

High Pressure Treatment Effect on Physicochemical and Nutritional Properties of Fluid Foods During Storage: A Review

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Abstract: Consumers demand foods that are easy to consume and that are of high nutritional and sensory quality. Therefore, they appreciate the similarity of minimally processed products to fresh products. In recent years, the food industry has shown increased interest in nonthermal preservation technologies, because they provide products of proven quality and can be an alternative to traditional thermal methods, thus increasing added value. This review examines the effects of high pressure processing (HPP) on the nutritional and physicochemical parameters of fluid foods. While some general trends can be observed, the effects of HPP differ not only according to treatment intensity, but also according to the food matrix, suggesting that each matrix should be studied separately.

Introduction

In the last decade, new products based on fruit or vegetable juices and milk, mixed or alone, which have good consumer acceptance and high nutritional value, largely due to their high bioactive compound content and their antioxidant capacity, have appeared in Europe and the North American market (Andlauer and Fürst 2002; Heckman and others 2010).

Traditionally, fluid foods have been preserved by thermal treatments such as pasteurization and sterilization. These processes are capable of preventing spoilage and potential human disease; however, they can also result in a loss of compounds responsible for organoleptic and nutritional attributes during the preservation/processing treatment and subsequent storage (Ludikhuyze and Hendrickx 2002).

Nonthermal food preservation technologies can be defined as those in which temperature is not the main factor in the inactivation of microorganisms and enzymes. In most of these technologies there is a slight increase in temperature (Deliza and others 2005; Barbosa-Cánovas and Juliano 2008), without reaching the temperature level that is used for traditional heat treatments (Raso and Barbosa-Cánovas 2003). The purpose of using these technologies is to inactivate the activity of the microorganisms present in the food and also certain enzymes of interest without destroying the nutritional and sensory components that are normally affected during heat treatment. Nonthermal processes are therefore being developed as an alternative to traditional thermal methods (Knorr 1993; Butz and others 2003; Norton and Sun 2008). High pressure (HP) processing has been used to achieve this goal without

affecting food quality. Although the effectiveness of these treatments for making food safe has been known for some time, it is only now that it has become possible to develop this technology and apply it on a large scale in order to bring HP-processed foods to market (Heinz and Buckow 2009; Valdez-Fragoso and others 2011). HP treatment is based on two fundamental principles: the Le Chatelier principle, which proposes that pressure favors all structural reactions and changes that involve a decrease in volume; and the isostatic principle, which proposes that the distribution of pressure is proportional in all parts of a foodstuff irrespective of its shape and size (Heremans 2002; Valdez-Fragoso and others 2011).

Industrial HP installations typically operate discontinuously and can attain pressures of up to 800 MPa, although pressures exceeding 400 MPa are not normally used for foods because they can bring about a reversible or irreversible disruption of inter- and intramolecular bonds (Knorr and others 2006; Heinz and Buckow 2009).

With this kind of treatment it is possible to inactivate and inhibit microorganisms, and it can activate or inactivate enzymes at low temperatures (USFDA 2000; Saucedo-Reyes and others 2009), while compounds of low molecular weight, such as vitamins and compounds related to pigmentation and aroma, remain unaltered (Rastogi and others 2007). In fluid foods, pressure is transmitted uniformly and instantly, that is, there are no gradients (it follows the so-called isostatic rule) (Thakur and Nelson 1998; Toepfl and others 2006). Unlike what happens with heat processes, HP treatment is independent of the size and geometry of the product, which reduces the time required to process large quantities of food (Rastogi and others 2007).

When HP is combined with mild heat treatment (10 to 40 °C), it is very suitable for the pasteurization of fruit juice (Deliza and others 2005; Barbosa-Cánovas and Juliano 2008) and it is used mostly for the production of refrigerated foods (Mújica-Paz and others 2011). This kind of treatment needs low

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storage and distribution temperatures in order to preserve their sensory and nutritional quality. HP treatment has also the potential to be used for sterilization of food products if applied at elevated temperature (60 to 90 °C) and using the temperature increase due to adiabatic compression. By choosing the appropriate process conditions, it is possible to completely inactivate both vegetative cells and microbial spores in order to obtain food products that are shelf-stable (Matser and others 2004; Black and others 2007).

In any case, the evaluation of the sensory and nutritional quality of foods processed by HP processing is a very important factor because it conditions consumer acceptance of the product. But their main drawback is probably the consumer's lack of confidence when deciding whether to buy a "pressurized" product because it is something new and unknown, although this attitude is gradually changing.

In recent decades, as a result of the development of HP treatment, there has been a considerable sales increase in the number of foods processed by this kind of technology. For example, such products have been marketed in Japan since 1990, and in the USA and Europe since 1996. There are currently 160 industrial installations, with volumes ranging between 55 and 420 liters/d and a total annual output of over 250,000 metric tons. HP treatment can be used for preserving a very wide range of foods, including juices and beverages, fruits, and vegetables (Heinz and Buckow 2009; Pereira and Vicente 2010; Mújica-Paz and others 2011).

HP processing is also suitable for other kinds of applications. For example, the combination of high pressure and low temperatures has permitted the development of a new field for the application of high pressure in the food industry in the form of pressure-supported freezing, thawing, and sub-zero storage (Urrutia-Benet and others 2004; Norton and Sun 2008). Another possibility that it offers is its use as a pretreatment to encourage extraction of various bioactive compounds (Knorr 2003; Corrales and others 2008).

Numerous authors have concentrated on studies to evaluate the effect of HP treatment on fluid foods and studies on refrigerated storage to evaluate possible losses of nutrients and physicochemical characteristics in fluid foods after applying HP treatments, in comparison with untreated samples or samples subjected to traditional pasteurization treatments.

Fruit and Vegetable Juices Physicochemical properties

Physical measurements are important because of their potential impact on sensory evaluation parameters such as mouthfeel. There are various studies focusing on HP effects on physicochemical characteristics in different fruit and vegetable juices (Table 1). Bull and others (2004) compared the quality and shelf-life of HP-processed (600 MPa/20 °C/1 min) Valencia and Navel orange juices, and their subsequent storage at 4 and 10 °C for 12 wk, with those of fresh juice and thermally pasteurized juice (65 °C, 1 min). For both juice types, the pH, °Brix, viscosity, titratable acid content, and alcohol-insoluble solids of the pressure-treated or thermally treated juices were not significantly different from those of fresh, untreated juices. The parameters did not change significantly during storage. Clarification (cloud loss) occurred in all treatments, but no difference was found between treatments. The degree of clarification increased significantly over time across all treatments. The authors did not find significant differences in the browning index of HP-processed (600 MPa/20 °C/60 s) Valencia and Navel orange juice, fresh juice, and thermally pasteurized juice (65 °C, 1 min). A significant increase in the browning index

