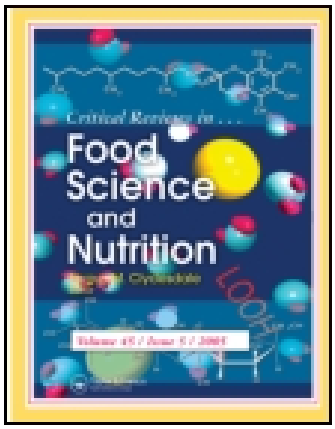

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Effects of High-Pressure CO_2 Processing on Flavor, Texture, and Color of Foods

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Effects of High-Pressure CO_2 Processing on Flavor, Texture, and Color of Foods

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High-pressure CO_2 (HPCD) is a pasteurization method that inactivates microorganism and enzymes through molecular effects of CO_2 under pressures below 50 MPa without exposing foods to adverse effects of heat. Thermal pasteurization can impart undesirable changes on organoleptic and nutritional quality of the foods, which can reduce sensory perception and consumer acceptance of the foods. As a novel nonthermal processing technique, HPCD does avoid drawbacks such as loss of flavor, denaturation of nutrients, production of side toxic reactions, as well as changes in physical, mechanical, and optical properties of the food materials involved in the processing. This review gives a survey and analysis of recent publications regarding the effects of HPCD on the flavor, texture and color of processed foods, and possible mechanisms explaining HPCD technique on the flavor, texture, and color of the foods were discussed.

Keywords High pressure CO_2, flavor, texture, color, mechanism

INTRODUCTION

Thermal processing is a well-known and traditional food preservation technique for killing food borne pathogens and spoilage microorganisms in foods. For heat-sensitive food products, however, thermal pasteurization can impart undesirable organoleptic changes in addition to some detrimental effects to the nutritional quality of the food (Garcia-Gonzalez et al., 2007). As consumer's increasing demand for minimally processed, micro-biologically safe, and stable food products that are additive-free, nonthermal technologies which tend to leave quality attributes intact are being investigated as alternatives for food preservation (Mertens and Knorr, 1992). Among updated nonthermal technologies, high-pressure CO_2 (HPCD) is a pasteurization method that inactivates microorganism and enzymes through molecular effects of CO_2 under pressures below 50 MPa without exposing foods to adverse effects of heat (Damar and Balaban, 2006).

HPCD has been reported as an alternative cold pasteurization technique for foods since it could effectively inactivate microorganisms and enzymes (Garcia-Gonzalez et al., 2007). Meanwhile, the quality change of foods after HPCD could not be ignorant, since it directly has to do with the acceptance of consumers. Color, flavor, and texture are important quality characteristics of foods and major factors affecting sensory perception and consumer acceptance of foods (Oey et al., 2008). Some detrimental effects of HPCD on food quality have been reported (Park et al., 2002; Zhou et al., 2009, 2010). But compared to traditional techniques, HPCD avoids drawbacks such as retention of flavor, denaturation of nutrients, production of side toxic reactions as well as changes in physical, mechanical, and optical properties of the material involved in the treatment (Spilimbergo and Bertucco, 2003). The effects of HPCD on food quality has mainly studied on fruit and vegetable juices, dairy products, meats, and some fresh-cut fruit and vegetable (Damar et al., 2006). Up to date, many studies on food quality after HPCD have shown that HPCD does not significantly affect or affects only slightly food quality, mainly including the flavor, texture, and color.

Several reviews concerning the effect of HPCD on foods have been published during the past 10 years (Spilimbergo and Bertucco, 2003; Damar and Balaban, 2006; Zhang et al., 2006; Garcia-Gonzalez et al., 2007; Hu et al., 2011; Ferrentino and Spilimbergo, 2011), which mainly focused on the microbial and enzyme inactivation after HPCD treatment. But no special

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review on the effects of HPCD on food quality has been reported yet. As an emerging nonthermal technology, HPCD has been attracted by academia, government agency, and food industry in recent years, and the publications of evaluation of food quality after HPCD treatment have increased in different journals. The aim of this review is to give a specific survey of most recent findings on how HPCD processing affects the flavor, color, and texture of foods. The survival of microorganisms in foods and food spoilage due to failure by HPCD pasteurization also caused the loss of flavor, color, and texture of foods, but this case was excluded in this review.

EFFECTS OF HPCD ON FLAVOR OF FOODS

Flavor was the sensory impression of a food, and was determined mainly by the chemical senses of taste and smell (Oey et al., 2008). Any changes in the compounds responsible for the sourness, sweetness, bitterness, or odor of foods may result in changes in their flavor (Oey et al., 2008). Until date, some progresses have been made in understanding HPCD-induced flavor modifications.

Taste

The sourness of foods was closely related to their pH and titratable acidity. The reductions in the pH of foods after HPCD were previously reported by Hofland et al. (1999), Park et al. (2002), Zhou et al. (2009), Garcia-Gonzalez et al. (2009), Ferrentino et al. (2009a), and Liao et al. (2009) (Table 1). HPCD processing of milk have been calculated to lower pH rapidly over the first 1.5 MPa, and quickly came to an asymptote at about pH 4.8 (Hofland et al., 1999). HPCD decreased the initial pH of 6.5–4.4 in carrot juice at 4.90 MPa (Park et al., 2002). Zhou et al. (2009) also reported that a decrease in pH from 6.74 to 5.95 and an increase in titratable acidity from 0.38 to 1.09 mg/L in carrot juice after HPCD at 10 MPa and 25°C for 15 min. The pH in liquid whole egg decreased from 7.4 to 6.3 after HPCD at 13 MPa and 45°C for 10 min; however, it completely returned to original value after 1 week of storage (Garcia-Gonzalez et al., 2009). The pH of apple juice decreased from 3.56 to 3.52 after HPCD (Ferrentino et al., 2009a). Gunes et al. (2005) indicated a more acidic or carbonated taste of treated juices that was undesirable after HPCD. Lowering pH effect of HPCD was due to CO_2 dissolution into liquid foods, dissociating into bicarbonate, carbonate, and hydrogen ions as shown in Eq. 1.

$$CO_2 + H_2O \leftrightarrow H_2CO_3$$

$$H_2CO_3 \leftrightarrow H^+ + HCO_3^- \cdots \mathrm{pKa} = 6.57$$

$$HCO_3^- \leftrightarrow H^+ + CO_3^{2-} \cdots \mathrm{pKa} = 10.62$$

Equation 1 Equations of CO_2 dissolution and dissociation (Damar and Balaban, 2006).

However, different results were also reported in previous studies. No reduction in pH but an increase in titratable acidity was observed by Arreola et al. (1991), Kincal et al. (2006), Ferrentino et al. (2009b), and Damar et al. (2009) in HPCD treated orange juice, apple juice and coconut water, this was possibly attributed to a lower pH (3.3∼4.2) in original juices, at this pH the carbonic acid formed by CO_2 dissolution into juices difficultly dissociates into free hydrogen ions, because the dissociation constants of carbonic acid and bicarbonate were pKa = 6.57 and pKa = 10.62 (Damar and Balaban, 2006), respectively. Besides, no significant difference between HPCD and control samples in pH and titratable acidity were found (Fabroni et al., 2010; Pozo-Insfran et al., 2006a; Pozo-Insfran et al., 2007; Niu et al., 2010a; Gasperi et al., 2009), this insignificant change in juice pH and titratable acidity might be attributed to low concentrations of CO_2 dissolved in the juices as CO_2 was stripped from the juices by vacuum during HPCD decompression.

The sweetness in foods mainly resulted from total soluble solids, as well as fructose, glucose, and sucrose, was not influenced by HPCD in literature (Arreola et al., 1991; Zhou et al., 2009; Niu et al., 2010a; Niu et al., 2010b; Gasperi et al., 2009). The consistent results, obtained in total soluble solids and sugars after HPCD treatment, were beneficial to food processing, since these quality traits were closely linked to consumer perception and likeability (Gasperi et al., 2009).

Polyphenols in plant-based food and drink were thought to be responsible for the mouth feeling of astringency (Noble, 2002; Vidal et al., 2004). No significant difference was detected for the polyphenols of HPCD-treated apple juice, melon juice, and red grapefruit juice (Gasperi et al., 2009; Chen et al., 2010; Ferrentino et al., 2009b). However, HPCD resulted in significant reduction of total polyphenols in peach juice sera (Zhou et al., 2010), since proteins and polyphenolic compounds could combine to form soluble complexes (Siebert et al., 1996) and the soluble complexes precipitates, or HPCD-denatured proteins could adsorb polyphenolic compounds.

