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Review

Advantages of high pressure sterilisation on quality of food products

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High pressure processing can be used for sterilisation of food products if applied at elevated temperatures and using the temperature increase due to adiabatic compression. By choosing the appropriate process conditions, it is possible to completely inactivate both vegetative cells and microbial spores resulting in food products that are shelf stable. The quality of high pressure sterilised products is usually superior to conventionally heat sterilised products. This applies particularly to texture, flavour and retention of nutrients. The effect of high-pressure sterilisation on colour is product dependent. This varies between a full retention of the fresh colour and the same colour change as obtained by conventional techniques.

Introduction

To extend the shelf life of food products, processing, such as freezing, drying, pasteurisation, or sterilisation, is often necessary. Traditional heating methods for preservation of products treated in a can or bottle have the disadvantage of a slow heating and cooling rate. This adversely affects product quality. Food scientists and the food industry are therefore searching for novel methods that may destroy undesired micro-organisms with less adverse effects on product quality. One of the solutions may be high pressure processing. Currently this method is successfully applied on a commercial scale for pasteurisation of a whole range of food products, for example fruit juices, guacamole, oysters and ham. At ambient temperatures, application of pressures in the range of 400–600 MPa inactivate vegetative micro-organisms and reduce the activity of enzymes resulting in a pasteurised product, which can be stored for a considerable time at 4–6°C (Cheftel, 1995). High-pressure inactivation of vegetative micro-organisms is caused by membrane damage, protein denaturation and decrease of intracellular pH, suggesting that pressure results in deactivation of membrane-bound enzymes associated with efflux of protons (Smelt, 1998). Inactivation of vegetative micro-organisms and enzymes, combined with retention of small molecules responsible for taste and colour and many vitamins, results in high pressure pasteurised products with a prolonged shelf life and fresh characteristics.

A recent innovation in sterilisation of food products by high pressure, is the complete inactivation of vegetative micro-organisms, as well as spores, resulting in ambient stable products (Meyer, Cooper, Knorr, & Lelieveld, 2000). In general sterilisation with high pressure is possible by starting high pressure treatment at elevated temperatures e.g. 60–90°C, and using the adiabatic compression for rapid heating to higher temperatures. High pressure sterilisation is a combined process where both pressure and temperature contribute to sterilisation by the inactivation of spores and enzymes. The result is a shelf stable product, and in many cases a higher general quality than those products obtained using conventional processing (Hoogland, De Heij, & Van Schepdael, 2001).

This paper describes the techniques and prerequisites for high pressure sterilisation and illustrates that a

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sterilisation process is indeed feasible. The main effects of high pressure sterilisation on food quality are described, proving that for a range of products, high pressuresterilisation results in better retention of the qualities associated with freshness compared to conventional techniques combined with a comparable shelf life.

High pressure sterilisation

By careful selection of pressure, temperature and treatment time and use of the adiabatic temperature rise, it is possible to sterilise with high pressure. Hayakawa, Kanno, Tomita, and Fujio (1994) have previously described how *Bacillus stearothermophilus* spores can be inactivated with an oscillatory pressure treatment at 600 MPa and 70°C. Following this publication, several patents and publications appeared concerning high pressure sterilisation. These are described below. The main difference with high pressure pasteurisation is the use of elevated temperatures. For high pressure sterilisation the following parameters are important:

- initial temperature of product, vessel and pressure liquid
- pressure used
- temperature during pressure treatment: due to the adiabatic heating the temperature rises but subsequent cooling can occur at the vessel wall
- treatment time
- number of cycles.

