Effect of high-pressure processing on colour, texture and flavour of fruit- and vegetable-based food products: a review

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Introduction

Plant-based foods are subjected to cooking or processing to increase their edibility and palatability. Processing also aims to prolong the shelf life while the original sensory and nutritional properties are maintained as high as possible within the constraints put forward by microbial safety. 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.

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, Van der Plancken, Van Loey, & Hendrickx, 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 (100–1000 MPa/–20 °C to 60 °C), (i) cell wall and membrane disruption (Michel & Autio, 2001; Préstamo & Arroyo, 1998; Van Buggenhout, Messagie, Van Loey, & Hendrickx, 2005); (ii) enzyme catalyzed conversion processes (Ludikhuyze, Rodrigo, & Hendrickx, 2000; Verlent, Smout, Duvetter, Hendrickx, & Van Loey, 2005; Verlent, Van Loey, Smout, Duvetter, & Hendrickx, 2004); (iii) chemical reactions (Indrawati, Arroqui, Messagie, Nguyen, Van Loey, & Hendrickx, 2004a; Indrawati, Van Loey, & Hendrickx, 2004b, 2005; Nguyen, Indrawati, & Hendrickx, 2003; Nguyen, Oey, Hendrickx, & Van Loey, 2006; Oey, Verlinde, Hendrickx, & Van Loey, 2006) and (iv) modification of biopolymers including enzyme inactivation, protein denaturation and gel formation (Balny, Masson, & Heremans, 2002; Indrawati, Van Loey, Fachin, Ly Nguyen, Verlent, & Hendrickx, 2002; Kolakowski, 2008).
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sensory properties.

In the past, a number of general reviews concerning HP
processing of foods have been published (Rastogi, Ragh-
varao, Balasubramaniam, Niranjan, & Knorr, 2007; San
Martin, Barbosa-Cánovas, & Swanson, 2002; Torres & Ve-
laquez, 2005). The current article aims at giving a thorough
overview of the most recent findings specifically on how
HP processing affects the colour, flavour and texture of fruit-
and vegetable-based foods and on the elucidation of possible
mechanisms behind the reported changes. In addition,
special attention is given to the possible impacts of HP
treatments combined with elevated temperatures on those
sensory properties.

The effect of HP processing on colour

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 foods
and vegetables can, however, change during storage due
to incomplete inactivation of enzymes and microorganisms,
which can result in undesired chemical reactions (both en-
zymatic and non-enzymatic) in the food matrix.

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 °C, HP treat-
ment affects their stability for example, a significant reduc-
tion in the chlorophyll content of broccoli juice (Butz,
Edenharder, Fernández García, Fister, Merkel, & Tauscher,
2002; Van Loey et al., 1998). The temperature dependency of the degradation rate constant of chlorophyll a is higher
than that of chlorophyll b. At a constant pressure level,
the values of the degradation rate constants of chlorophylls
increase with increasing temperature (Van Loey et al.,
1998) whereas at constant elevated temperatures, pressure
increase accelerates the degradation of chlorophyll a and
b. The pressure dependency of the degradation rate constant of chlorophyll b at 70 °C is higher than that of chlorophyll
a. For example, elevating pressure from 200 to 800 MPa ac-
celerates the degradation of chlorophyll a and chlorophyll
b of broccoli by 19.4% and 68.4%, respectively (Van
Loey et al., 1998). Matser, Kreebbers, Van den Berg, and
Bartels (2004) also reported chlorophyll degradation of
green beans and spinach due to HP processing at elevated
temperatures, even for a short exposure time (two pulses of
90 °C/700 MPa/1 min).

HP treatment at ambient and moderate temperatures re-

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 tem-
perature/1 min (Kreebbers, Matser, Koets, Bartels, & Van
den Berg, 2002a). 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 for example,
green beans after HP treatment at elevated temperature
(two pulses of 1000 MPa/75 °C/80 s) (Kreebbers et al.,
2002a) or basil after HP treatment of 860 MPa/75 °C/80
s or 700 MPa/85 °C/80 s (Kreebbers, Matser, Koets, Bartels,
& Van den Berg, 2002b).

During storage, the green colour of the vegetables HP

treated at room temperature turned into a pale yellow col-
our (decrease in a* value) probably due to chemical reac-
tions such as oxidation. By comparison, the vegetables
pressurized at elevated temperatures, which results in inac-
tivation of some enzymes, showed no further colour change
during storage. The colour of pressure-treated green beans
(Kreebbers et al., 2002a) and basil (Kreebbers et al., 2002b)
was still acceptable after storage time of one and two
months, respectively.