over time was observed across all treatments. Fernández-García and others (2001a) studied the effect of HP processing (500 to 800 MPa/room temperature/5 min) on various physicochemical properties of orange juice and orange-lemon-carrot juice. No significant changes in comparison with untreated juices were noticed in the properties measured, such as sugar content, total acidity, and pH, immediately after HP treatment and during storage (21 d at 4 °C). Barba and others (2011a, 2010) studied the effect of HP treatments (100 to 400 MPa/20 to 42 °C/2 to 9 min) and thermal treatments (90 °C for 15 or 21 s, and 98 °C for 15 or 21 s) on orange juice mixed with milk (**OJM**) and on a vegetable beverage (**VB**). No significant changes were noticed in pH and °Brix for either technology in the liquid foods studied. However, a significant increase was observed in the browning index of the orange juice and milk beverage when heat was applied, and a significant increase in the browning index of the VB when HP was applied. Zhang and others (2011) evaluated the effect of thermal treatment (60 °C for 5, 20, 40, and 60 min) and HP (300, 600, and 900 MPa/60 °C/5, 20, 40, and 60 min) on the color of watermelon juice. They found that the browning degree of the watermelon juice subjected to HP treatment was lower than that of the juice subjected to thermal treatment. Moreover, HP treatments (600 MPa/60 °C/60 min, 900 MPa/60 °C/20, 40, and 60 min) significantly decreased the browning degree of the treated watermelon juice in comparison to untreated juice. The authors concluded that HP treatment with a pressure higher than 600 MPa was effective to avoid browning of treated watermelon juice. They found that each treatment had a different effect on the browning degree of the watermelon juice. The browning degree of the HP watermelon juice decreased when pressure increased. Likewise, these authors found that the browning degree of the watermelon juice increased with an increase in thermal treatment time. However, they did not find significant changes in dynamic viscosity after HP and thermal treatments in comparison with untreated juice. Castellari and others (2000) studied the effects of HP treatment (300 to 900 MPa/20 °C/2 to 10 min) and the use of glucose oxidase-catalase enzymes on the browning index of white grape juice (**GJ**). They did not find significant changes in these parameters after refrigerated storage for 3 wk at 5 °C. Barba and others (2011b) studied the behavior of blueberry juice (**BJ**) after HP treatment (200 to 600 MPa/20 to 42 °C/5 to 15 min) and also did not observe changes in pH and °Brix. Porretta and others (1995) compared the effect of HP (500 to 900 MPa/3 to 9 min) and thermal treatments (98 °C, 15 min) on tomato juice. They found that both increased pressure and longer processing time increased total pectin content, the contribution of processing time was minimal. These authors also observed an increase in total pectin after applying thermal treatment, mainly due to an enzyme inactivation, obtaining that the maximum value for total pectin content, corresponding to a treatment at 900 MPa for 9 min, was lower than the value obtained by the thermal processing.

Color. The color of fruit and vegetable juices is an important attribute in consumer preferences and has been implemented in the quality control of different juice industries. It has also been used by researchers as an indicator of the organoleptic and nutritional quality of food during preservation/processing treatment and subsequent storage because it is connected with the perception of some characteristics that appear to be representative of the quality of processed juices.

Color results can be expressed in a number of different ways, with one of the most common being the Commission Internationale de l'Eclairages (CIE) $L^*a^*b^*$, which uses the following

Table 1—Effect of HP processing on physicochemical properties of some fruit and vegetable juices.

Product	Treatment conditions	Major findings	References
Orange juice	600 MPa/20 °C/1 min, 12 wk storage at 4 and 10 °C	pH, °Brix, total acidity and viscosity were not affected immediately after HP and subsequent storage. The degree of clarification and browning index increased significantly over time	Bull and others (2004)
	500 to 800 MPa/room temperature/5 min, 21 d storage at 4 °C	pH, °Brix, total acidity, and viscosity were not affected immediately after HP and subsequent storage	Fernández-García and others (2001a)
	500 to 900 MPa/60 °C/1 s to 10 min	Turbidity was maintained after HP for longer times	Parish (1998)
	500 to 900 MPa/60 °C/1 s to 10 min	Turbidity was maintained after HP for longer times	Goodner and others (1999)
	600 MPa/5 °C/1 min 500 to 600 MPa/35 to 40 °C/4 to 5 min, 1 to 3 mo storage at 0 to 30 °C	No changes in sensory properties Lower loss of flavor of untreated juice	Takahashi and others (1998) Polydera and others (2003; 2005a)
Orange–lemon–carrot juice	500 to 800 MPa/room temperature/5 min, 21 d storage at 4 °C	pH, °Brix, total acidity and viscosity were not affected immediately after HP and subsequent storage	Fernández-García and others (2001a)
Orange juice mixed with milk	100 to 400 MPa/20 to 42 °C/2 to 9 min	No significant changes in pH and °Brix. Significant decrease in turbidity for all times when pressure was higher than 200 MPa	Barba and others (2011a)
Vegetable beverage	100 to 400 MPa/20 to 42 °C/2 to 9 min	No significant changes in pH and °Brix and turbidity. Significant increase in browning index after HP	Barba and others (2010)
Watermelon juice	300 to 900 MPa/60 °C/5 to 60 min	No changes in dynamic viscosity. HP treatments decreased browning degree of treated juice	Zhang and others (2011)
Grape juice	300 to 900 MPa/20 °C/2 to 10 min, 3 wk storage at 5 °C	No significant changes in browning index after HP	Castellari and others (2000)
Blueberry juice	200 to 600 MPa/20 to 42 °C/5 to 15 min	No significant changes in pH and °Brix	Barba and others (2011b)
Tomato juice	500 to 900 MPa/3 to 9 min	Total pectin increased with increasing pressure and was not greatly affected by treatment time, even if maximum pectin content corresponded to the highest processing and pressure time. Viscosity was strongly dependent on the pressure applied, but independent of treatment time	Porretta and others (1995)
	400 to 500 MPa/2 to 40 °C/10 min, 60 d storage at 4 °C	The sensory characteristics of HP-treated juice remained more stable than those of control juice	Daoudi and others (2002)
	200 MPa/−4 °C/10, 20, 30 min 200 to 400 MPa	No changes in pH or viscosity of whole milk Increase in pH that depends on treatment pressure and time	Kim and others (2008) Schrader and others (1997), Schrader and Buchheim (1998),
Milk	400 MPa/40 to 60 °C/15 min	HP processing maintained or improved organoleptic quality of milk	Huppertz and others (2004), Zobrist and others (2005), García-Risco and others (2000)

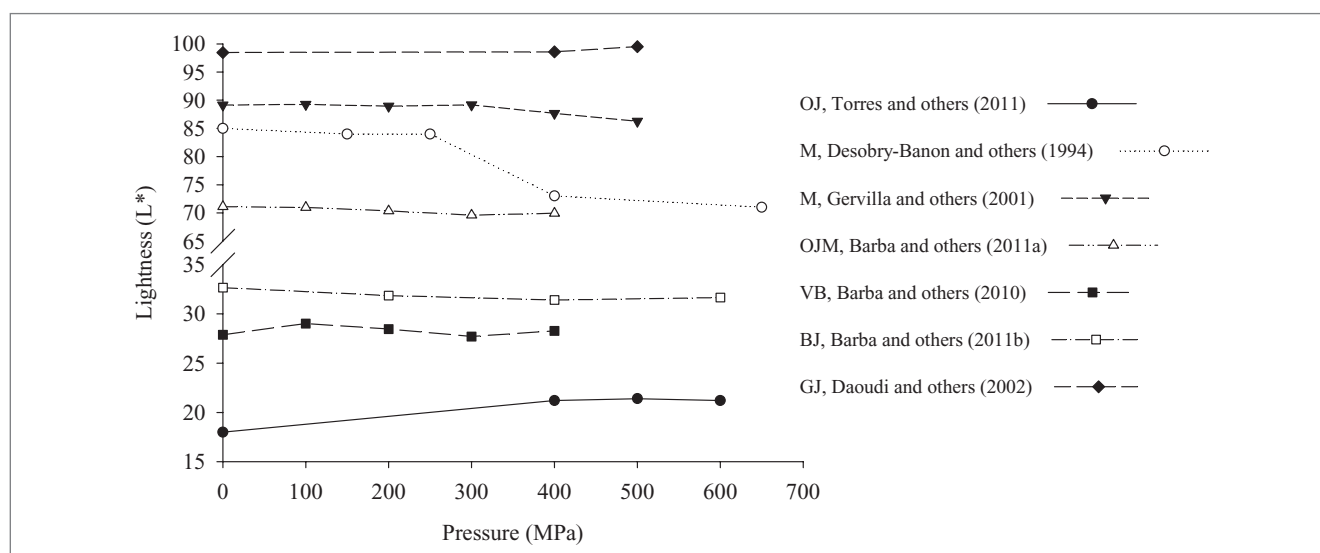


Figure 1—Lightness (L*) values obtained by different authors in orange juice (OJ), milk (M), orange juice mixed with milk (OJM), vegetables beverage (VB), blueberry juice (BJ), and grape juice (GJ) after high pressure processing.

color parameters: L^* , indicating lightness (0 = black, 100 = white), a^* ($-a^*$ = greenness, $+a^*$ = redness), and b^* ($-b^*$ = blueness, $+b^*$ = yellowness). In Figure 1 are shown the lightness values for different fruit and vegetable juices after application of HP treatments.