Meyer (2000) reported sterilisation in low-acid foods by applying a high pressure process with two or more pulses and an initial product temperature of at least 70°C. During pressure treatment, this temperature increases up to 105°C resulting in sterility in macaroni and cheese with an initial 10^6/g spore load of *Clostridium sporogenes*. Hirsch (2000) described a high pressure sterilisation process using one, relatively low pressure treatment of at least 70 MPa for more than 12 h. Examples described are the sterilisation of fruit, milk, cheese and orange juice by pressurising at 175 MPa for 5–8 days at ambient temperature (18–23°C). Wilson and Baker (2000) described another process. They used a single high pressure pulse, combined with a high initial product temperature. Sterilisation of meat, inoculated with spores of *Clostridium sporogenes*, *Bacillus subtilus* and *Bacillus stearothermophilus*, was achieved by a high pressure treatment at 621 MPa for 5 min at a starting temperature of 98°C with an initial spore concentration of 10^7–10^{13} spores/ml. The above examples illustrate that there are several possible methods for sterilisation using a high pressure treatment. The methods described by Meyer (2000) and Wilson and Baker (2000) are commercially the most interesting due to the relatively short treatment times.

Sterilisation with high pressure is interesting due to the combined effect of pressure and temperature resulting in adiabatic heating, the uniform temperature distribution, and the relatively short treatment times. Adiabatic heating is the uniform temperature rise within the product, which is solely caused by pressurisation. The magnitude of the temperature rise is determined by the initial product temperature and the material properties of the product by the following equation (Hoogland *et al.*, 2001):

$$\frac{dT}{dp} = \frac{\alpha T}{\rho C_p}$$

T temperature (K)
p pressure (Pa)
α volumetric expansion coefficient (1/K)
ρ density (kg/m^3)
C_p specific heat (J/kgK)

This equation describes the increase in temperature due to pressure treatment. However, for most (food) materials the material properties are not known, especially because these properties are a function of pressure and temperature. However, for water and some oils and alcohols, these properties are published. Table 1 gives the temperature change for a range of substances (Ting, Balasubramaniam, & Raghuber, 2002).

Adiabatic heating results in homogeneous heating of the product. This is a clear advantage of high pressure sterilisation compared to conventional heat sterilisation. However, as described by De Heij, Schepdael, Van Den Berg, and Bartels (2002) and Ting *et al.* (2002), in standard steel vessels, the vessel wall has a much smaller increase in temperature than the treated product. This results in cooling of the product near the vessel wall during the retention time of the pressure. Small temperature differences may have significant effects on the inactivation rate of spores. Therefore, calculation of the

Table 1. Temperature change due to adiabatic compression for selected substances (Ting *et al.* 2002)

Substance at 25°C	Temperature change per 100 MPa (°C)
Water	~3.0
Mashed potato	~3.0
Orange juice	~3.0
Tomato salsa	~3.0
2% Fat milk	~3.0
Salmon	~3.2
Chicken fat	~4.5
Water/glycol (50/50)	From 4.8 to <3.7[a]
Beef fat	~6.3
Olive oil	From 8.7 to <6.3[a]
Soy oil	From 9.1 to <6.2[a]

[a] Substances exhibited decreasing T as pressure increased.

temperature distribution of the product as a function of time and position in the vessel is necessary to aid process and equipment design (De Heij *et al*., 2002).

When comparing the temperature profile of high pressure sterilisation with conventional techniques (see Fig. 1), it is clear that high pressure sterilisation results in a shorter treatment time and a lower maximum temperature of the product. The time-temperature integration (the area below the temperature curve) of the high pressure treatment is much smaller than that of the conventional treatment. Due to the pressure, the maximum temperature during treatment can be reduced by roughly 10°C compared to a treatment at atmospheric pressure. It may be expected that this milder heat treatment has a positive effect on product characteristics which are more susceptible to heat. The main process advantages of high pressure sterilisation of canned products compared to conventional techniques are therefore shorter treatment times, lower maximum temperatures, faster heating and cooling, and a more uniform radial temperature distribution.