Carotenoids are important for the orange—yellow and
red appearance of fruits and vegetables. Carotenoids are
rather pressure stable. HP treatment increases the extraction
yields of carotenes from the plant matrix (De Ancos,
Gonzalez, & Pilar Cano, 2000; Fernández García, Butz, Bognár,
& Tauscher, 2001a; Fernandez Garcia, Butz, & Tauscher,
2001b; Tauscher, 1998). 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, Jiang, Wang,
& Gao, 2006). The colour of tomato purée remained un-
changed after HP treatment (up to 700 MPa) at 65 °C
even for 1 h (Rodrigo, Van Loey, & Hendrickx, 2007a).

Anthocyanins are water-soluble vacuolar flavonoid pig-
ments 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 °C/15 min) (Garcia-
Palazon, Suthanthangjai, Kajda, & Zabetakis, 2004). Anthocyanins in pressure-treated vegetables and fruits
were not stable during storage. A shelf-life study (7 days
at 5, 20 and 30 °C) on pressurized (200, 400, 600 and
800 MPa/15 min/20–22.5 °C) blackcurrants (Ribes nig-
rum) during a week-long storage at selected temperatures
showed that cyanidin-3-rutinoside and delphinidin-3-
rutinoside had different stabilities. Anthocyanins in pressurized
blackcurrants remained unchanged during storage at 4 °C (Kouniaki, Kajda, & Zabetakis, 2004).

There are various hypotheses on the degradation mechan-
ism of anthocyanins in pressurized fruits during storage. The first hypothesis of anthocyanin degradation is a reaction
caused by incomplete enzyme inactivation. A link between
enzyme inactivation (β-glucosidase, peroxidase and poly-
phenoloxidase) and anthocyanin stability has been found in
several fruits (Garcia-Palazon et al., 2004; Suthanthang-
jai, Kajda, & Zabetakis, 2005; Zabetakis, Leclerc, & Kajda,
2000a). For example, polyphenoloxidase inactivation was
linked to the stability of pelargonidin-3-glucoside and pe-
largonidin-3-rutinoside in pressurized (800 MPa/18–
22 °C/15 min) red raspberry and strawberry. Since HP
treatment at 800 MPa (18–22 °C/15 min) caused complete
PPO inactivation, the stability of these two pelargonidins
was maintained during storage (Garcia-Palazon et al.,
2004). This finding is also supported by Suthanthangjai
et al. (2005). Besides PPO, β-glucosidase and peroxidase
also play important roles in anthocyanin degradation during
storage. Suthanthangjai et al. (2005) showed that cyanidin-
3-glucoside and cyanidin-3-sophorosides (the major pig-
ments in raspberry) had the highest stability during 9
days’ storage at 4 °C after pressurization at 200 or 800
MPa (18–22 °C/15 min) compared with pressure treat-
ment at 400 or 600 MPa. A high loss of both pigments after
HP treatment at 400 and 600 MPa is probably due to a lower
degree of inactivation of β-glucosidase, peroxidase and
polyphenoloxidase.

The second hypothesis deals with the substrate specific-
ity of β-glucosidase acting on anthocyanins (Gimenez,
Kajda, Margomenou, Piggott, & Zabetakis, 2001; Zabetakis
et al., 2000a). Zabetakis et al. (2000a) found different levels
of anthocyanin (e.g. pelargonidin-3-glucoside and pelargo-
nidin-3-rutinoside) losses in strawberry after HP treatments
of 200, 400, 600 and 800 MPa (18–22 °C/15 min) and a
higher residual activity of β-glucosidase after HP treat-
ment at 400 MPa than at 200, 600 and 800 MPa. These au-
thors found a higher loss in pelargonidin-3-glucoside,
compared to pelargonidin-3-rutinoside at the same level of
residual enzyme activity probably because β-glucosidase
has higher substrate specificity to pelargonidin-3-glucoside
than to pelargonidin-3-rutinoside. A similar finding was
also observed in strawberry jam (Gimenez, Kajda, Margo-

The third hypothesis concerns the effect of ascorbic acid
on the stability of anthocyanins. Ascorbic acid apart from
being an antioxidant also tends to accelerate the degra-
dation of anthocyanins (Kouniaki et al., 2004). Anthocyanin
losses can be reduced by storing HP-treated products at
low temperature.