The total color difference ($\Delta E^* = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$) indicates the magnitude of color difference between processed and unprocessed fluid foods. Differences in perceivable color can be classified analytically as not noticeable (0 to 0.5), slightly noticeable (0.5 to 1.5), noticeable (1.5 to 3.0), well visible (3.0 to 6.0), and great (6.0 to 12.0) (Cserhalmi and others 2006).

Polydera and others (2003) found that color measurements of orange juice stored in laminated flexible pouches indicated that, although the color changed with storage time (1 to 2 mo), the change did not correlate with the type of HP processing (500 MPa/35 °C/5 min), thermal pasteurization (80 °C, 1 min), and storage temperature (0 to 15 °C). The same authors (Polydera and others 2005a) subsequently studied a high pressure treatment (600 MPa/40 °C/4 min) and post-processing storage of fresh orange juice at 0 to 30 °C compared with conventional thermal pasteurization (80 °C, 1 min). HP treatment led to lower rates of color change (based on L^* , a^* , and b^* values) compared with thermal pasteurization at all the storage temperatures studied, except at 30 °C (which is above the range of normal storage temperatures). An increase in storage temperature resulted in higher rates of browning of the orange juice. Similar results to those found in these studies were obtained by Bull and others (2004) when they studied HP-processed (600 MPa/20 °C/1 min) Valencia and Navel orange juices and compared them with thermally pasteurized juice (65 °C, 1 min) and fresh juice, and stored them at 4 and 10 °C for 12 wk. In comparison with untreated orange juice, HP or thermal treatments had no effect on the color of the juices. The results showed that there was an increase in the total color difference with time, regardless of the treatment. Donsì and others (1996) reported no significant changes in color parameters of high-pressurized orange juice (350 MPa/30 °C/1 min) during subsequent storage for 2 mo at 8 °C. Similarly, Nienaber and Shellhammer (2001) did not find significant alterations in color parameters of HP-treated orange juice (500 to 800 MPa/25 to 50 °C/1 min) or during storage at 4, 15, and 26 °C, however, they obtained significant changes in the samples stored at 37 °C. Torres and others (2011) found increases values a^* and b^* after applying HP treatments (400 to 600 MPa/20 °C/15 min) to blood orange juice. With regard to lightness, they obtained an increase when HP treatments (400 to 600 MPa/20 °C/15 min) were applied. They also found an increase in total color differences during storage for 10 d at 4 and 20 °C for both HP-treated and untreated juices. During storage at 20 °C, E for control samples was 18.2 compared with 10.7 for samples processed at 600 MPa for 15 min. Hsu (2008) studied the effects of thermal treatment (60 and 92 °C, 2 min) and HP (100 to 500 MPa/4, 25, and 50 °C/10 min) on color in tomato juice. They found that pressure treatments at or below 200 MPa at 4 and 25 °C maintained the color, while those at 500 MPa at 4 and 25 °C improved the color, obtaining a higher a^*/b^* ratio, a quality parameter in tomato juice, so that the quality of the HP-treated juice was higher than that of the fresh juice. Porretta and others (1995) also found a partial increase in the color of tomato juice, expressed in terms of a^*/b^* ratio, after HP (500 to 900 MPa/3 to 9 min) in comparison with thermal treatment (98 °C/15 min). They attributed this to the compacting and homogenizing effects of the former, as already ascertained for viscosity. Dede and others (2007) studied the impact of the application of HP (250 MPa,

35 °C for 15 min) and thermal treatment (80 °C, 1 min) during refrigerated storage for 30 d at 4 °C. They found that color changes in HP-treated tomato and carrot juices (250 MPa/35 °C/15 min) were less ($\Delta E = 10$) after refrigerated storage than those observed in the thermally treated juices ($\Delta E > 15$). Rodrigo and others (2007) studied the effect of thermal treatment (100 to 140 °C, 0 to 120 min) and HP (300 to 700 MPa/65 °C/60 min) on color in strawberry juice at different pH values (2.5, 3.7, and 5). They observed an increase in degradation rate constants with treatment temperature for all the temperatures studied, which indicates that, as the temperature increases, the rate at which color degradation occurs also increases. They did not find significant differences in L^*a^*/b^* between fresh juice and juice treated at 700 MPa at pH 2.5. On the other hand, for strawberry juice at pH 3.7 and 5, they observed significant differences between fresh juice and samples treated at 600 to 700 MPa (8.8% increase) and between the latter and samples treated at 300 to 500 MPa (5.4% increase). They attributed these differences to the redness, which increased significantly with pressure. Daoudi and others (2002) did not observe visual color differences (based on L^* , a^* , and b^* values) in white GJ immediately after HP treatments (400 MPa and 500 MPa/2 °C/10 min or 400 MPa/40 °C/10 min). During refrigerated storage for 60 d at 4 °C they observed significant changes in redness and yellowness, especially large in the yellowness of the control sample, and they also found a slight decrease in lightness, indicating a slight browning of the control GJ. In all cases, they concluded that the color parameters (L^* , a^* , and b^* values) of the pressure-treated samples remained more stable than those of the control juice during refrigerated storage for 60 d at 4 °C. Similarly, when Barba and others (2011b) applied various HP treatments (200 to 600 MPa/20 to 42 °C/5 to 15 min) to BJ they did not find significant changes in redness after different HP treatments. However, they found a significant decrease in yellowness in the BJ after application of HP in comparison with unprocessed juice. They showed the existence, for all times (5 to 15 min), of an interaction between pressure and treatment time when the pressure applied was 200 MPa. The lightness of the beverage decreased when the treatment time was longer, while an increase in lightness was observed when the pressure was higher, although when the time was longer than 9 min a decrease in lightness was observed when the pressure was 600 MPa. Zhang and others (2011) evaluated the effect of thermal treatment (60 °C for 5, 20, 40, and 60 min) and HP (300, 600, and 900 MPa/60 °C/5, 20, 40, and 60 min) on color in watermelon juice. They reported that redness of the watermelon juice subjected to HP treatment at 600 MPa was similar to that of the control, while 300 MPa treatment increased the redness, however the 900 MPa decreased it. They concluded that, compared to the thermal treatments, the HP treatment at 600 MPa kept the color of the juice much closer to that of the control. The authors also found that thermal treatments of 60 °C for 20 and 60 min kept the redness similar to that of the control. They observed that all HP-treated and thermally processed juice underwent a significant color change because ΔE after each treatment was higher than 3.0. ΔE of the watermelon juice subjected to the thermal treatment increased with treatment time. However, a higher pressure (or a shorter time) in the high pressure treatment reduced ΔE .

Similarly, Barba and others (2011a) studied an orange juice–milk beverage and after applying various heat treatments (90 °C for 15 or 21 s, and 98 °C for 15 or 21 s) and comparing them with HP treatments (100 to 400 MPa/20 to 42 °C/2 to 9 min). They found that in all the heat treatments, the ΔE value between thermally treated and unprocessed samples was higher than 5.8. The thermal

treatment caused a significant increase in yellowness, while a significant decrease in redness and lightness of the thermally treated orange juice–milk was obtained in comparison to untreated sample. On the other hand, total color change (ΔE) in HP-treated orange juice–milk (200 to 400 MPa for 2 to 9 min) was significantly different from unprocessed samples. The authors observed ΔE values to be different in behavior, depending on treatment time or HP intensity level. However, it was only in the HP treatment at 400 MPa for 9 min that the ΔE value was slightly higher than 3.0. With the various HP treatments applied, the yellowness decreased significantly when pressures higher than 300 MPa/5 min were applied, with the lowest yellowness appearing at 400 MPa/42 °C/9 min. They also observed a significant maximum decrease in redness at 400 MPa/42 °C/9 min. With regard to lightness, they found a significant decrease when HP treatments (200 to 400 MPa for 2 to 9 min) were applied.