Microbiology

As shown above, several process conditions are described that can achieve products that are sterilised with high pressure. For application of these processes, two important questions have to be answered. The first one is to prove that indeed sterility of the product is achieved and that the high pressure sterilisation process results in complete inactivation of all vegetative cells and spores. The second question is how does the quality of the food after high pressure processing compare to conventional heat treated food? Regarding the inactivation of micro-organisms, Meyer *et al*. (2000) described how commercial sterilisation can be achieved by a two pulse process (pulse length 1 min, interval time 30 s) at pressure and initial temperature conditions described in Table 2. The results are based on food products being inoculated with 10^6 spores/ g food product. The spores used were *B. subtilus*, *B. cereus*, *B. stearothermophilus*, and *C. sporogenes*. This table shows that increasing the pressure means that the initial product temperature can be lowered. This may have a positive effect on food product components that are heat labile. Table 3 shows the results of a high pressure sterilisation process with two pulses at 90°C and 700 MPa for a range of food products with naturally present micro-organisms, clearly showing that this process inactivated the vegetative cells and spores present in these products.

Various authors have reported the effect of a combination of high pressure and elevated temperature on the inactivation of spores. Rovere *et al*. (1999) showed that inactivation of *Clostridium sporogenes* spores is commercially possible by applying pressures of 600–800 MPa at temperatures above 100 °C during pressure treatment°. Reddy *et al*. (1999) reported a 5 log reduction of *Clostridium botulinum* type E spores after processing at 827 MPa and a final processing temperature of 50 or 55°C. The effect of pressures up to 400 MPa and a range of temperatures are described for *B. subtilis*, *B. stearothermophilus*, *B. coagulans* and *C. sporogenes* spores (Okazaki, Kakugawa, Yoneda, & Suzuki, 2000). These papers showed that by careful selection of pressure and temperature inactivation of spores is indeed possible.

In contrast to conventional batch sterilisation processes, during high pressure sterilisation the coldest spot is near the vessel wall. This is caused by heat loss taking

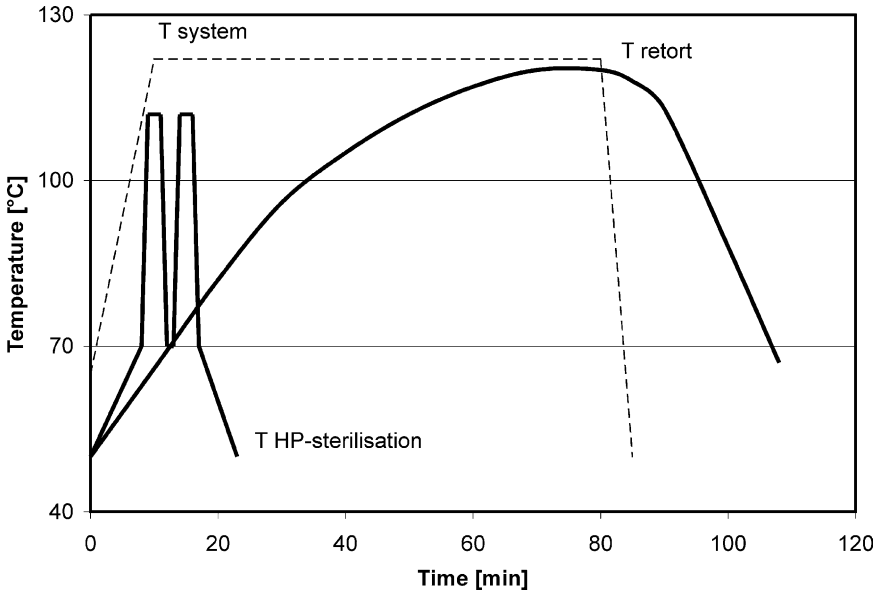

Fig. 1. Temperature in centre during conventional heat sterilisation of a 0.5 l can with spinach (T retort) compared to the temperature of the retort unit (T system). Temperature in centre during high-pressure sterilisation of spinach in a pouch (T HP-sterilisation).