Aroma

The aroma of foods generally came from volatile flavor compounds. Normally, HPCD reduced the concentrations of volatile compounds in foods. Thirty five percent depletion in the concentration of overall volatile compounds in fresh apple juice was found after HPCD, and the highest variation was observed for some esters (especially for hexyl acetate, pentyl acetate, isopentyl acetate, isobutyl acetate, and butyl acetate) and aldehydes (hexanal and (*E*)-2-hexenal), characterized by low threshold values, responsible for the changes in the odor/flavor of treated juices (Gasperi et al., 2009). HPCD significantly decreased the concentration (about 50–83%) of ethyl butyrate, trans-2-hexenol, α-pinene, phellandrene, and limonene in orange juice (Niu et al., 2010b). Ethyl hexanoate in

Table 1 Summary of studies on effect of HPCD on taste

Food species	taste parameters	Pressure (MPa)	Time (min)	CO_2/sample (w/w)	Temperature (°C)	System	Change	Corresponding mechanisms of taste change in Figure 1	References
Carrot juice	pH	4.9	5		5	Batch	Decrease	1.2	Park et al., 2002
Carrot juice	pH	10, 20, 30	15–60		25	Batch	Decrease	1.2	Zhou et al., 2009
	TA						Increase		
Milk	pH	0–6	15, 30		5, 25, 40, 50	Batch	Decrease	1.2	Hofland et al., 1999
Bovine colostrum	pH	20	15–75		37	Batch	Decrease	1.2	Liao et al., 2009
Nutrient broth	pH	10	50, 80, 90 10		30	Batch	Decrease	1.2	Erkmen, 2001
Liquid whole egg	pH	13			45	Batch	Decrease	1.2	Garcia-Gonzalez et al., 2009
Blood Orange juice	pH, TA	23,13	15	0.770, 0.385	36	Continuous	No change	1.2	Fabroni et al., 2010
Orange juice	pH, TA, total phenols	40	10–60		55	Batch	No change	1.2	Niu et al., 2010b
Orange juice	pH	7–34	15–180		35–60	Batch	No change	1.2	Arreola et al., 1991
	TA						Increase		
Orange juice	pH	38, 72, 107	10	0.40–1.18		Continuous	No change	1.2	Kincal et al., 2006
	TA						Increase		
Coconut water	pH	34.5	6	13%CO_2	25	Continuous	No change	1.2	Damar et al., 2009
	TA						Increase		
	Soluble phenolics						Reduction less than thermal treated samples		
Red grapefruit juice	pH	34.5	7		40	Continuous	No change	1.2	Ferrentino et al., 2009b
	TA						Increase		
	Total phenolic						No change		
Muscadine grape juice	pH, TA, Total soluble phenolics	34.5	6.25	8%, 16%	30	Continuous	No change	1.2	Pozo-Insfran et al., 2006
Muscadine grape juice	pH, TA	27.6	6.25	0, 7.5%, 15%	30	Continuous	No change	1.2	Pozo-Insfran et al., 2007
Apple juice	pH	7.0, 13.0, 16.0	40, 80, 150		35, 50, 60	Batch	Decrease	1.2	Ferrentino et al., 2009a
Apple juice	TA, malic acid, citric aci, ascorbic acid, fructose, glucose, sucrose, polyphenols	10	10		36	Batch	No change	1.2	Gasperi et al., 2009
Apple juice	pH	8, 10, 12	40		65, 70	Batch	No change	1.2	Bae et al., 2009
Apple cider	pH	6.9–48.3	/	0, 70, 140 g/kg	25–45	Continuous	No change	1.2	Gunes et al., 2006
Apple slices	pH	20	20		45, 55, 65	Batch	No change	1.2	Niu et al., 2010a
Peach juice	pH	30	0.5, 10, 40, 60		55	Batch	No change	1.2	Zhou et al., 2010
	Total phenols						Reduction	1.3	
Conference pear	pH	10	10		32, 40, 49, 58	Batch	No change	1.2	Valverde et al., 2010
Meat	pH	7.4, 15.2	10		31.1	Continuous	No change	1.2	Choi et al., 2008
Chilled pork	pH	7, 14, 21	30		50	Batch	No change at 7 and 14 MPa, decreased significantly at 21 MPa	1.2	Yan et al, 2010

Table 2 Summary of studies on effect of HPCD on flavor by instruments

Food species	Measurement method	Pressure (MPa)	Time (min)	CO_2/sample (w/w)	Temperature (°C)	System	Change	Corresponding mechanisms of aroma change in Figure 1	References
Apple juice	SPME GC-MS; PTR-MS	10	5, 10, 20		36	Multi-batch	Overall depletions of 35%	1.4	Gasperi et al., 2009
Orange juice	SPME GC	600	2.17		25	Batch	Significant for the lower-molecular-weight compounds	1.4	Boff et al., 2003
Orange juice	SPME-GC	40	10, 20, 30, 40, 50, 60		55	Batch	Significant for the lower-molecular-weight compounds	1.5	Niu et al., 2010b
Hami-melon juice	SPME GC-MS	35	60		55	Batch	Insignificant	/	Chen et al., 2010
Beer	GC-O/GC-FID/MS	27.6	5	10%	21	Continuous	Depletions of 49% for ethyl hexanoate	1.4	Dagan et a l., 2006

Table 3 Summary of studies on effect of HPCD on flavor by sensory analysis

Food species	Pressure (MPa)	Time (min)	CO_2/sample (w/w)	Temperature (°C)	System	Change	Corresponding mechanisms for changing in Figure 1	References
Apple juice	10	10		36	Multi-batch	Partly significant	1.4	Gasperi et al., 2009
Coconut water beverage	13.8, 24.1, 34.5	6	7%, 10%, 13%	20, 30, 40	Continuous	Insignificant	/	Damar et al., 2009
Orange juice	38, 72, 107	10	0.40-1.18		Continuous	Insignificant within two weeks, but significant from the third week	/	Kincal et al., 2006
Blood orange juice	13		0.385	36	Continuous	Significant from 25th day, off-flavor increased significant	/	Fabroni et al., 2010
Muscadine grape juice	35.5	6.25	8%, 16%	30	Continuous	Insignificant	/	Pozo-Insfran et al., 2006a
Grape juice	48.3		0.17	35	Continuous	Insignificant	/	Gunes et al., 2005
Beer	27.6, 20.7	5	10%	21		Insignificant	1.4	Dagan and Balaban, 2006

HPCD-treated beer was decreased on average by about 49% (Dagan and Balaban, 2006). However, more researches showed that HPCD slightly influenced the volatile compounds, especially as compared to the thermal treatment (Chen et al., 2010; Dagan and Balaban, 2006; Niu et al., 2010b) (Table 2). No change in ester composition (ethyl acetate, ethyl propanoate, ethyl butyrate, butyl acetate, and ethyl-2-methyl butyrate), and slight changes in alcohols and aldehydes, such as (Z)-nonel-3-ol, (E,Z)-2,6-nonadien, (Z)-nonel-6-ol, and nonanol, hexanal, (Z)-6-nonenal, nonanal, and 2-nonenal in hami-melon juice after HPCD at 35 MPa and 55°C for 60 min and four-week storage at 4°C were observed (Chen et al., 2010). Except ethyl hexanoate, the main volatile compounds (ethyl heptanoate, ethyl octanoate, ethyl phenylacetate, dodecenal, and dodecanoic acid) in beer after HPCD had negligible differences (Dagan and Balaban, 2006). Although concentration of ethyl butyrate and trans-2-hexenol decreased in HPCD-treated orange juice, they were higher than in the thermally processed juice (Niu et al., 2010b).

As shown in Table 3, sensory evaluations were applied by more researches, supporting the above results of chemical analysis. Sensory panelists did not recognize the aroma and taste differences between the HPCD-treated and fresh beer, although ethyl hexanoate decreased (Dagan et al., 2006). The aroma of HPCD- and heat-treated coconut water showed no difference, but the heat-treated samples had significantly higher taste difference and off-flavor from untreated samples as compared to that of the HPCD-treated samples (Damar et al., 2009). Weekly comparisons of treatments showed that HPCD-treated and heat-treated beverages were significantly different initially and became similar from the second week (Damar et al., 2009). No significant difference in taste and aroma between fresh and HPCD-treated muscadine grape juices, but significant difference to the heat-treated samples (Pozo-Insfran et al., 2006a). The panelists could not detect any significant difference between the controls (frozen, fresh orange juice) and the HPCD-treated orange juice after two-week storage at 1.7°C, when vacuuming at <1.02 Pa for 10 min was applied after processing to remove residual CO_2, but started to differentiate between the controls and treated samples by the third week (Kincal et al., 2006). Fabroni et al. (2010) indicated that the freshness, flavor, intensity of taste, and intensity of scent in the HPCD-treated blood orange juice decreased, while off-flavor increased significantly after 25 days. The flavor threshold could be an important factor of the relevance between the chemical analysis and sensory evaluation. This was why there were some volatile compounds decreased without being detectable to panelists (Dagan and Balaban, 2006).