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 ob-
served immediately after HP treatments, for example in
white grape juice after HP treatment at 400 MPa/2 °C,
500 MPa/2 °C or 400 MPa/40 °C/10 min (Daoudi et al.,
2002) or in mango pulps after HP treatments at 100–
400 MPa/20 °C/15 or 30 min (Ahmed, Ramaswamy, & Hir-
emath, 2005). Ahmed et al. (2005) observed that colour pa-
rameters 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 $\Delta E$.

During storage, discoloration of pressurized food prod-
ucts occurred during storage (3 °C) due to enzymatic brown-
ing. Guerrero-Beltran, Swanson, and Barbosa-Canovas
(2005) observed enzymatic browning in HP-treated (379–
586 MPa/room temperature/0.033, 5, 10, 15 or 20 min)
mango puree. Additions of ascorbic acid and cysteine in-
hibited the polyphenoloxidase activity resulting in less
browning. This inhibition was enhanced by HP treatment.
Polyderya, Stoforos, and Taoukis (2003) found discoloration
(based on $L^*$, $a^*$ and $b^*$ values) of pressure-treated
(500 MPa/35 °C/5 min) reconstituted orange juice during
storage (0, 10, 15 °C for 120 days) and the degradation trend
was not significantly different between pressure and ther-
mally treated juices. Similar results were observed by the
same authors (Polyderya, Stoforos, & Taoukis, 2005) in pres-
surized (600 MPa/40 °C/4 min) navel orange juice. The col-
our change (based on $L^*$, $a^*$ and $b^*$ values) had a linear
relationship with the ascorbic acid loss during storage (0,
5, 10, 15, 30 °C for 64 days) but it was not dependent on
the type of processing (comparison between temperature
pasteurization and HP pasteurization treatments). An in-
crease in storage temperature resulted in higher rates
of browning of orange juice. The activation energy for col-
or degradation of HP-treated juice due to browning was higher
than that of temperature pasteurized juice.

Structure and pigmentation of food interact with each
other to affect both colour and translucency/opacity. Tex-
ture modification may result in changes in the nature and
extent of internally scattered light and the distribution of
surface reflectance, which in turn may produce. Changes in
colour appearance would be more expected rather than
the changes in pigment concentration (Mac Dougall,
2002). Colour changes in HP-treated fruits and vegetables
can be related to changes in textural properties. This phe-
nomenon was observed in tomato based products. HP treat-
ment (400 MPa/25 °C/15 min) resulted in an increase in the
$L^*$ value of tomato purée indicating a lightening of the pu-
rée surface colour. The CIELab parameters were signifi-
cantly higher both in the untreated and in the HP-treated
tomato purée compared to the thermally treated purées
(Sánchez-Moreno, Plaza, De Ancos, & Cano, 2006). The
reason could be the formation of a jelly-like translucent
structure of tomato purée as observed by Verlent, Hen-
drickx, Rovere, Moldenaers, and Van Loey (2006) when
pressures dropped below 400 MPa.
The effect of HP processing on texture