Table 2. Recommended high-pressure sterilisation processes with a two-pulse process according to Meyer *et al.* (2000)

Food category	Initial product temperature (°C)	Pulse pressure (MPa)
Main meal entrees, meats, pasta dishes, sauces, most vegetables	90	690
Most vegetables, whole potatoes	80	828
All vegetables, all potato products, seafood	70	1172
Eggs, milk	60	1700

Table 3. Total aerobic count and spore count before and after high-pressure sterilisation (HPS, two pulse process, initial temperature 90°C, pulse pressure 900 MPa)

Product	Total count		Spore count	
	Initial	HPS	Initial	HPS
Green beans	6.1	< C.T.[a]	3.5	< C.T.
Spinach	8.2	< C.T.	3.5	< C.T.
Asparagus	6.9	< C.T.	4.7	< C.T.
Milk	4.4	< C.T.	0.7	< C.T.
Basil	4.8	< C.T.	3.9	< C.T.

[a] C.T.: confidence threshold: log 1.0–log 1.4 depending on product.

place at the vessel wall. For adequate sterilisation of products by high pressure, it is therefore necessary to know the temperature at several points in the vessel, and not only in the centre which is the hottest spot during high pressure sterilisation. When temperature and pressure are known as a function of time and position in the vessel during the high pressure sterilisation process, it is possible to predict the inactivation of spores. De Heij *et al.* (2002) showed that inactivation of *B. subtilus* spores can be described by a model using a modified Eyring-Arrhenius equation as a function of the position in the vessel during high pressure experiments. Thus high pressure sterilisation is a synergistic process of pressure and temperature, where pressure is used both for rapid and uniform heating, and also contributes to the inactivation of spores.

For commercial application of high pressure sterilised low-acid food products, validation is necessary to prove that it is a safe process. Sizer, Balasubramaniam, and Ting (2002) described that the Food and Drug Administration's regulation for "Thermally processed low-acid foods packaged in hermetically sealed containers" is applicable since high pressure sterilisation has a strong thermal component. They described a number of options for validation of the process consisting of establishing the process as a thermal process and using kinetic approaches.

Product quality

Given the fact that it is possible to inactivate spores in food products with high pressure, the question arises how good the food quality is after high pressure sterilisation compared to products which have undergone conventional heat sterilisation. As shown in Fig. 1, the intensity of the heat treatment differs considerably between both these methods. It may be expected that product characteristics that are dependent on the heat liability of certain components, are less significantly changed by high pressure sterilisation compared to conventional heat sterilisation. For the consumer the main quality criteria of preserved foods are taste (flavour), texture, colour, and nutrients. The effect of high pressure sterilisation on product quality is strongly depended on the product chosen. Some quality parameters for a range of products are described below.

Processing of herbs, which are food components that largely contribute to the smell and taste of products, can illustrate the effect of high pressure sterilisation on flavour. A disadvantage of conventional processing of fresh herbs is the large loss of flavour after processing. Potential high pressure sterilisation can be an interesting alternative. Fig. 2 shows the main flavour components in fresh basil, methyl chavicol and linalool, which accounted for approximately 90% of the total essential oil content (0.9 μg/g fresh weight) (Krebbers, Matser, Koets, Bartels, & Van den Berg, 2002). High pressure sterilisation resulted in the best retention of the essential oils compared to freezing, conventional heat sterilisation and drying of fresh basil. It can be expected that for other fresh herbs there will also be a good retention of the flavour components. It is worth mentioning that the treated basil smelt and tasted good. However, the texture and colour were clearly more similar to heat treated basil than to fresh basil. High pressure sterilisation therefore results in a flavour rich product, which can be used as ingredient for products such as tomato soups and sauces.