As shown in Figure 1, HPCD-induced flavor changes including the taste and aroma in foods could be attributed to biochemical or enzymatic reactions, chemical reactions, and some physical effects. Normally, lowering pH effect of HPCD resulted in the sourness change in food taste due to CO_2 dissolution and dissociation. However, HPCD-induced changes in food aroma were more complex. The physical effects were the followings. Volatile compounds could be stripped off by CO_2 during HPCD decompression and supercritical extraction (Supercritical CO_2 was CO_2 at a temperature and pressure above its critical point values: $T_c = 31.1$°C, $P_c = 7.38$ MPa). In fact, HPCD was reported to be used to the removal of the undesirable flavor of the pigment extracts from crucifer plants (Liao et al., 2008; Yang et al., 2011). Low-molecular-weight compounds were easily lost than high-molecular-weight compounds, different kinds of food products had different volatile compounds, so there were

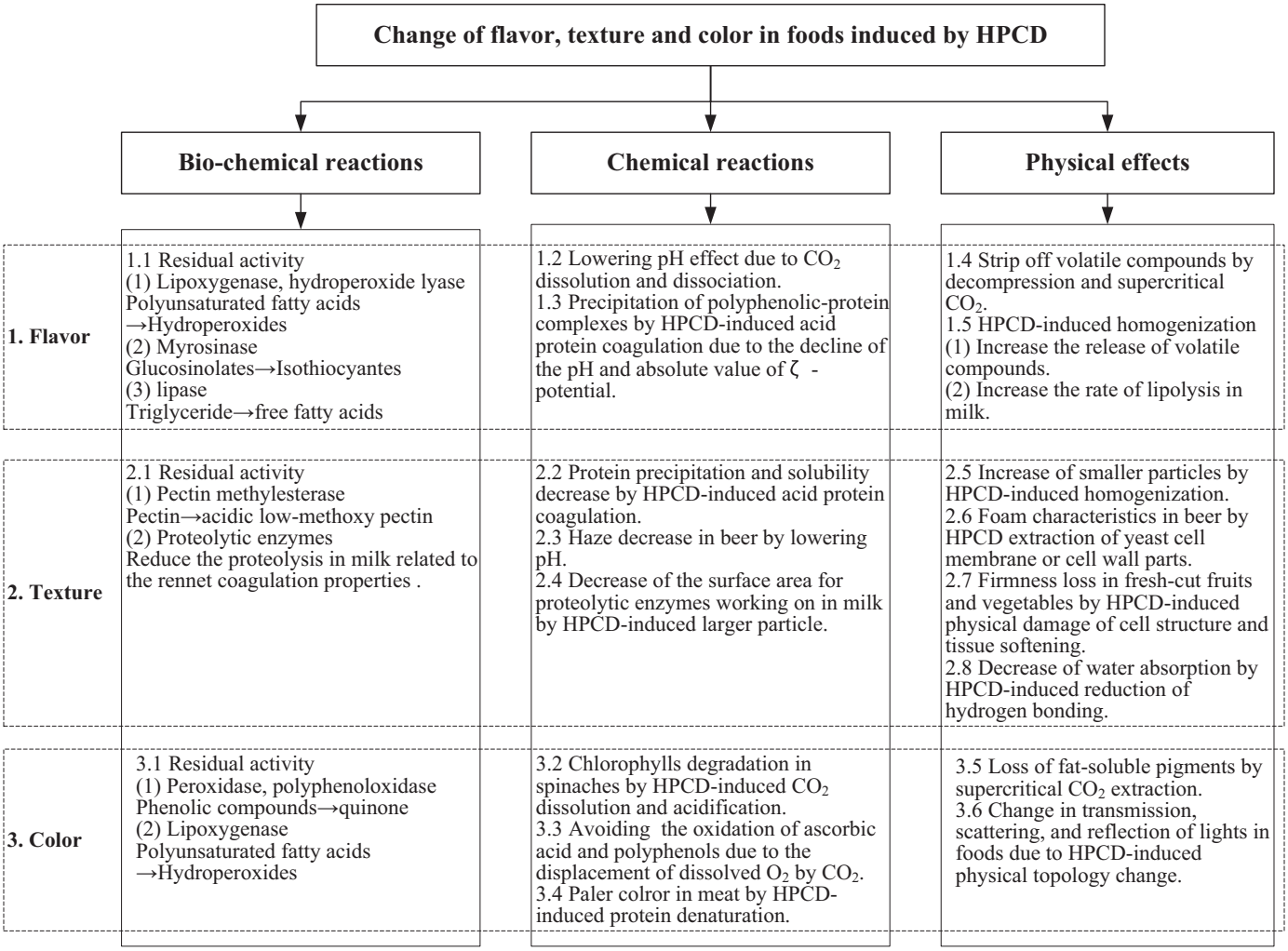

Figure 1 Assumption of possible mechanisms of high pressure CO_2 on flavor, texture, and color of foods.

different results after HPCD (Gasperi et al., 2009; Niu et al., 2010b). Moreover, HPCD-induced homogenization made the larger size particles in foods to smaller, and promoted volatile compounds in foods to release and changed mouth feel. Niu et al. (2010b) reported that the volatile compounds in HPCD-treated orange juice increased. The chemical reactions in foods were closely temperature-dependent. Low and moderate temperature during HPCD could avoid the loss of heat-sensitive compounds degraded by traditionally thermal processing (Dagan and Balaban, 2006; Damar et al., 2009; Pozo-Insfran, et al., 2006a). The biochemical reactions in foods resulted from indigenous enzymes. Indigenous enzymes in foods catalyzed the substrates and produced off-flavors of HPCD-treated foods during storage due to their residual activity. Lipoxygenase and hydroperoxide lyase were partly responsible for the development of the rancid taste as they catalyzed the oxidation of polyunsaturated fatty acids (Oey et al., 2008), and the pathway of the oxidation metabolism leading from linolenic acid to volatile aldehydes was shown in Fig. 2 (Casey et al., 1996). Yang et al. (2011) reported the residual myrosinase in HPCD-treated red cabbage catalyzed the glucosinolates into the odorous products such as isothiocyantes. Chen et al. (2010) also found that the lipoxygenase activity influenced the volatile flavor of hami-melon juice, especially after storage for four weeks. Tisi (2004) found that the free fatty acid in all HPCD-treated-milk was significantly higher than the control. The increase in the rate of lipolysis was due to HPCD homogenization effect, which caused increase in surface area of fat globule and allowed the lipoprotein lipase more access to its substrate (Tisi, 2004).

EFFECTS OF HPCD ON TEXTURE OF FOODS

Textural parameters of solid and semi-solid foods were perceived with the sense of touch, either when the product was picked up by hand or placed in the mouth and chewed (Barrett et al., 2010), while for liquid foods such as puree and juice, it also related to the clarification, cloud, turbidity, and rheology. The terms texture, rheology, consistency, and viscosity were often used interchangeably, despite in the fact that they described

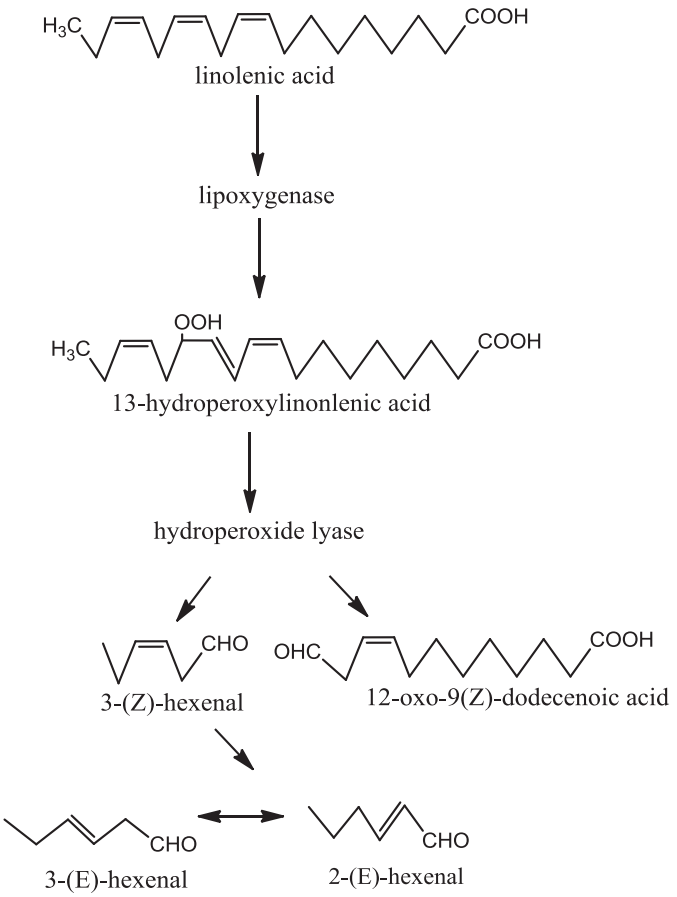

Figure 2 Pathway of oxidation of polyunsaturated fatty acids by lipoxygenase and hydroperoxide lyase (Casey, et al., 1996).

properties that were somewhat different (Barrett et al., 2010). Cloud, turbidity, rheology, consistency, viscosity, particle size distribution, firmness, hardness, water retention ability, water absorption, and foam capacity were all included in the scope of the texture terms in this review (Table 4).