Barba and others (2010) compared the effects of thermal treatment (90 °C for 15 or 21 s, and 98 °C for 15 or 21 s) and HP treatment (100 to 400 MPa/20 to 42 °C/2 to 9 min) on color in a VB. The HP samples were very close to the unprocessed beverage, while thermal treatment caused a decrease in lightness. In the VB, the total color change (ΔE) in all the processed samples was significantly different from the unprocessed samples. In all cases, the ΔE^* values were lower for the VB treated by HP than those obtained after thermal processing. The authors concluded that it was quite clear that the application of HP had a smaller effect on color changes than thermal processing. For the pressurized VB, they observed a ΔE of about 3.5 or less, while for the heat-treated beverage the color change was more intense, reaching a maximum of 7.6.

Other authors, such as Goodner and others (1999) and Parish (1998), applied treatments of 500 to 900 MPa/60 °C/1 s to 10 min in order to stabilize clouding of juices and found that when they applied higher pressures for longer times the turbidity was maintained. Barba and others (2011a) studied the effects of thermal treatments (90 °C for 15 or 21 s, and 98 °C for 15 or 21 s) in an orange juice to milk beverage and compared them with HP treatments (100 to 400 MPa/20 to 42 °C/2 to 9 min). They found a significant decrease in turbidity for all times (2 to 9 min) when the pressure was higher than 200 MPa. However, they did not observe significant changes in turbidity in comparison with the untreated samples. Barba and others (2010) did not find significant changes in the turbidity of a VB treated by HP (100 to 400 MPa/20 to 42 °C/2 to 9 min), but they found a significant increase in the turbidity, for all the treatments (90 °C for 15 or 21 s, and 98 °C for 15 or 21 s), when the VB was treated thermally.

Aroma and flavor. The flavor of orange juice is easily altered during processing and storage. Irreversible changes are produced in the flavor of the juice as a result of chemical reactions that are initiated or occur during thermal processing (Braddock 1999). The changes in flavor are also associated with a number of deteriorative reactions that take place during storage, giving rise to the development of off-flavor. Takahashi and others (1998) studied the sensory characteristics of HP-processed orange juice (600 MPa/5 °C/1 min). They did not find changes in sensory properties immediately after treatment and during storage for 20 wk at 0 °C in comparison with untreated juice. Takahashi and others (1993) also did not observe changes in mandarin juice after applying HP (400 to 600 MPa/room temperature/5 to 30 min) in comparison with fresh juice. In a study performed by Butz and Tauscher (2002), they used a triangle test to evaluate the effect of different HP treatments (500 to 800 MPa/10 °C/5 min) on odor and aroma of an orange–lemon–carrot juice mixture. They observed

that the changes in aroma, taste, and general quality after 21 d storage at 4 °C were imperceptible compared with fresh beverage. Parish (1998), using a trained panel, concluded that the flavor of HP-treated orange juice (500 to 900 MPa/60 °C/1 s to 10 min) was better than that of juice after heat treatment (75 to 98 °C, 10 s) and during 16 wk of refrigerated storage at 4 °C. Baxter and others (2005) found that the odor and flavor of HP juice (600 MPa/18 to 20 °C/1 min) was acceptable to consumers after storage for 12 wk at temperatures up to 10 °C. Similarly, Polydera and others (2003; 2005a) found that HP orange juice (500 MPa/35 °C/5 min and 600 MPa/40 °C/4 min) resulted in lower loss of the flavor of untreated juice and superior sensory characteristics compared with thermal pasteurization (80 °C, 30 to 60 s) and during subsequent storage (0 to 30 °C, 1 to 3 mo). Castellari and others (2000) studied the effects of HP treatment (300 to 900 MPa/20 °C/2 to 10 min) and the use of glucose oxidase–catalase enzymes on the sensory properties of white GJ. Sensory analysis showed that the use of enzymes and HP treatment improved the aroma and taste of juices during storage for 3 wk at 5 °C in comparison to untreated juices. Daoudi and others (2002) obtained similar sensory characteristics in fresh GJ and HP-treated juice (400 to 500 MPa/2 to 40 °C/10 min) on the first day. The sensory characteristics of pressure-treated samples remained more stable than those of the control juice during 60 d of storage at 4 °C. Fernández-García and others (2001a) observed differences between the aroma of HP-treated juice (500 to 800 MPa/room temperature/5 min) and fresh juice, and Porretta and others (1995) found an increase in *n*-hexanal dependent on treatment time and pressure after applying HP (500 to 900 MPa/3 to 9 min) to tomato juice. Sampedro and others (2009) studied an orange juice–milk beverage and observed that the percentage of volatile compound losses after applying HP (450 to 650 MPa/30 to 50 °C/15 min) ranged between 14.4 and 7.5% at 30 °C and between 22.9 and 42.3% at 50 °C.

Bioactive compounds

There are few reports concerning the loss of bioactive compounds and antioxidant activities in fruit and vegetable juices after HP treatment. Some reports on the effect of HP on bioactive compounds and antioxidant capacity are shown in Table 2.

The effect of high pressure on the stability of vitamins is one of the studies that arouses most interest among the various authors that have evaluated this process. Researchers have used vitamin C as a quality indicator in fruits and vegetables because it is a sensitive bioactive compound that provides an indication of the loss of other vitamins and therefore acts as a valid criterion for other organoleptic or nutritional components. Bull and others (2004) did not find significant differences in vitamin C content between HP-treated orange juice (600 MPa/20 °C/1 min), pasteurized juice (65 °C, 1 min), and fresh juice. However, they found a decrease in vitamin C concentration in all the juices with storage time during a period of 12 wk, irrespective of the treatment applied and storage temperature (4 and 10 °C). Similarly, Fernández-García and others (2001a) did not observe losses in vitamin C concentration when they studied the effect of HP (500 to 800 MPa/room temperature/5 min) in orange juice and in a juice mixture of orange–lemon–carrot in comparison with untreated juices. They did not observe significant losses in the vitamin C concentration of HP-treated juices during storage at 4 °C for 21 d. Sánchez-Moreno and others (2003a) and Plaza and others (2006a) compared the shelf life of a HP-treated orange juice (100 to 400 MPa/30 to 60 °C/1 to 5 min) with that of a heat-treated juice (70 °C, 30 s), kept in refrigerated

Table 2—Effect of HP processing on bioactive compounds and antioxidant activities of some fruit and vegetable juices.