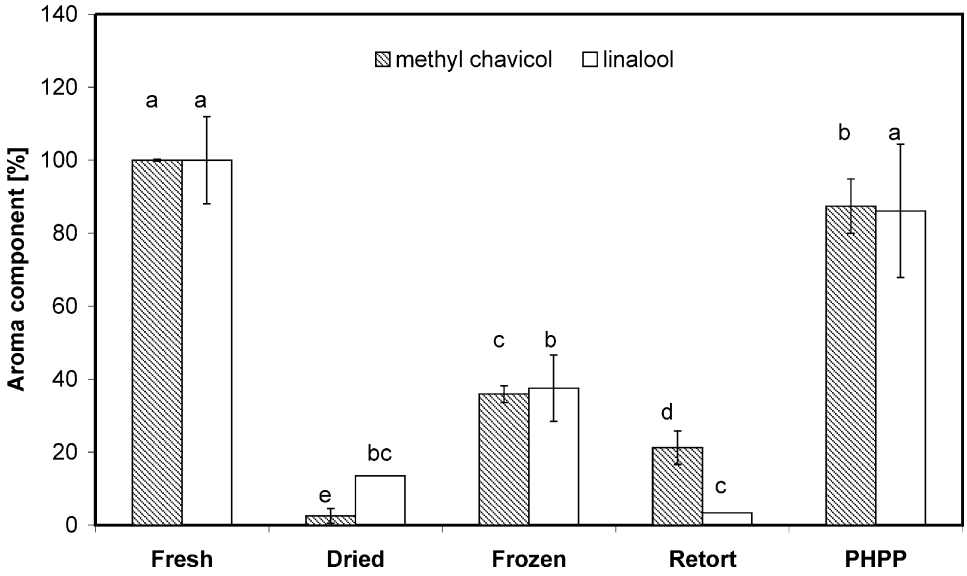

Fig. 2. Effect of treatments on the retention of methylchavicol and linalool (as% of fresh) in fresh basil after drying, freezing, conventional heat sterilisation or high-pressure sterilisation (two pulses, 85°C, 700 MPa), after Krebbers, Matser *et al.* (2002). Different letters above bars corresponding to the same flavour component indicate significant differences between mean values of treatments ($P < 0.05$).

Conventional processing of vegetables in tins or glass jars often results in a considerable loss of texture. Nowadays consumers prefer preserved vegetables that are firmer in texture. Blanching prior to freezing results in significant improvement in the texture of a range of vegetables. Fig. 3 shows that high pressure sterilisation resulted in significantly better retention of the firmness of green beans compared to freezing, drying or conventional heat sterilisation (Krebbers, Koets *et al.*, 2002). This good retention of the texture was observed for a whole range of vegetables and fruits, however, for some products e.g. apples and strawberries, high pressure sterilisation resulted in softening of the product similar to conventional heat sterilisation.

The effect of high pressure sterilisation on colour is strongly product depended. In general, high pressure sterilisation results in a good retention of the colour which is contrary to conventional processing. Some chlorophyll containing green products are affected in a similar way as with retort e.g. green beans, while other products show less change in colour e.g. spinach. or a good retention of the colour e.g. carrots. Fig. 4 shows that the colour of spinach and tomato puree is significantly better than that of heat sterilised, while there is no significant difference between the colour of heat and pressure sterilised green beans. Rovere *et al.* (2000) evaluated the colour of a meat containing-tomato sauce after high pressure sterilisation at 900 MPa and a temperature of 110°C during pressure treatment. They described that the colour, expressed as the absorbance index of the serum, was clearly affected by conventional retorting, while high pressure sterilisation did not affect the colour.