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). Due to cell disruption, HP processing facilitates the occurrence of enzymatic and non-enzymatic reactions. 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 pectinmethylase (PME), lower the polygalacturonase (PG) activity (occurring mostly at moderate temperature), and retard β-elimination [a reaction where loss of two substituents from adjacent atoms (such as carbon, nitrogen, oxygen) results in the formation of new unsaturated bonds] (possibly occurred at elevated temperatures). Pectinases, such as orange PME (Van den Broeck, Ludikhuyze, Van Loey, & Hendrickx, 2000), strawberry PME (Ly Nguyen et al., 2002), tomato PG (Fachin, Van Loey, Ly Nguyen, Verlent, Indrawati, & Hendrickx, 2003), carrot PME (Ly Nguyen et al., 2003a), banana PME (Ly Nguyen, Van Loey, Smout, Verlent, Duchetter, & Hendrickx, 2003b), pepper PME (Castro, Van Loey, Saraiva, Smout, & Hendrickx, 2006) and plum PME (Nunes, Castro, Saraiva, Coimbra, Hendrickx, & Van Loey, 2006) show differences in their pressure and temperature stability. As a consequence, 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, Smout, Elliot, Van Loey, & Hendrickx, 2006; Sila, Smout, Vu, & Hendrickx, 2004), 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. Disruption of cell integrity was observed in HP-treated (400 MPa/30 min/5 °C) spinach and cauliflower by microscopic (cryo-SEM) examination (Préstamo & Arroyo, 1998). 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. Basak and Ramaswamy (1998) studied the effect of HP processing (100–400 MPa/5–60 min/room temperature) on the firmness of different fruits and vegetables such as apple, pear, orange, pineapple, carrot, celery, green pepper and red pepper. The authors observed a rapid firmness loss during compression. During the pressure holding period (30–60 min), the firmness either decreased further or recovered gradually, such as for pear, orange, pineapple, carrot, celery, green pepper and red pepper treated at 100 and 200 MPa. Pectinmethylase activity was suggested to be the major reason for the observed increase in firmness. Upon HP treatment, pectinmethylase is liberated and contacts its substrate, the highly methylated pectin, leading to demethylation. The de-esterified pectin (low-methoxy-pectin) is capable of forming a gel-network with divalent ions resulting in increased hardness. After HP treatments carried out at elevated temperatures, pronounced texture preservation is found in contrast to thermal treatment at atmospheric pressure, as shown for pressure-treated (two pulses of 1000 MPa/75 °C/80 s) green beans (Krebbers et al., 2002a) and pressure-treated (600 MPa/80 °C/ up to 90 min) carrot disks (De Roeck, Sila, Duvetter, Van Loey, & Hendrickx, 2007). Both the action of pectinases (such as PME) and reduced chemical reactions (such as β-elimination) probably contribute to texture preservation during HP treatment at elevated temperatures. However, the exact mechanisms behind texture preservation at elevated temperature and pressure are not known and further research is needed in this area.

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 & 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, Ledward, & Ames, 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, purée, pulp and juice. The observed effects are dependent on the conditions of the HP process and the type of fruit and vegetable. 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).

The viscosity of tomato homogenate decreased considerably at pressures ≤400 MPa but increased at higher pressure levels, such as 500 MPa combined with temperatures up to 60 °C (Plaza, Muñoz, de Ancos, & Pilar Cano, 2003; Sánchez-Moreno et al., 2006; Verlent et al., 2006). However, 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 (Polydéra 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.

The effect of HP processing on flavour

Flavour is the sensory impression of a food that is determined mainly by the chemical senses of taste and smell. 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. Any changes in the compounds responsible for the sourness, sweetness or odour of fruits and vegetables may result in changes in their flavour.

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. This has been observed, by means of both chemical and sensory analysis, in a number of studies where strawberry purée (Lambert, Demazeau, Largeteau, & Bouvier, 1999), mandarin juice (Takahashi, Ohta, Yonei, & Ifuku, 1993), orange—lemon—carrot juice (Fernandez Garcia et al., 2001a), white grape juice (Daoudi et al., 2002) and guava juice (Yen & Lin, 1999) have been treated at pressures of 200—600 MPa combined with ambient temperature. 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. Navarro, Verret, Pardon, and El Moueffak (2002) observed that HP processing at 400 MPa (ambient temperature/20 min) more than doubled the hexanal content of strawberry purée. Lambert et al. (1999), on the contrary, observed less pronounced effects of pressure on the hexanal content of strawberry purée but pressurization at 800 MPa (ambient temperature/20 min) resulted in a slight decrease in the hexanal content. For HP-treated (300 MPa/25 °C/30 min) onions, a 40% increase in the concentration of hexanal and the generation of a braised or fried odour probably due to increased contents of propyl trans-propenyl disulphide and 3,4-dimethylthiophene have been found (Butz, Koller, Tauscher, & Wolf, 1994). Porretta, Birzi, Ghizzoni, and Vicini (1995) reported that HP treatment (500, 700 or 900 MPa/room temperature/3, 6 or 9 min) of fresh tomato juice resulted in the generation of such a strong rancid taste, that the juice was unsuitable for sensory analysis. n-Hexanal was suggested to be responsible for the rancid taste, because the n-hexanal content in all pressure-treated tomato juices was much higher (6.4 mg kg⁻¹) than in the fresh juice (0.3 mg kg⁻¹). 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. Lipoxigenase 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 polysaturated fatty acids. At 20 °C, lipoxigenase and hydroxyperoxide lyase endogenously present in tomato juice have different pressure stabilities. At pressures lower than 500 MPa (20 °C), tomato hydroperoxide lyase is more labile than tomato lipoxigenase, while their stabilities are opposite at pressure ≥ 500 MPa (Rodrigo, Jolie, Van Loey, & Hendrickx, 2007b).