Fruit and Vegetable Juices

HPCD have been applied mostly to liquid foods, particularly fruit and vegetable juices. Cloud stability was an important texture quality parameter in fresh unpasteurized juice (Park et al., 2002), and was usually presented as cloud and turbidity. In cloudy juices, cloudy mass provided significant quality attributes related to the flavor, turbidity, and color of the juices in processing. Consumers usually associated cloud loss with spoilage and quality loss of juices. Hence, maintenance of cloud was significant in terms of eye appeal, flavor compounds associated with the cloud matrix, and overall quality of the product (Korner et al., 1980).

Cloud values for continuously HPCD-treated orange juice were higher than for untreated juice, the largest increase of 846% in cloud value was found at 38 MPa and 1.18 CO_2/juice (w/w), and no link was found between PME inactivation and cloud retention (Kincal et al., 2006). Arreola (1991) found that cloud of orange juice was enhanced from 1.27 to 4.01 times regardless of treatment temperature and time after batch HPCD. Zhou et al. (2009) reported that cloud of carrot juice increased significantly (8–59%) with increasing the treatment time. As shown in Table 4, other researchers also found similar enhancement of juice cloud by HPCD (Ferrentino et al., 2009b; Zhou et al., 2009, 2010; Fabroni et al., 2010; Niu et al., 2010b). The cloud of red grapefruit juice mean values remained 1.9 times higher than the untreated samples for all periods of storage despite cloud decrease during six-week storage (Ferrentino et al., 2009b), but cloud values of orange juice remained unchanged regardless of storage time (Fabroni et al., 2010). Boff et al. (2003) reported that CO_2-assisted high-pressure processing juice had the greatest cloud stability by evaluating the effect of high-pressure processing, high-pressure processing+CO_2, and thermal processing on the cloud stability of single-strength Valencia orange juice over four months of storage at 4 and 30°C. The juices remained physically stable at 4 and 30°C during four-month storage although high levels of residual PME activity were present in high-pressure processing+CO_2 juice (Boff et al., 2003). However, some controversial results of juice cloud were found (Park et al., 2002; Niu et al. 2010a). Cloud was greatly influenced by HPCD in the study of Park et al. (2002), showing a 60% loss at 4.90 MPa, meanwhile 47% of cloud was lost under combined treatment of 4.90 MPa HPCD and 600 MPa HHP, with the lowest PME residual activity of 35% (Park et al., 2002). Moreover, Niu et al. (2010a) found that turbidity of cloudy apple juice from HPCD-pretreated apple slices was significantly lower than from mild heat-treated apple slices although the residual activity of PME in the cloudy apple juice from HPCD-pretreated apple slices was significantly lower. After seven-day storage at 4°C, the greatest loss of cloudy apple juice turbidity was 40.35% by HPCD at 65°C even if the sample had the lowest residual activity of PME (Niu et al., 2010a).

Normally, clarification or cloud loss was mainly due to the enzymatic activity of pectin methylesterase (PME, EC 3.1.1.11). Pectin surrounding the cloud particles was attacked by PME, yielding acidic low-methoxy pectin, which could form insoluble pectate precipitates with polycations (Ly Nguyen et al., 2003; Guiavarc'h et al., 2005), and the reaction of pectin catalyzed by PME was shown in Figure 3. However, HPCD seemed to influence the cloud of juices in a nonenzymatic way in these studies (Park et al., 2002; Niu et al., 2010a). Zhou et al. (2010) proposed an interaction mechanism between HPCD-induced acid protein coagulation and HPCD-induced homogenization for increasing or maintaining juice cloud. On one hand, the decline of the pH

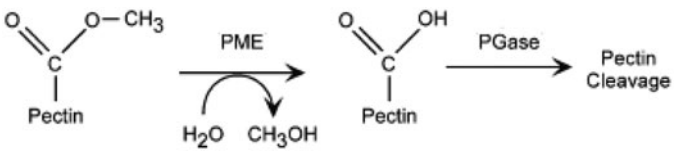

Figure 3 Reaction of pectin catalyzed by pectinmethyl esterase (Francis et al., 2006).

Table 4 Summary of studies on effect of HPCD on texture

Food species	Texture parameter	Measurement method	Pressure (MPa)	Time (min)	CO_2/ sample (w/w)	Temperature (°C)	System	Change	Corresponding mechanisms of texture change in Figure 1	References
Orange juice	Cloud	Absorbance at 660 nm	8.3, 13.1, 20, 26.9, 31.7	120, 240		45, 50,	Batch	Increased by 127–401%	2.1, 2.5	Arreola et al., 1991
Orange juice	Cloud	Absorbance at 660 nm	38, 72, 107	10	0.40–1.18		Continuous	Increased between 446% and 846%	2.1, 2.5	Kincal et al., 2006
Orange juice	Cloud	Absorbance at 660 nm	40	10, 20, 30, 40, 50, 60		55	Batch	Increased by 91–115%	2.1, 2.5	Niu et al., 2010b
Orange juice	Cloud	The percent transmission at 650 nm	600	2.17		25	Batch	1–1.5%	2.1	Boff et al., 2003
Carrot juice	Cloud	Weighing method	4.90	10		5	Batch	60% loss	2.1,	Park et al., 2002
Carrot juice	Cloud	Nephelometric turbidity	10, 20, 30	15, 30, 45, 60		25	Batch	Increased by 8–59%	2.1, 2.2, 2.5	Zhou et al., 2009
Red grapefruit juice	Cloud	Absorbance at 660 nm	13.8, 24.1, 34.5	5, 7, 9		40	Continuous	Increased by 91%	2.1, 2.5	Ferrentino et al., 2009b
Blood orange juice	Cloud	Absorbance at 660 nm	13, 23		0.770, 0.385	36	Continuous	Increased by 109.59%, 162.20%, 263.27%	2.1, 2.5	Fabroni et al., 2010
Apple juice	Turbidity	Nephelometric turbidity	20	20		25, 35, 45, 55, 65	Batch	Increased by 0–37.20%	2.1, 2.2	Niu et al., 2010a
Peach juice	Turbidity	Absorbance at 660 nm	30	0.5, 10, 40, 60		55	Batch	Increased	2.2, 2.5	Zhou et al., 2010
Carrot juice	PSD	Particle size analyzer	10, 20, 30	15, 30, 45, 60		25	Batch	Increased significantly	2.2, 2.5	Zhou et al., 2009
Peach juice	PSD	Particle size analyzer	30	0.5, 10, 40, 60		55	Batch	Increased significantly	2.2	Zhou et al., 2010
Orange juice	PSD	Particle size analyzer	40	10, 20, 30, 40, 50, 60		55	Batch	Increased	2.1, 2.5	Niu et al., 2010b
Raw whole milk, raw skim milk	PSD	Malvern Mastersizer	7, 62		0.101	15, 22, 42, 40	Continuous	Changed	2.2, 2.4, 2.5	Tisi 2004
Casein	PSD	Wet-sieving method	5.52, 4.13,		0.036, 0.042	38	Continuous	Increased	2.2, 2.5	Tomasula et al., 1997
Bovine colostrum	PSD	Particle size analyzer	20	15, 30, 40, 60, 75		37	Batch	Increased	2.2, 2.5	Liao et al., 2009
Carrot juice	Viscosity	Rheometer	10, 20, 30	15, 30, 45, 60		25	Batch	Increased significantly	2.5	Zhou et al., 2009
Peach juice	Viscosity	Rheometer	30	0.5, 10, 40, 60		55	Batch	Increased significantly	2.2	Zhou et al., 2010
Bovine colostrum	Viscosity	Rheometer	20	15, 30, 40, 60, 75		37	Batch	Decreased	2.2	Liao et al., 2009