These results demonstrate that it is necessary to evaluate each product to verify if high pressure sterilisation results in a better colour compared to conventional sterilised products. A heat labile component of food products is vitamin C. Conventional heat treatment results in considerable reduction of vitamin C due to heat degradation and leakage of vitamin C to the surrounding fluid (Fennema, 1996). High pressure sterilisation has the advantage of shorter treatments at lower temperature. Therefore retention of vitamin C, and other heat labile ingredients, can be expected. Fig. 5 demonstrates the effect of high pressure sterilisation on the retention of ascorbic acid in green beans, spinach and apple juice. From this figure, it can be concluded that the effect of temperature and pressure on ascorbic acid is matrix dependent. In general, the high pressure sterilised samples had a significantly higher retention of ascorbic acid than the conventionally processed samples. For ascorbic acid added to apple juice, both conventional sterilisation and high pressure sterilisation showed only a small decrease of ascorbic acid compared to the fresh sample. This is possibly due to protective effects of the matrix. It can be expected that less heat sensitive vitamins e.g. carotenoids and vitamin A, experience a less positive influence of high pressure sterilisation. For these components, conventional heat sterilisation showed less decrease (Fennema, 1996), so high pressure resulted in a smaller advantage.

Conclusions

High pressure sterilisation is an extension of the possibilities of high pressure technology. By combining pressure and temperature and using the temperature

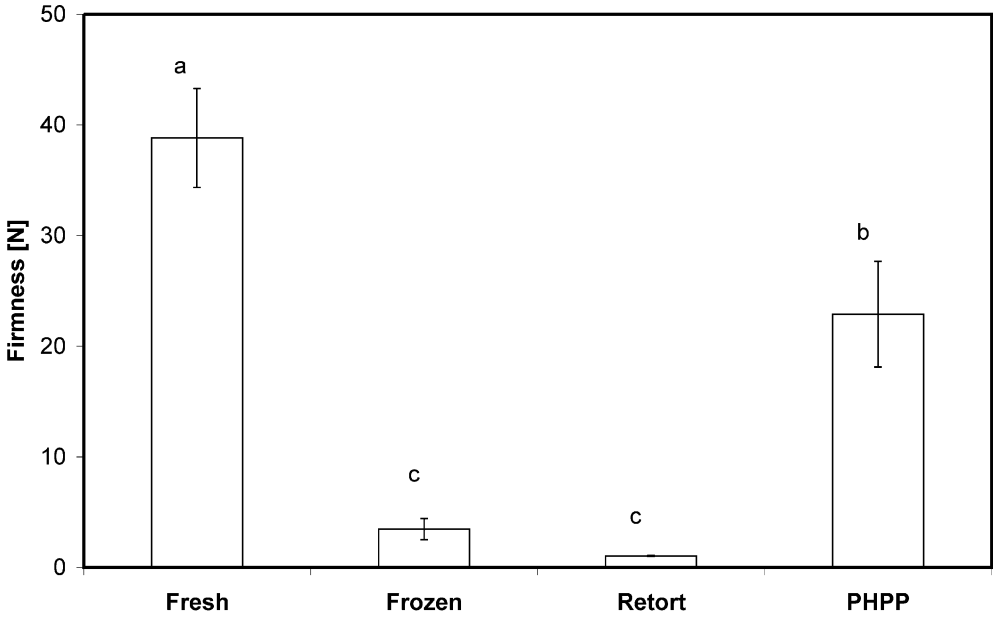

Fig. 3. Effects of high-pressure sterilisation (two pulses, 75°C, 1000 MPa) and conventional treatments on firmness of green beans, after Krebbers, Koets *et al.* (2002). Different letters indicate significant differences between mean values of treatments ($P < 0.05$).