Regarding strawberry based food products, HP processing at 800 MPa (20 °C/20 min) modified the flavour profile of strawberry purée (Lambert et al., 1999). Some new compounds were formed, e.g. γ-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 purée processed at 800 MPa (20 °C/20 min) than in the unprocessed purée. 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 HP-treated (200, 400, 600 or 800 MPa/18—22 °C/15 min) strawberries were lower than in the untreated strawberries (Zabetakis, Koulentianos, Orruño, & Boyes, 2000b). The best acid retention was observed for strawberries pressure-treated at 400 MPa. The concentration of the alcohol 1,6,10-dodecatetrien-3-ol increased in strawberries treated at 800 MPa. The level of 2,5-dimethyl-4-hydroxy-2H-furan-3-one (DMHF), one of the most important flavour compounds in fresh strawberry, was, however, not much altered after HP treatments or during storage.

Ester compounds belong to the most important flavour compounds in strawberries but the stability of ester compounds during pressure is still under discussion. Lambadaríos and Zabetakis (2002) observed only a small decrease in ester concentration when model systems containing fruit esters in buffer solution were subjected to HP treatment.
(400 or 800 MPa/18–22 °C/15 min) at various pH values (pH 4, 6 and 8). Lambert et al. (1999) also reported the presence of many esters in HP treated (200, 500 or 800 MPa/20 °C/20 min) strawberry purée. Zabetakis et al. (2000b), on the contrary, found no ester compounds in HP (200, 400, 600 or 800 MPa/18–22 °C/15 min) treated strawberries. It is possible that the ester compounds in the study of Zabetakis et al. (2000b) were lost during sample extraction.

Gimenez et al. (2001) reported that strawberry jam prepared by HP processing (400 or 800 MPa/22 °C/5 min) smelled more chemical, rancid and less fruity than traditionally processed jam. However, none of the flavour compounds generated by heat-sterilization (120 °C/20 min) was found in HP-treated (200–800 MPa/ambient temperature/20 min) strawberry purée (Lambert et al., 1999). The finding on better flavour retention of HP processed (600 MPa/ambient temperature/5 min) strawberry purée in comparison with heat-treated (80 °C/5 min) purée has been supported by a study where an electronic nose detector was used to analyse the volatiles of the treated purées. HP-treated strawberry purée differed from heat-treated and unprocessed strawberry purée, 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 purées (Dalmadi, Polyak-Fecher, & Farkas, 2007).

Based on sensory evaluation, the flavour of HP-treated (room temperature/500 MPa/90 s or 5 min, 700 MPa/60 s or 800 MPa/5 min) orange juice was not as fresh as the flavour of untreated orange juice (Fernández García et al., 2001a; 2001b; Parish, 1998). Fernández García et al. (2001a) reported that the carrot aroma was more intense in HP treated (800 MPa/room temperature/5 min) than in fresh orange–lemon–carrot juice. The taste of HP-treated orange juice was judged better than traditional heat pasteurized orange juice (Parish, 1998; Polydiera et al. 2003; 2005) and the typical off-flavour of heat-treated mandarin juice was not detected in HP-treated (400 MPa/ambient temperature/10 min) juice (Takahashi, Ohta, Yonei, & Ifuku, 1993). Baxter, Easton, Schneebeli, and Whitfield (2005) observed no differences in the concentration of volatile flavour compounds between freshly frozen, heat-treated (85 °C/25 s) or high-pressure-treated (600 MPa/18–20 °C/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 flavour between the differently treated orange juices.