(Continued on next page)

Table 4 Summary of studies on effect of HPCD on texture *(Continued)*

Food species	Texture parameter	Measurement method	Pressure (MPa)	Time (min)	CO_2/ sample (w/w)	Temperature (°C)	System	Change	Corresponding mechanisms of texture change in Figure 1	References
Orange juice	Viscosity	Rheomete	40	10, 20, 30, 40, 50, 60		55	Batch	Decreased	/	Niu et al., 2010b
Spinach leaves	Firmness	Visual	7.5, 10	10, 20, 40		40	Batch	Decreased	/	Zhong et al., 2008
Conference pear	Firmness	Penetrometer	49		10	32, 40, 49, 58	Batch	Decreased	2.7	Valverde et al., 2010
Carrot slices	Hardness	Texture analyzer	1.5, 3, 5	2, 5, 8, 12, 15		20	Batch	Increased for two minutes, but decreased slowly after five minutes	2.1, 2.7	Bi et al., 2011
Beer	Haze	Nephelometric turbidity	27.6, 20.7	3, 4, 5		25, 35, 45	Continuous	Decreased	2.3	Dagan et a., 2006
	Foam capacity							Increased	2.6	
Milled rice	Water absorption	Weighing method	0.4, 0.6, 0.8	120, 150, 180, 210, 240, 300, 360, 480, 600, 720, 840			Batch	Decreased	2.8	Noomhorm et al., 2009
	Hardness	Back extrusion test						Decreased	/	
	Paste viscosity	Rapid Visco Analyzer						Decreased	/	
Chilled pork	Water retention capability	Weighing method	7, 14, 21	30		50	Batch	No significantly change	/	Yan et al., 2010
	TBA value	Spectrophotometry						No significantly change	/	

and absolute value of ζ-potential of juices after HPCD treatment caused the coagulation of protein and decrease of particle charge, responsible for the acceleration of the precipitation formation (Zhou et al., 2010), which resulted in loss of juice cloud. ζ-potential was measured as the electrophoretic mobility of hydrocolloids to characterize the surface charge (Lutz et al., 2009). And it has been used to assess the stability of colloidal systems because it was a very good index of the magnitude of colloidal electrostatic repulsive forces (Sorrivas et al., 2006). On the other hand, depressurization of HPCD led to homogenization of the juices causing smaller particles of the juice colloid, thereby increasing cloud and stability to PME attack (Kincal et al., 2006; Ferrentino et al., 2009b; Zhou et al., 2009). As a matter of fact, the juice cloud was maintained through the balance between HPCD-induced acid protein coagulation and HPCD-induced homogenization. If HPCD-induced homogenization was less intensive than HPCD-induced acid protein coagulation, the precipitation in juices was accelerated and the juice cloud decreased or lost by HPCD. If HPCD-induced homogenization was more intensive than HPCD-induced acid protein coagulation, the juice cloud was enhanced or retained by HPCD.

In addition to cloud, particle size distribution and viscosity were determined to evaluate the texture quality of HPCD-treated juices. The particle size of HPCD-treated carrot juices for 15, 30, and 45 min increased significantly as compared to untreated juice, but it for 60 min showed a noticeable decrease and was almost close to untreated juice (Zhou et al., 2009). The kinetics of juice particle size as a function of HPCD treatment time was characterized with initial increase and late decrease. Similar results in peach juice (Figure 4) and orange juice treated by HPCD were also observed (Zhou et al., 2010; Niu et al., 2010b). Similar to change of juice cloud, the increase or decrease of juice particle size was also due to HPCD-induced acid protein coagulation and HPCD-induced homogenization. Zhou et al. (2009) proposed that the longer the treatment time or the higher the pressure was, the more intensive the homogenization was. Moreover, HPCD significantly enhanced the viscosity of carrot and peach juice without changing the Newtonian flow behavior (Zhou et al., 2009; 2010), since HPCD-induced homogenization possibly contributed to an increase in solubilization of pectin in cell walls into juices (Zhou et al., 2009). However, the viscosity of HPCD-treated orange juice significantly decreased as compared with untreated juice, and decreased with the increasing treatment time (Niu et al., 2010b).

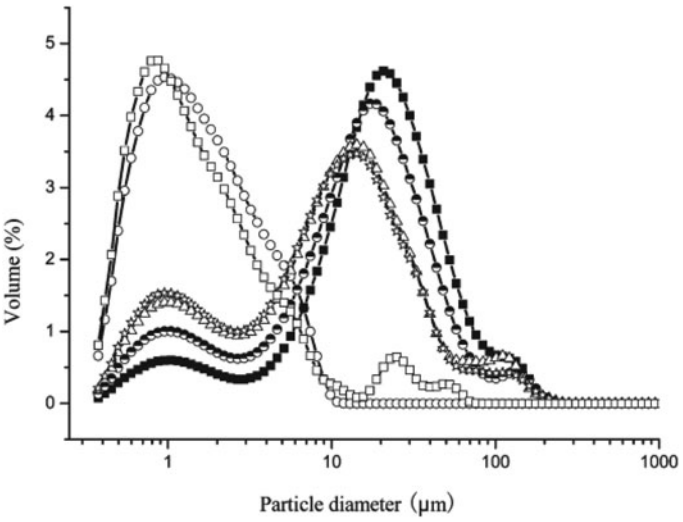

Figure 4 Particle size distribution patterns of peach juices treated by high pressure CO_2 at 30 MPa and 55°C and heat at 90°C for 1 min (Zhou et al., 2010).

Beer

Effects of HPCD on beer texture were only studied by Dagan and Balaban (2006), including changes in haze formation, foaming capacity, and stability. The beer haze was reduced by HPCD from 146 NTU to 95 NTU, this change was caused by the pH change associated with this process (Dagan and Balaban, 2006). The pH dropped by the creation of carbonic acid, which would affect protein and polyphenol conformation, interfering with protein-polyphenol complexes (Dagan and Balaban, 2006). Foam capacity and stability were minimally influenced by HPCD, changes would most likely be unnoticed by consumers (Dagan and Balaban, 2006). Changes seen in foam characteristics due to HPCD may have been caused by the extraction of yeast cell membrane or cell wall parts that may have changed the amount of hydrophobic compounds in the beer, therefore, changed foaming (Dagan and Balaban, 2006).

Fresh-Cut Fruits and Vegetables

Fresh-cut fruits and vegetables must have an attractive appearance, acceptable flavor, appropriate texture, and a positive nutritional image to attract initial and continued purchase by consumers (Barrett et al., 2010). While consumers generally cited flavor as the most important quality attribute for fruits and vegetables, textural defects, and the interactions of flavor and texture were more likely to cause rejection of a fresh product (Harker et al., 2003). The HPCD-treated fresh-cut pears lost their firmness more than if only heat was applied, and furthermore, this loss was higher as pressure was increased (Valverde et al., 2010). Similar findings were reported in strawberries and melon (Haas et al., 1989). The HPCD-treated spinach leaves also showed the great decrease of firmness (Zhong et al., 2008). This firmness loss was manifested as a softer aspect and a loss of liquid, which could be related to the physical damage that the pressure could originate (Valverde et al., 2010). HPCD caused a significant increase of relative electrolyte leakage in carrot slices (Bi et al., 2011), which indicated HPCD resulted in physical membrane damage to cell structures. However, the firmness of fresh-cut carrot slices was increased by 11.0–25.8% after HPCD immediately, and then its largest loss of 7.9% was obtained at 5 MPa and 20°C for 15 min (Bi et al., 2011). Except the firmness loss from HPCD-induced physical damage to cell

structures, an increase in firmness was observed and could be attributed to the activation of PME. Bi et al. (2011) reported that HPCD increased the activity of PME by 27.2–32.9% in carrot slices. PME hydrolyzed the methyl ester linkages in pectin molecules, releasing methanol and free galacturonic acid moieties and the resulting free carboxyl groups may then form cross-links between pectin polymers through salt-bridge formation with divalent cations (notably Ca^{2+}) naturally present in the tissues (Ni et al., 2005). However, excessive demethylation caused by PME remaining in HPCD treated-samples also changed the pectin configuration and caused tissue softening by loosening of cell wall components (Bi et al., 2011).