Product	Treatment conditions	Major findings	References
Orange juice	600 MPa/20 °C/1 min, 12 wk storage at 4 and 10 °C	Vit. C and β -carotene remained stable immediately after HP and during storage	Bull and others (2004)
	500 to 800 MPa/room temperature/5 min, 21 d storage at 4 °C	No significant changes in Vit. C, carotene content, and TAC during storage	Fernández-García and others (2001a)
	100 to 400 MPa/30 to 60 °C/1 to 5 min, 40 d storage at 4 °C	No significant changes in Vit. C immediately after HP and 14% losses during subsequent storage. Significant increase in TC after HP and less than 11% decrease during subsequent storage	Sánchez-Moreno and others (2003a)
	100 to 400 MPa/30 to 60 °C/1 to 5 min, 40 d storage at 4 °C	Increase (22 to 34%) in hesperitin concentration after HP and increase in flavanones during subsequent storage	Sánchez-Moreno and others (2003b)
	400 MPa/40 °C/1 min, 20 d storage at 4 °C	Naringetin and hesperitin increased 20 and 40%, respectively. No changes in TAC	Sánchez-Moreno and others (2005)
	100 to 400 MPa/30 to 60 °C/1 to 5 min, 40 d storage at 4 °C	No significant changes in Vit. C immediately after HP and 18% losses during subsequent storage	Plaza and others (2006a)
	400 MPa/40 °C/1 min, 20 d storage at 4 °C	Increase in flavanone concentration immediately after HP and decrease during subsequent storage	Plaza and others (2011)
	400 MPa/42 °C/5 min, 7 wk storage at 4 and 10 °C	Decrease of 4% in TC and no changes in TPC in comparison with fresh juice immediately after HP. 24% TC losses and 5% increase in TPC during storage at 4 °C. Decrease in TAC smaller than pasteurized juice	Esteve and Frígola (2008)
	400 to 600 MPa/20 °C/15 min, 7 wk storage at 4 and 10 °C	Vit. C losses lower than 6% after HP. First-order degradation kinetics for Vit. C and anthocyanin (cyanidin-3-glucoside) during storage. The cyanidin-3-glucoside concentration was greater in HP than untreated juice	Torres and others (2011)
	500 to 800 MPa/25 to 50 °C/1 min	No significant changes in Vit. C after HP. Losses lower than 20% during storage	Nienaber and Shellhammer (2001)
Citrus juices Orange–lemon– carrot juice	500 to 600 MPa/35 to 40 °C/4 to 5 min	Vit. C degradation rates lower than pasteurized juice immediately after HP and during subsequent storage. Lower TAC loss of HP samples during storage	Polydera and others (2003; 2005a; 2005b)
	100 to 800 MPa/30 to 100 °C/0 to 90 min	Pressure induced thermal degradation of folic acid. TAC decreased as a function of treatment time	Indrawati and others (2004)
	50 to 350 MPa/30 to 60 °C/2.5 to 15 min, 30 d storage at 4 °C	20 to 43% increase in TC at 350 MPa. Better preservation in TC during storage than fresh juice. TAC decreased during storage	De Ancos and others (2002)
Orange juice mixed with milk	200 to 500 MPa/30 °C/1 min	No changes in Vit. C, and vitamins B ₁ , B ₂ , B ₆ , and niacin after HP	Donsi and others (1996)
	500 to 800 MPa/room temperature/5 min, 21 d storage at 4 °C	No significant changes in vitamin C, carotene content, and antioxidant capacity during storage	Fernández-García and others (2001a)
Vegetable beverage	100 to 400 MPa/20 to 42 °C/2 to 9 min	Vit. C losses lower than 9% and significant increase when pressure time increased. TPC increased after HP and TAC was higher in pressurized samples	Barba and others (2011a)
Blueberry juice	100 to 400 MPa/20 to 42 °C/2 to 9 min	Vit. C losses lower than 9% and 16 to 48% losses in TC after HP. TPC remained stable. TAC decreased as treatment pressure increased	Barba and others (2010)
Vegetable soup "gazpacho"	200 to 600 MPa/20 to 42 °C/5 to 15 min	Vit. C losses lower than 8%. Increase in TPC after 200 MPa during 5 to 15 min and 400 MPa during 15 min. TAC decreased when 400 MPa/15 min and 600 MPa/5 to 15 min were applied	Barba and others (2011b)
Tomato juice	150 to 350 MPa/60 °C/15 min, 40 d storage at 4 °C	Decrease in carotene concentration as treatment pressure increased. Decrease (40 to 46%) in total carotenoid concentration after storage and TAC decreased as treatment pressure increased	Plaza and others (2006b)
	250 MPa/35 °C/15 min, 30 d storage at 4 °C and 25 °C	Vit. C losses lower than 30% and TAC loss of 10% after storage at 4 °C	Dede and others (2007)
Carrot juice	200 MPa at 4 and 25 °C	Pressure treatments at and below 200 MPa at 4 and 25 °C maintained the extractable TC and lycopene and TAC	Hsu and others (2008)
	250 MPa/35 °C/15 min, 30 d storage at 4 °C and 25 °C	Vit. C losses of 55% after storage at 25 °C and TAC loss of 10% after storage at 4 °C	Dede and others (2007)
Pineapple juice	100 to 800 MPa/30 to 100 °C/0 to 90 min	5-Methyltetrahydrofolic acid is rather unstable at pressures exceeding 500 MPa/60 °C	Indrawati and others (2004)
	600 MPa/75 °C/40 min	Small losses of carotenes after HP	Tauscher (1998)
Grape juice	600 MPa/40 to 75 °C/40 min	Vit. C losses 20 to 26% to 60 to 70% as treatment temperature increased	Taoukis and others (1998)
Muscadine grape juice	400 to 550 MPa/15 min	Vit. C losses of 16% after HP at 400 MPa and 82% after 550 MPa. Greater losses in anthocyanin concentration at 400 MPa than at 550 MPa. TAC decreased as treatment pressure increased	Del Pozo-Insfran and others (2007)
White grape juice	HP at 600 and 900 MPa slowed degradation of nonflavonoid phenolics during storage		
Strawberry "coulis"	300 to 900 MPa/20 °C/2 to 10 min, 3 wk storage at 5 °C		
Watermelon juice	200 to 600 MPa/20 °C/30 min	Vit. C losses lower than 12% after HP	Sancho and others (1999)
Apple juice	300 to 900 MPa/60 °C/5 to 60 min	All- <i>trans</i> -lycopene, total <i>cis</i> -lycopene, and total lycopene better preserved after HP than thermally treated	Zhang and others (2011)
	600 MPa/60 °C/30 min, 1 mo storage at 4 °C	No changes in TAC immediately after HP and during subsequent storage	Fernández-García and others (2000)
Pomegranate juice	200 to 600 MPa/15 to 65 °C	Hydroxycinnamic and procyanidin acids increased significantly after 400 MPa/10 min	Baron and others (2006)
	400 to 600 MPa/25 to 50 °C/5 to 10 min	Anthocyanin concentration influenced mainly by the pressure and temperature levels	Ferrari and others (2010)
Milk	400 MPa/25 °C/30 min	No significant losses in vitamins B ₁ and B ₆	Sierra and others (2000)
	200 MPa/−4 °C/10 to 30 min	Losses in Vit. C, niacin, and riboflavin as treatment time increased	Kim and others (2008)
	400 to 600 MPa/22 to 27 °C/5 min	No changes in vitamin C and tocopherols	Molto-Puigmartí and others (2011)

Vit. C = vitamin C; TC = total carotenoids; TPC = total phenolic compounds; TAC = total antioxidant capacity.

