HP treatment can affect the rheological properties of food products such as crushed fruits and vegetables, pure´e, pulp and juice (Oey *et al.*, 2008).

Ahmed *et al.* (2005) reported that the viscosity of mango pulp increased after HP treatments at 100 or 200 MPa (20 °C/15 or 30 min), while a reduction in viscosity was observed after HP treatments at 300 and 400 MPa (20 °C/15 or 30 min).

In the presence of NaCl (0.8%), the effect of pressure was the opposite the viscosity increased with increasing pressure up to 400 MPa (Plaza *et al.*, 2003).For some fruit juices, cloud stability is an important quality aspect. A shelf-life study on navel orange juice (Polydera *et al.*, 2005) showed that (i) pressure treatment (600 MPa/40 °C/4 min) resulted in a higher viscosity than thermal treatment (80 °C/60 s) and (ii) a limited cloud loss and a small decrease in the viscosity of HP-treated juice were observed during storage (0, 5, 10, 15 or 30 °C for 64 days) even at an elevated storage temperature (30 °C). It is suggested that residual PME activity is responsible for the quality loss of orange juice during storage.

Effect of HPP on the texture of meat and meat products

Low pressures (200 MPa) can tenderize pre-rigor meat, whereas tenderization post-rigor with HPP can only be achieved by higher temperatures (Sun and Holley, 2010). In fresh meat, the application of low pressure levels can be used to improve the functional and rheological properties of turkey meat with low pH or PSE meat (Chan *et al.*, 2011). The influence of HPP on the meat tenderness is depending on the rigor stage, pressure and temperature level applied, and their combination (Sun and Holley, 2010). Meat tenderization by HPP is likely caused by lysosome breakdownand subsequent proteolytic activity release to the medium (Bajo *et al.*, 2012). Prerigor treatment of fresh meat by HPP was shown to be very effective to improve the tenderness of fresh meat. However, the application of HPP at pre-rigor state would require the development of hot boning at slaughterhouses (Rastogi *et al.*, 2007). The application of HPP can be used to improve the water retention properties of raw material used for the production of meat products and as a result to the development of products with reduced salt content (Chan *et al.*, 2011).

The first pressure treatment of raw material is designed to denature myofibrillar proteins and to create the correct product characteristics of consistency and texture, while the second pressure treatment is carried out after the pressurized raw material is emulsified using raw liver in the bowl chopper to increase the shelf-life and to ensure final product characteristics. The comparison of the traditional process and the novel process is shown in Fig. 1. Replacing the two thermal steps results in a significantly smoother and homogenous product with an increased liver-taste as well as significant improvements in time and energy consumptions and nutritional value (Bajo *et al.*, 2012).

The effect of HP processing on colour

Chlorophyll is a green compound found in the leaves and green stems of plants. Chlorophylls a and b have different stabilities towards pressure and temperature. At room temperature, chlorophylls a and b exhibit extreme pressure stability but at temperatures higher than 50 ºC, HP treatment affects their stability for example, a significant reduction in the chlorophyll content of broccoli juice (Butz *et al.*, 2002; Oey *et al.*, 2008). HP treatment (at low and moderate temperatures) has a limited effect on pigments (e.g. chlorophyll, carotenoids, anthocyanins, etc.) responsible for the colour of fruits and vegetables. The colour compounds of HP processed fruits and vegetables can, however, change during storage due to incomplete inactivation of enzymes and microorganisms, which can result in undesired chemical reactions (both enzymatic and non-enzymatic) in the food matrix. The pressure dependency of the degradation rate constant of chlorophyll b at 70 ºC is higher than that of chlorophyll a. For example, elevating pressure from 200 to 800 MPa accelerates the degradation of chlorophyll a and chlorophyll b of broccoli by 19.4% and 68.4%, respectively (Oey *et al.*, 2008). HP treatment at ambient and moderate temperatures results in limited colour change of green vegetables. In many cases, the green colour of vegetables becomes even more intense (decrease in L*, a* and b* values) for example green beans after HP treatment of 500 MPa/ambient temperature/ 1 min (Krebbers *et al.*, 2002). This might be caused by cell disruption during HP treatment resulting in the leakage of chlorophyll into the intercellular space yielding a more intense bright green colour on the vegetable surface. However, at elevated temperature, the green colour shifted visibly to olive-green with a concomitant increase in the a* value. During storage, the green colour of the vegetables HP treated at room temperature turned into a pale yellow colour (decrease in a* value) probably due to chemical reactions such as oxidation. By comparison, the vegetables pressurized at elevated temperatures, which results in inactivation of some enzymes, showed no further colour change during storage (Oey *et al.*, 2008).

Fengxia *et al.*, (2014) used high hydrostatic pressure (HHP, 600 MPa/1 min) and high temperature short time (HTST, 110 °C/8.6 s) treatments of mango nectars were comparatively evaluated by examining their effects on antioxidant activity, antioxidant compounds, color, and browning degree (BD) immediately after treatments and during storage of 16 weeks at 4 and 25 °C. Steam blanching was used prior to HHP and HTST to inactive endogenous enzymes. Their results showed that antioxidant capacity (FRAP assay), L-ascorbic acid, sodium erythorbate, total phenols, total carotenoids, the redness (a*), the yellowness (b*), and BD changed insignificant after HHP or HTST treatment. The lightness (L*) exhibited a significant decrease in HTST-treated mango nectars, while no significant changes in HHP-treated samples. After 16 weeks storage at 4 and 25 °C, there were significant changes in antioxidant activity, antioxidant compounds, color, and BD of mango nectars, whereas differences between HHP- and HTST-treated samples were not significant except for the decrease in L-ascorbic acid and sodium erythorbate, which was more pronounced in HHP-treated samples.