In the majority of the above mentioned investigations the HP treatment was carried out at room temperature. HP processing at room temperature does not necessarily result in inactivation of pressure resistant bacterial spores and enzymes, which may spoil the HP-treated product during storage. Therefore, cold storage is needed to preserve the high quality of the treated product. Navarro et al. (2002) reported that when HP-treated (400 MPa/ambient temperature/20 min) strawberry purée was stored for 30 days at 4 °C, increases in the contents of methyl butyrate, mesifuran, 2-methyl-butyric acid, hexanoic acid, ethyl butyrate, ethyl hexanoate, 1-hexanol and linalool were observed. During storage, the content of 1-hexanol in the pressure-treated strawberry purée increased probably due to the residual activity of lipoxygenase. In this case, peroxidase was not considered responsible for flavour changes during storage, as the activity of peroxidase was very low after the HP treatment. Another shelf-life study showed that the sweetness and acidity of the HP-treated (500 MPa/2 °C/10 min) grape juice were maintained for 60 days during storage at 4 °C but fresh fruit and grass aroma were slightly reduced during storage (Daoudı et al., 2002). Similar results were observed for HP-treated guava juices. The volatile flavour compounds in HP-treated (600 MPa/25 °C/15 min) guava juice remained stable during 30 days’ storage at 4 °C, but changes in the concentrations of volatiles were observed after 60 days’ storage. The concentrations of methanol and ethanol increased and the concentrations of many ester and aldehyde compounds decreased probably due to residual enzyme activity (Yen & Lin, 1999).

Up to date, studies on the flavour effects of HP treatment conducted at elevated temperatures are limited. Only one report concerning the flavour of plant material subjected to HP treatment at elevated temperatures was found in the literature. The flavour of HP-treated basil (two pulses/860 MPa/75 °C and two pulses/700 MPa/85 °C) was more intense than the aroma of conventionally heat-sterilized, frozen or dried basil. The contents of methylchavicol and linalool, two essential oils important for the characteristic fresh basil flavour, were not changed by HP processing.

In conventionally heat-sterilized basil the concentrations of methylchavicol and linalool were reduced with more than 80%. After two months storage at 20 °C, the characteristic basil aroma was still observed in pressure-treated basil (Krebbers et al., 2002b).

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 β-glucosidases, enzymes naturally present in many plants (Pogorzelski & Wilkowska, 2007). Linalool, nerol, geraniol and citronellol are some examples of glycosidically-bound aroma compounds typically present in fruits (Pogorzelski & Wilkowska, 2007). HP processing may have potential in releasing flavour compounds from plant-based foods since the activity of for example strawberry β-glucosidase is enhanced after HP treatment at 200 or 400 MPa (18–22 °C/15 min) (Zabetakis et al., 2000b). The increased activity of β-glucosidase did, however, not result in decreased levels of 2,5-dimethyl-4-hydroxy-2H-furan-3-one-glucoside (DMHF-glucoside), which is a precursor of 2,5-dimethyl-4-hydroxy-2H-furan-3-one (DMHF), one of the most important volatile flavours...
in fresh strawberries. The increased levels of benzaldehyde in HP-treated (400 MPa/20 °C/10 min) peaches was attributed to β-glucosidase activity (Sumitani, Sukeane, Nakatani, & Tatsuka, 1994). In this context, it may be possible to boost the release of bound aroma compounds by adding commercial enzyme preparations containing β-glucosidase activity to fruit products. For example, Gueguen, Chemardin, Janbon, Arnaud, and Galzy (1996) reported a 705% increase in volatile flavour compounds in strawberry juice treated with Candida molischiana β-glucosidase. The enzyme treatment resulted in an increase in the concentrations of linalool, benzyl alcohol and 2-phenylethanol. It would be interesting to find out whether the release of flavour compounds could be further enhanced by performing the β-glucosidase treatment under pressure. However, this approach must be taken with caution for anthocyanin-containing fruits since β-glucosidase can also hydrolyze glucosylated anthocyanidins leading to colour loss.

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. In strawberries, for example, more than 350 volatile compounds have been identified (Zabetakis & Holden, 1997). A complex mixture of furanone, esters, aldehydes, alcohols and sulphur compounds are considered responsible for the strawberry flavour. Some compounds have a greater impact on overall flavour than others due to differences in the odour thresholds of the compounds. Due to interactions between individual flavour compounds, even a small change in the concentration of one compound may have major effects on the overall flavour. Therefore it is obvious that sensory analysis is needed in addition to pure chemical and mechanical analysis to gain a better understanding of the HP effects on the overall sensory properties of plant-based foods.

Conclusions
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). Based on current knowhow, elucidation of the HP effects on sensory properties of fruit- and vegetable-based 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. Moreover, the effect of HP treatment on sensory properties cannot be generalized since (i) study on basic insight in this subject is still limited and (ii) sensory property is product dependent.

With regard to the application of HP treatment at elevated temperatures, anticipation based on knowledge of HP effects at moderate temperatures must be taken with precaution. 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. All considered, these issues become interesting and important for further investigation.

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