storage at 4 °C for 40 d. The concentration of vitamin C remaining in the pasteurized orange juice was similar to that found in the heat-treated juice. At the end of the refrigerated storage, the HP- and heat-treated juices showed similar vitamin C losses (14 and 18%, respectively) in comparison with untreated juice, although the HP-treated juices maintained the vitamin C concentration for more days than the heat-treated juices. Esteve and Frígola (2008) studied the effect of HP treatment (400 MPa/42 °C/5 min) and thermal pasteurization (90 °C, 20 s) on orange juice and its subsequent storage (4 and 10 °C, 7 wk). In all cases, the vitamin C loss was higher for high-pressurized juice. The shelf life of the HP-treated juice (based on vitamin C loss) was greater than that of the pasteurized juice (400 MPa/42 °C/5 min). Similarly, when Torres and others (2011) applied HP (400 to 600 MPa/20 °C/15 min) to blood orange juice they observed vitamin C losses lower than 6% for all pressure-treated samples. They determined that the degradation of vitamin C in processed samples during storage for 7 wk at 4 and 10 °C had first-order kinetics. Vitamin C losses were significantly higher at a storage temperature of 20 °C than at 4 °C for both HP-processed and untreated control samples. Nienaber and Shellhammer (2001) did not find significant differences in vitamin C in HP-treated orange juice (500 to 800 MPa/25 to 50 °C/1 min) and fresh juice. During refrigerated storage for 3 mo at 4 °C or 2 mo at 15 °C, they observed vitamin C losses lower than 20% in HP-processed orange juice. Barba and others (2010, 2011a) studied the effect of HP treatments (100 to 400 MPa/20 to 42 °C/2 to 9 min) and thermal treatments (90 °C for 15 or 21 s and 98 °C for 15 or 21 s) on **OJM** and on a VB. Vitamin C losses were lower in both beverages after HP (9%) than after thermal treatment (18%). In another study, Barba and others (2011b) also did not observe significant losses of vitamin C concentration in BJ (8%) after applying HP (200 to 600 MPa/20 to 42 °C/5 to 15 min). Polydera and others (2003; 2005a; 2005b) observed the impact of HP treatment (500 MPa/35 °C/5 min or 600 MPa/40 °C/4 min) and thermal pasteurization (80 °C, 30 to 60 s) on orange juice and its subsequent storage (0 to 30 °C, 1 to 3 mo). In all cases, the vitamin C degradation rates were lower for HP-treated juice, leading to an extension of its shelf life compared with conventionally pasteurized juice. Taoukis and others (1998) studied the effect of combining high pressure with heat (600 MPa/40 to 75 °C/40 min) on vitamin C in pineapple, grapefruit, and GJs and observed losses ranging from 20 to 26% to 60 to 70% as treatment temperature increased. Dede and others (2007) found losses of 30% of vitamin C concentration during storage of tomato and carrot juices for 30 d at 4 °C after applying 250 MPa/35 °C/15 min, but they observed an increase in losses (55%) of vitamin C concentration in carrot juice when it was stored at 25 °C. In all cases, the losses after applying HP were lower than those found after heat treatment at 80 °C/1 min. However, Del Pozo-Insfran and others (2007) found that HP treatment of muscadine GJ at 400 MPa and 550 MPa for 15 min produced decreases in vitamin C concentration of 84 and 18%, respectively, immediately after processing. They attributed the greater degradation of vitamin C in matrices of this kind to enzyme activity, which is produced at pressures below 550 MPa. Donsi and others (1996) observed that there were no changes in the initial concentrations of vitamin C or in the concentrations of vitamins B₁, B₂, B₆, and niacin after applying HP (200 to 500 MPa/30 °C/1 min) to various citrus juices. Sancho and others (1999) evaluated the effect of HP (200, 400, and 600 MPa/20 °C/30 min) on hydrosoluble vitamins (C, B₁, and B₆) in strawberry "coulis" (a type of strained purée) and observed losses of approximately 12% and 11% of vitamin C after treatments

at 200 and 600 MPa, respectively. On the other hand, Indrawati and others (2004a) evaluated the effect of combining HP treatment with heat (100 to 800 MPa/30 to 100 °C/0 to 90 min) on folic acid in orange and carrot juices and found that the order of stability at the pressure and temperature of the folic acid in orange juice was as follows: 5-methyltetrahydrofolic acid > 5-formyl-tetrahydrofolic acid > tetrahydrofolic acid. They also observed that, in orange juice, an increase in degradation of folic acid when HP treatment was combined with elevated temperatures, since at 80 °C pressure favors conversion of 5-formyl-tetrahydrofolic to 5,10 methenyl-tetrahydrofolic, whereas 5-methyltetrahydrofolic acid is fairly resistant to pressures exceeding 500 MPa/60 °C. In carrot juice, however, 5-methyltetrahydrofolic acid is rather unstable to treatments in excess of 500 MPa/60 °C.

With regard to liposoluble vitamins, few studies evaluate the effect of high pressure on this kind of vitamin. Research has concentrated basically on the effect that HP might have on the extractability of carotenoids, some of which have provitamin A activity. Bull and others (2004) studied HP-processed (600 MPa/20 °C/1 min) Valencia and Navel orange juices, thermally pasteurized juice (65 °C, 1 min), and fresh orange juice and did not find changes in the β -carotene concentration. They also observed no significant variations during storage at 4 and 10 °C (12 wk). Esteve and Frígola (2008) studied the effect of high pressure processing (400 MPa/42 °C/5 min) on total carotenoids in Navel orange juice. In parallel, a conventional heat treatment (90 °C, 20 s) was applied to the juice, and the results were compared. The total carotenoid concentration in the pasteurized juice decreased (−12.8%) significantly in comparison with the fresh juice, and there was a smaller decrease (−4.2%) in the juice treated by HP. The same authors, Esteve and Frígola (2008), subsequently compared the evolution and modification of total carotenoid content in untreated orange juice, pasteurized orange juice (90 °C, 20 s), and orange juice treated by HP during 7 wk of storage at 4 and 10 °C. The decrease in the concentrations of total carotenoids in pasteurized (90 °C, 20 s) and HP-processed (400 MPa/42 °C/5 min) orange juice was around 24% in both cases during storage at 4 °C. However, the decrease in the concentration of total carotenoids during storage at 10 °C was greater in the pasteurized orange juice (−17%) than in the HP-processed juice. Esteve and others (2009) studied the effect of HP (400 MPa/30 °C/5 min) on total carotenoids in orange juice and compared the result with heat treatment (90 °C, 20 s). They then kept the processed samples in refrigerated storage for 7 wk at 4 and 10 °C. The decrease in total carotenoids in the HP-treated orange juice (−4%) was not significant in comparison with the untreated sample in the conditions selected. However, the total carotenoid concentration in the pasteurized juice decreased (−13%) significantly in comparison with the fresh juice. The authors concluded that the concentration of carotenoids in refrigerated orange juice is affected less by HP treatment than by conventional thermal treatment. Fernández-García and others (2001a) did not find changes in total carotenoid concentration in orange juice and orange–lemon–carrot juice after treatment with HP (500 to 800 MPa/room temperature/5 min) or after storage at 4 °C for 21 d.

Moreover, numerous studies endorse the use of HP as a suitable treatment for increasing extraction of carotenes from the matrix, which would be associated with an increase in nutritional value. The effects of HP treatment on orange juice carotenoids (β -carotene, α -carotene, zeaxanthin, lutein, and β -cryptoxanthin) associated with nutritional (vitamin A) values were investigated by De Ancos and others (2002). Various HP treatments (50 to

350 MPa) combined with different temperatures (30 and 60 °C) and treatment times (2.5, 5, and 15 min) were assayed. The juice was subsequently stored at 4 °C. The authors found that HP treatments at 350 MPa produced significant increases of 20 to 43% in the carotenoid content of fresh orange juice. In the treatment at 350 MPa/30 °C/5 min, they observed an increase in the vitamin A (45%). During storage, the orange juice subjected to high pressure was better preserved and even increased its total carotenoid content and vitamin A activity. The authors indicated, therefore, that HP treatment might be an efficient processing method for preserving orange juice as freshly squeezed for up to 30 d from the point of view of sensory (carotenoid) and nutritional (vitamin A) quality. Sánchez-Moreno and others (2003a, 2005) and Plaza and others (2011) studied the stability of the main carotenoids (lutein, zeaxanthin, α -cryptoxanthin, β -cryptoxanthin, α -carotene, and β -carotene) just after HP (100 to 400 MPa/30 to 60 °C/1 to 5 min) and thermal treatment (70 °C, 30 s) and during 40 d of refrigerated storage at 4 °C. They found a significant increase in total carotenoids and vitamin A value in the HP-treated samples increased compared to the control, while the thermally treated samples did not. Then during storage, the samples lost a similar, small percentage of their post-processing carotenoid levels, resulting in the HP-treated samples having higher absolute levels after storage at 4 °C. Zhang and others (2011) evaluated the effect of thermal treatment (60 °C for 5, 20, 40, and 60 min) and HP (300, 600, and 900 MPa/60 °C/5, 20, 40, and 60 min) on carotenoids in watermelon juice. The all-*trans*-lycopene concentration of the HP watermelon juice was significantly higher than that of the juice subjected to thermal treatment. The total *cis*-lycopene concentration of all the processed watermelon juices after each treatment was similar to that of the untreated sample. The authors concluded that HP treatment was more effective than the thermal treatments to maintain the all-*trans*-lycopene, total *cis*-lycopene, and total lycopene concentrations of the treated watermelon juice like the untreated sample. Barba and others (2011a) evaluated the effects of HP (100 to 400 MPa/20 to 42 °C/2 to 9 min) and thermal treatment (90 °C for 15 or 21 s, and 98 °C for 15 or 21 s) on total carotenoids in an orange juice–milk beverage. They found a significant increase in total carotenoid content in all the HP-treated samples (100 to 400 MPa) at 7 and 9 min in comparison with the unprocessed samples. These authors also observed a significant increase in total carotenoids after thermal treatment (21 to 48%) in all cases in comparison with the fresh beverage. In other study, Tauscher (1998) found relatively small losses of carotenes (maximum 5%) in carrot juice after applying HP (600 MPa/75 °C/40 min). On the other hand, Hsu (2008) observed that HP levels equal to or less than 200 MPa (4 and 25 °C) preserved carotenoids and lycopene in tomato juice, and at 500 MPa (4 and 25 °C) they even increased in comparison with the fresh juice. When Barba and others (2010) studied the effect of HP (100 to 400 MPa/20 to 42 °C/2 to 9 min) and compared it with various heat treatments (90 °C for 15 or 21 s, and 98 °C for 15 or 21 s), they observed that total carotenoids were particularly affected, and the HP samples had a lower total carotenoid content (16 to 48%) than that of the unprocessed samples. They also found that the pasteurization treatment did not significantly affect the total carotenoid content, and in some cases there was even an increase in total carotenoids (7%). Plaza and others (2006b) conducted a study of cold vegetable soup to which they applied HP (150 to 350 MPa/60 °C/15 min) and they found a decrease in carotene concentration as treatment pressure increased. In the same study, the authors observed a