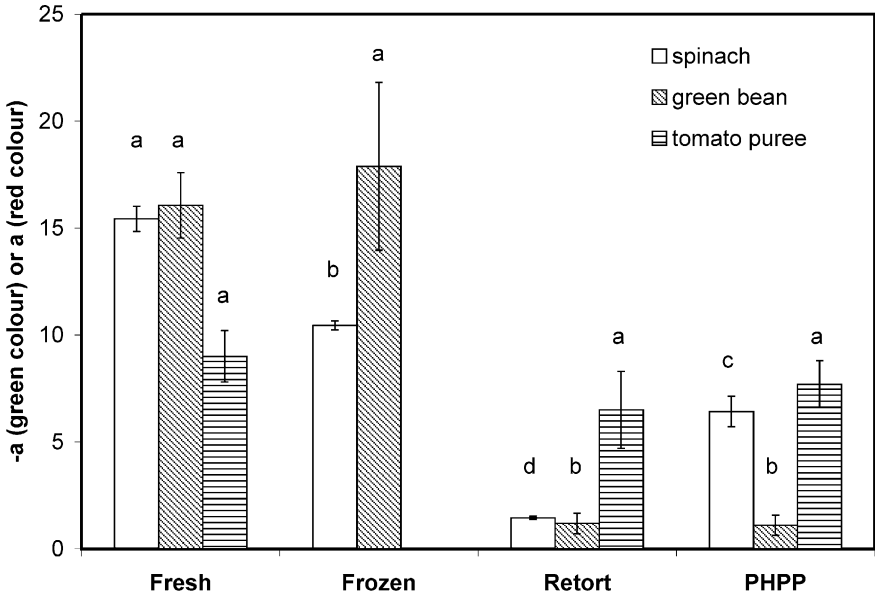

Fig. 4. Colour (-a for green beans and spinach; a for tomato puree) of fresh and preserved products, after freezing, conventional heat sterilisation and high-pressure sterilisation (two pulses, 90°C, 700 MPa). Different letters above bars corresponding to the same product indicate significant differences between mean values of treatments ($P < 0.05$).

increase caused by adiabatic compression, it is possible to inactivate microbial spores and therefore sterilise food products. High pressure sterilisation can be executed under various process conditions. Temperature and pressure have been shown to play an important role during the treatment. Contrary to high pressure pasteurisation, the temperature rise during the process and the temperature differences between various positions in the vessel play an essential role and need accurate monitoring.

High pressure sterilisation does considerably less damage to the product than conventional heat sterilisation. Texture, taste and retention of nutrients are generally better for high pressure sterilised products than for conventional retort. The effects on colour are product dependent and vary between the same as fresh to

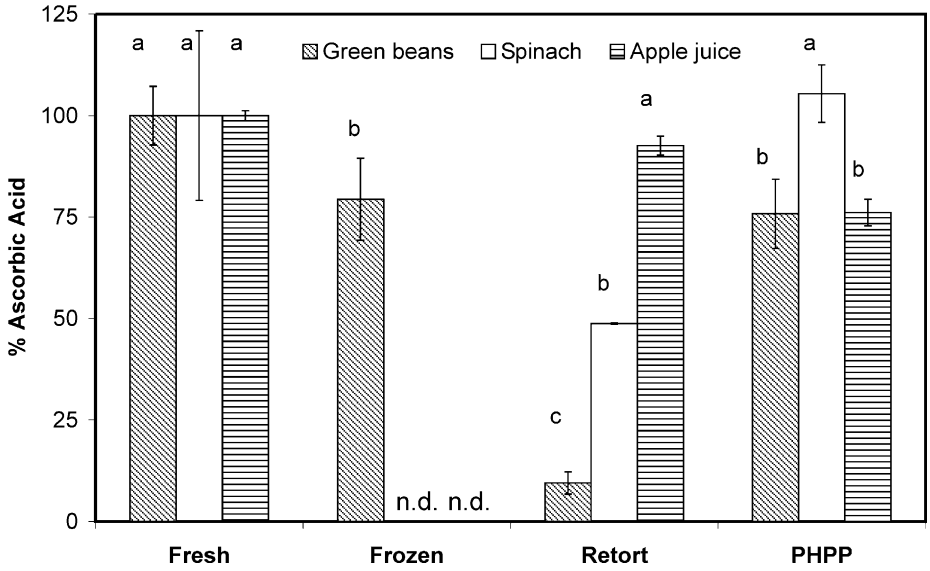

Fig. 5. Ascorbic acid content as percentage of fresh and preserved green beans, spinach and ascorbic acid added to apple juice after freezing, conventional heat sterilisation and high-pressure sterilisation (two pulses, 75°C, 1000 MPa), after Krebbers, Koets *et al.* (2002). Different letters above bars corresponding to the same product indicate significant differences between mean values of treatments ($P < 0.05$).

no distinction from conventional retort. The results of research on high pressure sterilised products showed that effects are product dependent and that careful selection of the appropriate process conditions is necessary.