Carotenoids are important for the orangeeyellow and red appearance of fruits and vegetables. Carotenoids are rather pressure stable. HP treatment increases the extraction yields of carotenes from the plant matrix (Ferna´ndez *et al.*, 2001). Pressure-induced isomerization of all-trans lycopene in hexane was observed during HP treatment at 500 and 600 MPa (room temperature/ 12 min). This phenomenon was not, however, observed in food matrices such as in tomato puree (Qiu *et al.*, 2006). The colour of tomato pure´e remained unchanged after HP treatment (up to 700 MPa) at 65 ºC even for 1 h (Rodrigo *et al.*, 2007). Anthocyanins are water-soluble vacuolar flavonoid pigments responsible for the red to blue colour of fruits and vegetables. Anthocyanins are stable during HP treatment at moderate temperature, for example, pelargonidin-3- glucoside and pelargonidin-3-rutinoside in red raspberry (Rubus idaeus) and strawberry (Fragaria x ananassa) during HP treatment at 800 MPa (18-22 ºC/15 min) (Garcia 2004). Anthocyanins in pressure-treated vegetables and fruits were not stable during storage.

Kyung *et al.*, (2014) found that after HHP treatment, the hardness and color values of L*(lightness), a*(redness), and b*(yellowness) of garlic samples decreased, while the cohesiveness value of garlic samples was increased ($P < 0.05$). Besides the instability of colour pigments, browning plays an important role in the discoloration of HP-treated food products. In fruit-based food products, no visual colour differences (based on L*, a* and b* values) are observed immediately after HP treatments. Ahmed *et al.* (2005) observed that colour parameters such as (a/b), C and h values of mango pulps remained constant after HP treatment indicating pigment stability, while increasing pressure intensity decreased the value of DE. During storage, discoloration of pressurized food products occurred during storage (3 ºC) due to enzymatic browning. Colour changes in HP-treated fruits and vegetables can be related to changes in textural properties. This phenomenon was observed in tomato based products. HP treatment (400 MPa/25 ºC/15 min) resulted in an increase in the L* value of tomato pure´e indicating a lightening of the pure´e surface colour.

Effect of HPP on the color of meat and meat products

Studies indicate That HPP provokes drastic changes in freshmeat color,while the changes in curemeat products are acceptable and depending on the water content and aw value. The color of meat depends on the optical properties of the meat surface as well as on the myoglobin content of the muscle. In contrast, the color of cured meat products is mainly created due to the presence of nitrosylmyoglobin, resulting from the reaction of nitric oxide (from sodium nitrite or sodium nitrate) with myoglobin (Ferrini *et al.*, 2012). The effect of HPP on minced beef and concluded that L* color values increased significantly in the pressure range 200–350MPa, giving themeat a pink color, while a* values decreased at 400–500MPa, resulting in a gray-brown color (Carlez *et al.*, 1995).

High pressure caused dramatic changes in the color of fresh meat and thus makes difficult the commercialization of HPP freshmeats since they lack the typical color of freshmeat from the consumer's perspective (Bajo *et al.*, 2012). By keeping the ratio oxy- to deoxymyoglobin low before pressurization aminor conversion to ferricmyoglobin was observed in amodel system (Wackerbarth *et al.*, 2009).

Studies on cured meat products reported an increase in lightness and a decrease in redness when products are pressurized. But Ferrini *et al.* (2012) showed that the changes in lightness and redness were dependent on the water content of the meat products. HPP treatment increased L* and reduced a* and b* in raw cured hams with high water contents. The HPP treatment had negligible effect on the raw cured hams with low water contents. Bak *et al.*, (2012) showed that pork meat treated above 300 MPa became significantly less red and more yellow within the first day of storage. This fact was explained by the formation of a short lived ferrohemochrome myoglobin specie which is transformed into a brown, ferric form of the pigment within the first day of storage.

Conclusions

Elucidation of the HP effects on sensory properties of food products such as colour, flavour and texture is not that straightforward due to the presence of various enzymatic and chemical reactions both during processing and storage. The effect of HP treatment on sensory properties cannot be generalized since study on basic insight in this subject is still limited and sensory property is product dependent. At elevated temperatures, the effects of pressure- enhanced chemical reactions on sensory properties could give additional contributions to the effects of pressure-induced enzymatic reactions and inactivation. Two major concerns regarding meat quality, safety and tenderness, can be addressed by applying pressure either in a hydrostatic. HPP is a well-known method to enable the control of pathogenic and spoilage microorganisms in meat products. HPP induced changes to the color quality depending on the content of myoglobin and those are more significant for fresh red meat than for white meat and cured meat products. Undesired changes can be limited by changing the process parameters such as pressure, time and temperature.

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