decrease (40 to 46%) in total carotenoid concentration after storage of HP-treated samples of “gazpacho,” a cold vegetable soup, for 40 d at 4 °C.

Phenolic compounds are beneficial components mainly found in fruits and vegetables. They have been implicated in the reduction of degenerative human diseases, principally because of their antioxidant potential. Moreover, several studies have shown that a diet rich in phenolic compounds correlates with reduced risk of coronary heart diseases. Esteve and Frígola (2008) did not observe changes in the concentration of total phenolic compounds in orange juice immediately after applying HP (400 MPa/42 °C/5 min) and after applying heat treatment (90 °C, 20 s) in comparison with fresh juice. During storage for 7 wk at 4 °C, they found an increase in total phenolic compounds in the HP-treated (5%) and thermally treated (7%) samples in comparison with untreated juice (day 0). The phenolic compound concentration did not alter during storage for 7 wk at 10 °C in the case of HP, whereas with heat treatment it decreased (–2%). Sánchez-Moreno and others (2003b) also investigated the behavior of phenolic compounds in orange juice after HP treatment (100 to 400 MPa/30 to 60 °C/1 to 5 min) and observed that as treatment pressure increased there was no increase in extraction of flavanones, whereas the hesperitin concentration increased by 34 and 22%, respectively, after HP treatment at 350 MPa/30 °C/2.5 min and 400 MPa/40 °C/1 min. The authors found an increase in the extraction of flavanones during refrigerated storage of orange juice after applying HP (350 to 450 MPa/40 to 60 °C/1 to 5 min). Plaza and others (2011) also found an increase in total flavanone concentration (15.46%) in orange juice after applying HP (400 MPa/40 °C/1 min). However, they found a decrease in flavanone concentration in orange juice treated by HP (400 MPa/40 °C/1 min) and stored for 20 d at 4 °C, although the losses were less than those observed in orange juice treated thermally at 70 °C/30 s and stored under the same conditions. Similarly, Torres and others (2011) did not find changes in the concentration of anthocyanins (cyanidin-3-glucoside) in blood orange juice after applying HP (400 to 600 MPa/20 °C/15 min). When they conducted a study of storage for 10 d at 4 and 20 °C, they found a first-order degradation kinetics in the cyanidin-3-glucoside concentration in orange juice after applying HP (400 to 600 MPa/20 °C/15 min), although the losses were considerably greater at 20 °C. The cyanidin-3-glucoside concentration in the HP-treated samples was greater than that of the untreated samples during storage for 10 d at 4 and 20 °C. Barba and others (2011a) compared the effects of HP treatments (100 to 400 MPa/20 to 42 °C/2 to 9 min) and thermal treatments (90 °C for 15 or 21 s and 98 °C for 15 or 21 s) on total phenolic compounds in an orange juice–milk beverage. They reported that the levels of total phenolic compounds in the HP-treated orange juice–milk increased significantly, reaching a maximum at 100 MPa/7 min (22% increase) in comparison with unprocessed samples. These authors also found a significant increase (8 to 17%) in total phenolics after thermal treatment in all cases in comparison with the fresh beverage.

Sánchez-Moreno and others (2005) observed increases of 20% and 40%, respectively, in concentrations of naringenin and hesperetin after hydrolysis of orange juice extract pressurized at 400 MPa/40 °C/1 min. On the other hand, Baron and others (2006) after applying HP (200 to 600 MPa/15 to 65 °C) to apple juice, obtained significant changes in the phenolic compound profile, since the hydroxycinnamic and procyanidin acids were increased significantly after 400 MPa/10 min in comparison with fresh juice. Catechins were the compounds that experienced the

greatest variations, whereas dihydrochalcones were not altered. Del Pozo-Insfran (2007) studied the effect of HP on GJ and observed greater losses in the anthocyanin concentration at 400 MPa (70%) than at 550 MPa (46%). Ferrari and others (2010) observed similar results in pomegranate juice after applying HP (400 to 600 MPa/25 to 50 °C/5 to 10 min), finding that the anthocyanin concentration was influenced mainly by the pressure and temperature levels. At 25 °C, the highest pressure levels and the longest processing times led to a decrease in the anthocyanin concentration. When the temperature was equal to or greater than 45 °C, processing time did not influence the anthocyanin concentration. At 45 °C there was a decrease in total anthocyanin concentration, whereas at a temperature above 45 °C it was similar to or greater than the concentration in fresh pomegranate juice. Castellari and others (2000) studied the effects of HP treatment (300 to 900 MPa/20 °C/2 to 10 min) and the use of glucose oxidase-catalase enzymes on white GJ, observing that the treatments at 600 and 900 MPa slowed degradation of nonflavonoid phenolics during refrigerated storage over 3 wk at 5 °C. Similarly, when Barba and others (2011b) applied HP treatments (200 to 600 MPa/20 to 42 °C/5 to 15 min) to BJ they reported that phenolics appeared to be relatively resistant to HP and even observed a significant increase (13 to 27%) after 200 MPa for 5 to 15 min and 24% after 400 MPa for 15 min. Barba and others (2010) studied the effects of HP treatments (100 to 400 MPa/20 to 42 °C/2 to 9 min) on total phenolic compounds in a VB and compared the results with thermal treatments (90 °C for 15 or 21 s and 98 °C for 15 or 21 s). They concluded that total phenolics appeared to be relatively resistant to the effect of processing, observing that HP and thermal treatment did not have a significant effect on the levels of phenol compounds.

Total antioxidant capacity

The correlations among the different methods used for the determination of the antioxidant capacity depend on food, that is, mainly due to compounds (lipid and water-soluble) of the different food matrix. Various authors have obtained correlations between the results found after analyzing antioxidant capacity with the TEAC and ORAC methods in fruits and vegetables. However, this seems to be for foods in which the main antioxidants are water-soluble and, as seen, the action of these antioxidants takes place easily with both methods. Thus, different methods must be used in order to evaluate the antioxidant capacity of a food product when a new food preservation technology is used (Prior and others 2005; Zulueta and others 2009).