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References

Cheftel, J. C. (1995). Review: high pressure, microbial inactivation and food preservation. *Food Science and Technology International, 1*, 75–90.

De Heij, W., Van Schepdael, L., Van den Berg, R., & Bartels, P. (2002). Increasing preservation efficiency and product quality through control of temperature distribution in high pressure applications. *High Pressure Research, 22*, 653–657.

Fennema, O. R. (1996). *Food chemistry*. New York: Marcel Dekker.

Hayakawa, I., Kanno, T., Tomita, M., & Fujio, Y. (1994). Application of high pressure for spore inactivation and protein denaturation. *Journal of Food Science, 59*, 159–163.

Hirsch, G. P. (2000). *Hydraulic pressure sterilization and preservation of foodstuff and feedstuff*. United States Patent 6 033 701

Hoogland, H., De Heij, W., & Van Schepdael, L. (2001). High pressure sterilisation: novel technology, new products, new opportunities. *New Food, 3*, 21–26.

Krebbers, B., Koets, M., Van den Wall, F., Matser, A. M., Moezelaar, R., & Hoogerwerf, S. W. (2002). Effects of high pressure processing on the quality of green beans. In R. Hayashi (Ed.), *Trends in High Pressure Bioscience and Biotechnology* (pp. 389–396). Elsevier Science B.V.

Krebbers, B., Matser, A. M., Koets, M., Bartels, P. V., & Van den Berg, R. W. (2002). High pressure-temperature processing as an alternative for preserving basil. *High Pressure Research, 22*, 711–714.

Meyer, R.S. (2000). *Ultra high pressure, high temperature food preservation process*. United States Patent 6 017 572.

Meyer, R. S., Cooper, K. L., Knorr, D., & Lelieveld, H. L. M. (2000). High pressure sterilization of foods. *Food Technology, 54*(11), 67,68,70,72.

Okazaki, T., Kakugawa, K., Yoneda, T., & Suzuki, K. (2000). Inactivation behaviour of heat-resistant bacterial spores by thermal treatments combined with high hydrostatic pressure. *Food Science & Technology Research, 6*, 204–207.

Reddy, N. R., Solomon, H. M., Fingerhut, G. A., Rhodehamel, E. J., Balasubramaniam, V. M., & Palaniappan, S. (1999). Inactivation of Clostridium botulinum type E spores by high pressure processing. *Journal of Food Safety, 19*, 277–288.

Rovere, P., Lonnerborg, N. G., Gola, S., Miglioli, L., Scaramuzza, N., & Squarcina, N. (1999). Advances in bacterial spores inactivation in thermal treatments under pressure. In H. Ludwig (Ed.), *Advances in high pressure bioscience and biotechnology*. Berlin: Springer.

Rovere, P., Squarcina, N., Gola, S., Sandei, L., Iametti, S., & Carpi, G. (2000). Effect of thermal treatment under high pressure on the quality of a meat sauce. *High Pressure Research, 19*, 99–107.

Sizer, C. E., Balasubramaniam, V. M., & Ting, E. (2002). Validating high pressure processes for low-acid foods. *Food Technology, 56*, 36, 38–42.

Smelt, J. P. P. M. (1998). Recent advances in the microbiology of high pressure processing. *Trends in Food Science and Technology, 9*, 152–158.

Ting, E., Balasubramaniam, V. M., & Raghubeer, E. (2002). Determining thermal effects in high pressure processing. *Food Technology, 56*, 31–35.

Wilson, M.J., & Baker, R. (2000). *High temperature/ultra-high pressure sterilization of foods*. United States Patent 6 086 936.