Dairy Products and Soybean Protein

There have been some papers related to the effects of HPCD on proteins. Hu et al. (2011) also reviewed on enzyme inactivation and its mechanism of HPCD in food processing using HPCD, therefore the enzymes were not discussed. Here, we emphasized the effect of HPCD on proteins in dairy products and soybean proteins. Changes of textures of diary products after HPCD were observed (Tomsasula et al., 1997; Hofland et al., 1999; Tisi, 2004; Khorhid et al., 2007). HPCD changed the particle size distribution of raw, whole milk, and skim milk as compared to untreated controls (Tisi, 2004). The peak in the main mode of the control sample was at about 4 μm, while a new peak in HPCD-treated milk emerged in the particle size distribution at about 8 μm, which became larger with increasing temperature (Tisi, 2004). The particle size distribution of the bovine colostrum increased, but its viscosity decreased after HPCD (Liao et al., 2009). This change of particle size distribution in milk products was due to HPCD-induced denatured proteins. HPCD induced the denaturation of protein due to the decline of pH and the absolute value of ζ-potential (Zhou et al., 2010), resulting protein aggregation and/or precipitation, as well as decrease of solubility (Tisi, 2004; Liao et al., 2009). Therefore, HPCD utilization for precipitation of casein instead of organic acids have been investigated in previous studies (Jordan et al., 1987; Tomasula et al., 1995; Tomasula et al., 1997; Hofland et al., 1999; Calvo and Balcones, 2001; Khorshid et al., 2007). HPCD was able to precipitate 99% of the casein in skim milk at 3.5 MPa and 50°C with or without a holding time at operating pressure, and low processing temperatures could inhibit precipitation (Jordan et al., 1987). Tomasula et al. (1995) obtained same yield of casein after HPCD by pressures between 2.8 and 5.5 MPa, independent with holding times. These results suggested that treatment temperature of HPCD was a critical variable in casein production rather than holding time. The HPCD batch system used in these studies had a long come up time and once the isoelectric point was reached, all susceptible casein was precipitated (Jordan et al., 1987). Moreover, Tomasula et al. (1997) found that the casein yield from the tubular reactor was greater than that from the spary reactor and both reactors gave casein products of good quality. Calcium was regarded one of the most important minerals in dairy foods. Curd Ca contents from continuous and batch HPCD operation, averaged 1.4% by weight dry basis, were similar (Tomasula et al., 1995; Tomasula et al., 1997), but about three times greater than that obtained by Jablonka and Munro (1985) for mineral acid precipitated curd. High Ca content in HPCD-precipitated casein was also found (Hofland et al., 1999). Unlike precipitation with mineral acids that lead to an almost Ca-free curd, precipitation of casein with CO_2 results in a curd where some of the micellar Ca phosphate remained with the curd, due to the higher precipitation pH of 5.8 as opposed to that of acid casein's 4.8 (Tomasula et al., 1997). In addition, the curd precipitated by HPCD at high pH 5.8 and with high Ca content did not have the rubbery feel of the curd by mineral acid at pH 4.8 (Tomasula et al., 1997). Similarly, HPCD was also used for precipitation of soybean proteins (Khorshid et al., 2007). It was possible to achieve 68.3 wt% of soy protein precipitate using HPCD at 3 MPa, pH 5.60 and 22 $\pm$ 1°C. The qualitative analysis using RP-HPLC for soy protein precipitated at 3 MPa showed two separated peaks, one for soy protein glycinin with molecular weight of 350 kDa and the other for soy protein β-conglycinin with molecular weight of 180 kDa, while the precipitate at 4 MPa showed only one peak for pure soy protein β-conglycinin with a lower molecular weight.

HPCD was inhibitory to the rate of proteolysis of milk and skim milk by acting on the enzymes and/or substrate (Tisi, 2004). Proteolysis in milk products can produce desirable flavors and texture during cheese ripening (Farkye and Fox, 1992), while uncontrolled proteolysis can alter the rennet coagulation properties of milk, leading to poor curd formation (Srinivasan and Lucey, 2002), development of bitter flavors, increase in viscosity, and gelation of heated milks (Datta and Deeth, 2003; Kohlmann et al., 1991). Milk treated at 7 MPa had a significantly lower rate of proteolysis than that of sample treated at 62 MPa treatments at all temperatures (Tisi, 2004). This was probably caused by more than one force acting in tandem, treatments at 7 MPa produced a larger particle than at 62 MPa (19.3 vs. 14.6 μm in volume mean diameters); with less surface area for the enzyme to work on in the 7 MPa treatments, the rate of proteolysis was effectively reduced (Tisi, 2004).

Meat Products

HPCD-induced textural changes in meat product processing were also investigated (Choi et al., 2008; Yan et al., 2010). When HPCD was applied to meat, both the pressure and temperature could affect molecular interactions and protein conformation, leading to protein denaturation (Messens et al., 1997). Choi et al. (2008) showed that the solubility of sarcoplasmic (from 80.73 mg/g to 70.26 mg/g) and total protein (from 215.8 mg/g to 202.4 mg/g) in porcine *longissimus dori* muscle decreased after HPCD, and the major denatured protein were determined to be phosphorylase b, creatine kinase, triosephosphate isomerase, and one unknown protein (about 26 kDa). HPCD could not change the water holding capacity and water retention

capability immediately in meat product (Yan et al., 2010; Choi et al., 2008), but higher HPCD pressure had the worse effect on the water holding capacity during the storage at 0∼4°C (Yan et al., 2010). As reported by Huff-Lonergan and Lonergan. (2005), rate and extent of pH decline, proteolysis and even protein oxidation were key in influencing the ability of meat to retain moisture. However, HPCD had no significant effect on myofibril fragmentation index value of chilled pork (Yan et al., 2010).

Rice Product

HPCD-induced textural changes in rice product were also investigated (Noomhorm et al., 2009). Noomhorm et al. (2009) investigated HPCD as a possible means of controlling *Sitophilus zeamais* in milled rice. Water absorption, cooked rice hardness, final viscosity, setback, and consistency decreased with increasing the pressure range of 0.4–0.8 MPa. Reduction of hydrogen bonding by blocking water binding sites of CO_2 might explain the decrease in water absorption and setback value, which indicated retarding of retrogradation in cooked rice (Noomhorm et al., 2009)

EFFECTS OF HPCD ON COLOR OF FOODS

Color is one of important quality characteristics of foods and major factor related to sensory perception and consumer acceptance of foods. Table 5 gave a survey of HPCD on food color. HPCD led to the increase of lightness in Hunter system for orange juice (Kincal et al., 2006; Arreola et al., 1991; Yagiz et al., 2005), cloudy apple juice (Gui et al., 2006), carrot juice (Park et al., 2002; Zhou et al.,2009), hami-melon juice (Chen et al., 2010), bovine colostrum (Liao et al, 2009), chilled pork (Yan et al., 2010), and meat (Choi et al., 2008). However, some studies observed that the lightness did not significantly change in orange juice (Niu et al., 2010b), cloudy apple juice (Niu et al., 2010a), and red grape juice (Ferrentino et al., 2009b). Moreover, Fabroni et al. (2010) and Valverde et al. (2010) observed the lightness of HPCD treated-blood orange juice and pear decreased by 9.26–17.48% and 30.53–44.09%, respectively. The color change during storage was also investigated among these studies. The lightness of HPCD-treated cloudy apple juice was higher than that of the control during the four-week storage at 4°C, and the initial lightness of the control was 55.27 ± 0.01 (Gui et al., 2006). Similar results were found in other studies (Kincal et al., 2006; Ferrentino et al., 2009b; Chen et al., 2010).

The observation of the redness and yellowness in HPCD-treated foods showed differences in literature. HPCD decreased the redness in orange juice by approximately 7% and 14.09–17.48%, respectively in Kincal et al. (2006) and Fabroni et al. (2010) study, 4.82–14.43% in cloudy apple juice (Ferrentino et al., 2009a), 13% in carrot juice (Park et al., 2002), 20.62–24.32% in meat (Choi et al., 2008), and 12.28–20.73% in chilled pork (Yan et al., 2010). However, HPCD resulted in the redness increased by 1.58–24.67% in carrot juice (Zhou et al., 2009), 18.56% in red grape fruit juice (Ferrentino et al., 2009b), approximately 10–20% bovine colostrum (Liao et al., 2009) and 55.38–378.57% in pear (Valverde et al., 2010). Niu et al. (2010a) also reported the redness increased by approximately 50% in cloudy apple juice from HPCD-treated apple slices (The specific data was not given in Niu's study). However, Gui et al. (2006) showed that the redness in cloudy apple juice remained constant after HPCD. The yellowness did not change in HPCD-treated orange juice (Kincal et al., 2006), cloudy apple juice (Gui et al., 2006), carrot juice (Zhou et al., 2009), and red grape juice (Ferrentino et al., 2009b). HPCD resulted in the increase of the yellowness by approximately three times in carrot juice (Park et al., 2002), 40% in bovine colostrum (Liao et al., 2009), 7.87–54.13% in pear (Valverde et al., 2010) and 30.09–35.93% in meat (Choi et al., 2008). Fabroni et al. (2010) found that the yellowness in blood orange juice decreased by 10.52–29.68%, and Niu et al. (2010a) showed the yellowness changed with fluctuation.

Among these above-mentioned studies, some showed that the total color difference of HPCD-treated samples decreased with increasing the pressure (Kincal et al, 2006, Gui et al., 2006, Chen et al., 2010). But some observed the opposite situation (Park et al., 2002; Choi et al., 2008) and others found that the total color difference increased with increasing the treatment time (Zhou et al., 2009; Liao et al., 2009). The color density of red grape fruit juice became higher while the hue hint did not change (Ferrentino et al., 2009b) and a slight color reduction on color intensity was found in paprika (Calvo and Torres, 2010).

Others also investigated visually the color change of foods after HPCD. The orange juice turned more yellowness (Arreola et al., 1991; Yagiz et al., 2005; Niu et al., 2010b).The yellowness of orange juice and egg mixtures became less intense, and shrimp and chicken meat turned whitish after HPCD (Wei et al., 1991). The spinach lost green color after HPCD (Zhong et al., 2008). No visual change in the diluted apple cider was observed after continuous HPCD (Gunes et al., 2006).

Normally, the color of foods was influenced by three modes including biochemical reactions, chemical reactions, and physical effects during HPCD processing. Firstly, color change in HPCD-treated foods was closely related to the enzymatic activity, such as polyphenoloxidase and peroxidase. The polyphenoloxidase and peroxidase in foods were not totally inactivated by HPCD (Park et al., 2002; Gui et al., 2006; Chen et al., 2010; Niu et al., 2010a), which catalyzed oxidation of phenolic compounds containing two o-dihydroxy groups to the corresponding o-quinone (Joslyn and Ponting, 1951) (Figure 5), and indicated the enzymatic browning. It was also found that the HPCD inactivated chlorophyllase and, therefore, protected chlorophyll from loss (Huang et al., 2010). Pozo-Insfran et al. (2007) observed losses of total anthocyanins (from initial concentration 1275 mg/L to 1075–1093 mg/L at different processing pressures and CO_2 concentrations) in muscadine grape juice after HPCD, and it was possibly attributed to that anthocyanin

Table 5 Summary of studies on effect of HPCD on color

Food species	Color parameter	Pressure (MPa)	Time (min)	CO_2/juice (w/w)	Temperature (°C)	System	Change	Corresponding mechanisms of color change in Figure 1	References
Orange juice	Lightness, redness, and yellowness, color difference	38, 72, 107	10	0.4–0.8		Continuous	Lightness increased, redness decreased, while yellowness did not change. ΔE decreased as pressure increased	/	Kincal et al., 2006
Orange juice	Lightness, redness, and yellowness	7–34	15–180		35–60	Batch	Lightness increased	/	Arreola et al., 1991
Orange juice	Lightness, redness, and yellowness	13.8–41.4	7–9		25–45	Continuous	Lightness and yellowness increased, redness decreased	/	Yagiz et al., 2005
Orange juice	Lightness, redness, and yellowness, hue and chroma	40	10–60		55		Lightness unchanged, redness decreased and yellowness increased, hue and chroma did not change	/	Niu et al., 2010b
Citrus fruit juice	Lightness, redness, and yellowness					Batch	Lightness increased	/	Jwa et al., 1996
Blood orange juice	Lightness, redness, and yellowness	23, 13		0.77, 0.385		Continuous	The lightness, redness, and yellowness decreased	/	Fabroni S., et al., 2010
	Ascorbic acid, anthocyanins, and flavanones total phenols						No change under less pressure and reduction at higher pressure		
Apple juice	Lightness, redness, and yellowness	20	20		25, 35, 45, 55, 65	Batch	Lightness did not increase except at 35°C, redness increased and yellowness decreased at 35°C and 55°C	3.1	Niu et al., 2010a
	Browning degree						Decreased		
Apple juice	Lightness, redness, and yellowness, color difference	8, 15, 22, 30	60		55	Batch	Lightness insignificantly increased, redness and yellowness remained almost constant. ΔE decreased as pressure increased	3.1	Gui et al., 2006
	Browning degree						Decreased		
Apple juice	Lightness, redness, and yellowness, color difference	7, 13, 16	40, 80, 150		35, 50, 60	Batch	lightness and redness decreased, yellowness changed with fluctuation	/	Ferrentino et al., 2009a

	Polyphenols	10	10		36	Batch	No significant difference	/	Gasperi et al., 2009
Diluted apple cider	Visually	6.9, 27.6, 48.3		0, 70, 140 g/kg	25, 35, 45	Continuous	No visual change in the cider were detected	/	Gunes et al., 2006
Carrot juice	Lightness, redness, and yellowness, color difference	10, 20, 30	15, 30, 45, 60		25	Batch	Lightness and redness increased, yellowness did not significantly change. The ΔE value increased	3.1	Zhou et al., 2009
	Browning degree						Decreased significantly		
	Carotenoids						No significant difference		
Carrot juice	Lightness, redness, and yellowness, color difference	4.9	10		5	Batch	lightness and yellowness increased, redness decrease, and ΔE value increased with pressure increase	/	Park et al., 2002
Hami-melon juice	Lightness, redness, and yellowness, color difference	8, 15, 22, 30, 35	5, 15, 30, 45, 60		35, 45, 55, 65	Batch	ΔE decreased as pressure increased.	3.1	Chen et al., 2010
	Browning degree						Decreased		
	Ascorbic acid						No change		
Coconut Water	Visually	34.5	6	13%CO_2	25	Continuous	Turned pink during storage	/	Damar et al., 2009
Muscadine grape juice	Anthocyanins Soluble phenolics	27.6, 38.3, 48.3		0, 7.5%, 15% CO_2			Reduction loss than thermal treated samples	3.1	Pozo-Insfran et al., 2007
Muscadine grape juice	Anthocyanins	34.5	6.25	8%, 16% CO_2		Batch	higher retention in HPCD-treated juice than thermally pasteurized juices at the end of storage	3.3	Pozo-Insfran et al., 2006a
Muscadine grape juice	Anthocyanins Total soluble phenolics	34.5	6.25	8%, 16% CO_2		Batch	No significant change	3.3	Pozo-Insfran et al., 2006b
Red grape fruit juice	Lightness, redness, and yellowness, color difference				40	Continuous	Lightness and yellowness did not change, redness increased.	/	Ferrentino et al., 2009b
	Color density and hue tint						Hue tint values insignificantly changed while the color density value was higher		
	Total phenolic content						No change		

(Continued on next page)

Table 5 Summary of studies on effect of HPCD on color *(Continued)*

Food species	Color parameter	Pressure (MPa)	Time (min)	CO_2/juice (w/w)	Temperature (°C)	System	Change	Corresponding mechanisms of color change in Figure 1	References
Peach juice	Total phenols	30	0.5, 10, 40, 60		55	Batch	Reduction	3.1	Zhou et al., 2010
Bovine colostrum	Lightness, redness, and yellowness, color difference	20	30,45, 60, 75		37	Batch	Lightness, redness, yellowness, and ΔE increased	/	Liao et al., 2009
Pear	Lightness, redness, and yellowness	6–30	10		25–55	Continuous	Lightness decreased, redness increased, and yellowness decreased	3.1,3.3	Valverde et al., 2010
Chilled pork	Lightness, redness, and yellowness, color difference	7, 14, 21	30		50	Batch	Lightness insignificantly increased, redness decreased	3.4	Yan et al., 2010
Meat	Lightness, redness, and yellowness	7.4, 15.2	10		31.1	Batch	Lightness increased significantly, redness decreased while yellowness increased significantly.	3.4	Choi et al., 2008
Spinach	Visually	7.5, 10	10, 20, 40		40	Batch	It lost color	3.2	Zhong et al., 2008
Chicken meat and shrimp	Visually	6.18, 13.7	120		35	Batch	The outer layer turned whitish	3.4	Wei et al., 1991
Orange juice and egg mixtures							The normal yellow color become less intense	/	

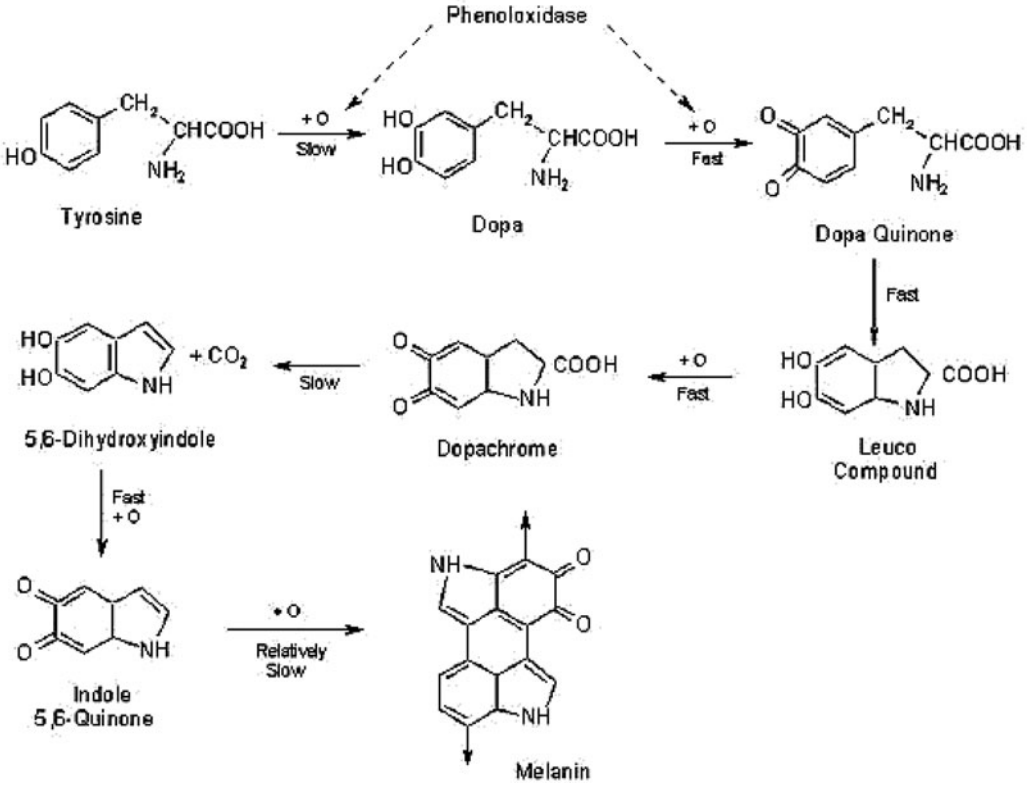

Figure 5 Pathway of enzymatic browning by polyphenoloxidase (Seo et al., 2003).

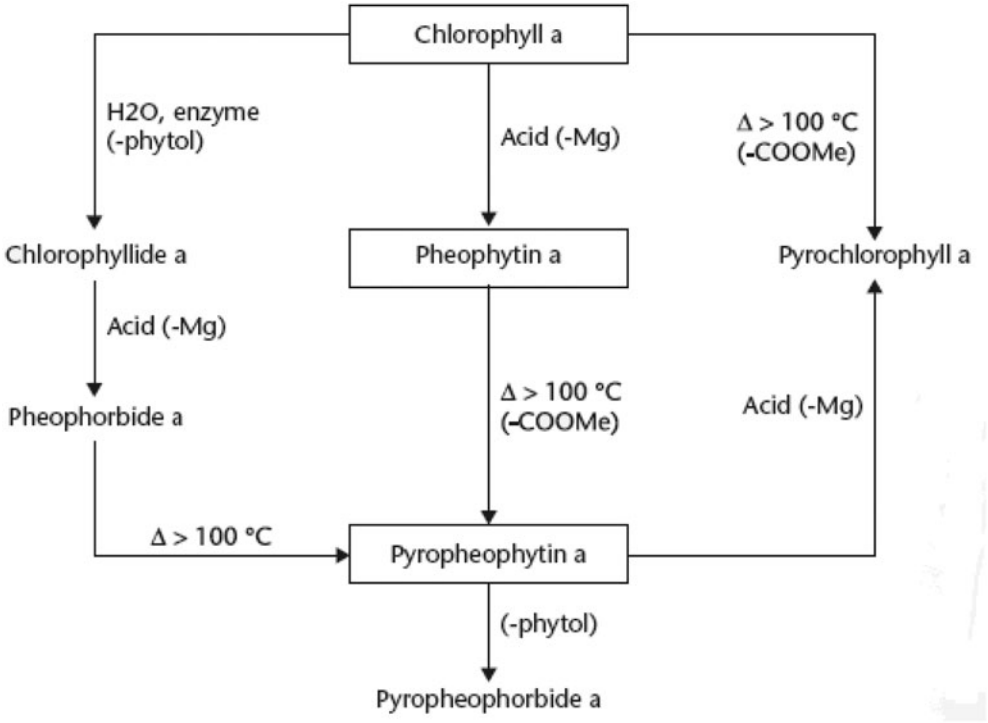

Figure 6 Pathways of the chlorophyll degradation (Kovari, 2004).

degradation in the presence of secondary reactions products from less inactivated polyphenoloxidase in the juice (Fabroni et al., 2010).

Secondly, chemical reactions, such as pigment degradation and oxidation of ascorbic acid and polyphenols, also occurred in HPCD-induced color loss. Longer processing time and higher pressure also resulted in greater leaf discoloration, the discoloration is possibly caused by the dissolution of the CO_2 into leaf tissues, which acidified the leaves and degraded chlorophylls (Zhong et al., 2008). A high concentration of hydrogen ions was formed during HPCD, and the magnesium in the centre of the chlorophyllic group was rapidly replaced by hydrogen ions to form pheophytin, which was a well-known pathway of chlorophyll degradation in Figure 6 (Heaton and Marangoni, 1996; Van Boekel, 1999, 2000). However, the carotenoids of HPCD-treated carrot juices were stable (Zhou et al., 2010). The oxidation of ascorbic acid (Mingotaud et al., 1996) and polyphenols (Corrales et al., 2008) could also lead to the color change as well. No significant difference was detected for the ascorbic acid and polyphenols of HPCD-treated apple juice and melon juice (Gasperi et al., 2009; Chen et al., 2010). Ferrentino et al. (2009b) also reported that the total polyphenols of red grapefruit juice did not change after HPCD and during storage. Normally, CO_2 in HPCD-treated foods was probably beneficial to those antioxidant components retention due to the displacement of dissolved oxygen from the liquid matrix (Boff et al., 2003). Thirdly, extraction of fat-soluble pigments was related to color change during HPCD processing, we did not discuss here. And numerous studied have observed the benefit of supercritical CO_2 extraction. Gnayfeed et al. (2001) used supercritical CO_2 extract carotenoids, tocopherols, and capsaicinoids of paprika. And about 65% lycopoene and 35% b-carotene were extracted from ripe tomatoes by supercritical CO_2 at 4000 psi and 80°C (Cadoni et al., 1999). The denaturation of proteins in foods and texture change modifies the physical topology of foods after HPCD. The paler color for meat after HPCD was found to be associated with the sarcoplasmic protein denaturation (Choi et al., 2008; Yan et al., 2010).

CONCLUSIONS AND FUTURE WORK

HPCD is a unique and potentially promising nonthermal technology in food industry, which can effectively inactivate microorganisms and enzymes. This review illustrated the effects of this technique on flavor, color and texture of foods during processing and storage in recent studies, suggesting that HPCD retained these quality attributes of some foods in most cases. But some controversial observations in which HPCD exhibited detrimental impacts on foods quality were also obtained in some studies. Possible mechanisms, including biochemical reactions, chemical reactions, and physical effects, of HPCD on the effects of flavor, texture, and color of foods were assumed. However, studies on the effects of HPCD on food quality were still limited, and knowledge on the effects on HPCD on food compositions was inadequate. More work needs to be performed in the future. The future work dealing with HPCD on food nutrition, quality, and function should be highlighted. Food nutrition, quality, and function highly depend on food compositions, and the change of the compositions is mainly attributed to biochemical reactions and chemical reactions, sometimes physical effects play a role to some extent. Therefore, the effects of HPCD on food compositions should be addressed, and mechanisms underlying the retention and change of nutrition, quality and function of foods after HPCD processing should be elucidated, especially on the effects of HPCD on bioactive phytochemicals in foods. Moreover, comparison of HPCD with other nonthermal technologies on the effects of food nutrition, quality, and function needs to be studied as well.

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