During the processing and subsequent storage of fluid foods, their antioxidant capacity may be altered. There is now great interest in the measurement of antioxidant capacity because it provides considerable information about the resistance to oxidation, the quantitative contribution of antioxidant substances, and the antioxidant capacity that a foodstuff may have in vivo when it is ingested (Huang and others 2005; Serrano and others 2007). Numerous studies have been conducted to evaluate the total antioxidant capacity (TAC) of several foods. Despite this there is no standardized official method, and as a result there are several methods of measurement whose use is recommended (Frankel and Meyer 2000; Prior and others 2005; Zulueta and others 2009). The methods used to measure TAC can be classified basically into two groups, depending on the reaction mechanism: methods based on hydrogen atom transfer (HAT), with the ORAC method being the one most used, and methods based on electron transfer (ET), notably ABTS, also known as Trolox equivalent antioxidant ca-

capacity (TEAC), and the DPPH method (Huang and others 2005). The methods most used at present are the ones based on generation of free radical species, whose disappearance is determined by the presence of antioxidants (Arnao and others 2001).

Fernández-García and others (2000) applied HP treatment (600 MPa/60 °C/30 min) to apple juice and did not find significant alterations in the antioxidant potential (ABTS) of apple juice immediately after processing and during refrigerated storage for 1 mo at 4 °C. Fernández-García and others (2001a) also did not find changes in antioxidant capacity (DPPH) immediately after treating orange-lemon-carrot juice with HP (500 to 800 MPa/room temperature/5 min) or when it was subsequently stored at 4 °C for 21 d. Dede and others (2007) studied the effects of HP treatment (250 MPa, 35 °C for 15 min) and thermal treatments (60 °C, 5 to 15 min and 80 °C, 1 min) on the antioxidant capacity (DPPH) of carrot and tomato juices during refrigerated storage for 30 d at 4 °C. They found that both heat treatments resulted in a significant loss in free radical scavenging activity as compared to untreated samples. However, the HP-treated juices showed a small loss of antioxidants (below 10%) during storage. Esteve and Frígola (2008) compared the effect of HP treatment (400 MPa/42 °C/5 min) with the effect of heat treatment (90 °C, 20 s) on orange juice kept in refrigerated storage at 4 and 10 °C. Total antioxidant capacity (TEAC) decreased significantly after processing the orange juice with both types of treatment, but the decrease was much smaller in the HP-treated juice than in the pasteurized juice (decreases of 4.20 and 38.21%, respectively). The authors concluded that the antioxidant capacity of the HP-treated orange juice was more like that of untreated juice. They also observed a decrease in antioxidant capacity in thermally treated and HP-treated samples during refrigerated storage at 4 and 10 °C, with a greater decrease in the samples stored at 10 °C. They concluded that, in comparison with conventional pasteurization, HP treatments led to a higher total antioxidant activity in orange juice immediately after processing (time 0 of storage), as well as during storage at 4 to 10 °C. Sánchez-Moreno and others (2005) found that the total antioxidant capacity (DPPH) of orange juice treated by mild pasteurization (70 °C, 30 s) and HP (400 MPa/40 °C/1 min) did not undergo significant changes, whereas pasteurization (90 °C/1 min) produced a decrease. Polydera and others (2005) studied the total antioxidant activity of HP-treated fresh navel orange juice (600 MPa/40 °C/4 min) compared with thermally pasteurized fresh navel orange juice (80 °C, 1 min) as a function of storage (0 to 30 °C). These authors found an increased retention of antioxidant capacity during storage after application of HP treatment compared to thermally treated juices. They also observed a correlation between the depletion of vitamin C and decrease of antioxidant capacity in HP- and thermally treated orange juices during storage. De Ancos and others (2002) studied the effect of HP treatments (50 to 350 MPa) combined with different temperatures (30 and 60 °C) and times (2.5, 5, and 15 min) on the antioxidant capacity (DPPH) of orange juice measured as free radical scavenging capacity. They obtained a decrease in the free radical scavenging capacity of the untreated and HP-treated orange juices during refrigerated storage at 4 °C. There were significant differences between the untreated sample (37.5% inhibition) and the orange juices treated at 350 MPa/30 °C for different treatment times (2.5, 5, and 15 min), with approximately 20% inhibition. Indrawati and others (2004b) studied the combined effect of pressure, temperature, and time (100 to 800 MPa/30 to 65 °C/0 to 90 min) on orange and carrot juices and observed that total antioxidant capacity (TEAC) of orange juice decreased slightly after

treatment by HP (100 to 800 MPa) at moderate temperatures (30 °C) in comparison with untreated juices, while a synergistic pressure effect on antioxidant degradation was found at elevated temperature (65 °C) and when time was increased. However, these authors obtained an increase in TEAC values of carrot juice after HP for all treatments. This increase in antioxidant capacity of carrot juice occurred more quickly when pressure was increased at 40 °C, while increasing the pressure at temperatures above 40 °C decreased the rate of increase in antioxidant capacity. In any case, for carrot juices, increased processing time led to increased TEAC values. Del Pozo-Insfran and others (2007) found that HP treatment of muscadine GJ at 400 MPa and 550 MPa for 15 min produced decreases in antioxidant capacity, immediately after processing, of 45 and 21%, respectively. They observed greater losses of antioxidant capacity (ORAC) as treatment pressure increased, and these losses correlated with losses of anthocyanin concentration. Plaza and others (2006b) also observed that losses of antioxidant capacity (DPPH) in a VB increased as treatment pressure increased. Barba and others (2011b) studied the effects of HP treatments (200 to 600 MPa/20 to 42 °C/5 to 15 min) on antioxidant capacity (TEAC) in BJ. They found that treatments at 200 MPa for 5 to 15 min obtained similar TEAC values to those of fresh juice, but they obtained the lowest TEAC values after applying 400 MPa/15 min and 600 MPa for all time periods (5 to 15 min), establishing a relation with the results found for vitamin C. Barba and others (2010) compared HP treatments (100 to 400 MPa/20 to 42 °C/2 to 9 min) and thermal treatments (90 °C for 15 or 21 s and 98 °C for 15 or 21 s) on antioxidant capacity in an orange juice–milk beverage. They observed that, for all time periods (2 to 9 min), HP samples processed at 100 and 300 MPa had significantly lower antioxidant capacity values for the TEAC method when compared with unprocessed samples. However, they obtained the lowest antioxidant values for the ORAC method at 100 MPa for 5 min. They also found that the mean antioxidant capacity values for orange juice–milk samples treated at 200 MPa (2 and 7 min), for the TEAC and ORAC methods, and also at 200 MPa for 9 min for the ORAC method, were higher than for the unprocessed samples. They obtained the lowest antioxidant capacity values for the Trolox equivalent antioxidant capacity (TEAC) and ORAC methods after thermal treatment at 98 °C, 21 s, representing significant ($p < 0.05$) overall decreases of 34% and 12%, respectively. Barba and others (2010) evaluated the effects of HP treatments (100 to 400 MPa/20 to 42 °C/2 to 9 min) and thermal treatments (90 °C for 15 or 21 s and 98 °C for 15 or 21 s) on antioxidant capacity in a VB. For this purpose, they performed a multiple regression analysis in order to evaluate the influence of pressure and time on the HP treatment. The results they obtained showed that only pressure significantly affected the antioxidant capacity values obtained by the ABTS and ORAC assays. With HP treatments there was a decrease in the antioxidant capacity of the VB. On the other hand, they detected a significant increase in the ABTS and ORAC values of the VB after conventional thermal processing at 98 °C for 15 and 21 s.

Fruit and Vegetable Purées/Pastes

Fruit and vegetable purées/pastes are used in a variety of products including jams, conserves and smoothies and contain many health promoting antioxidant compounds. The role of these in reducing the risk of many chronic diseases such as cancer, coronary heart disease, immune system decline has been well documented (Willcox and others 2004). Some recent studies have revealed HP

treatment as a good technology in order to preserve these products quality. Hence HP processing at moderate temperatures (30 to 60 °C) may be appropriate to produce nutritious and fresh like purées. Some of these studies are listed in Table 3.

Physicochemical properties

Krebbes and others (2003) compared the effects of HP treatments (300 to 700 MPa/20 to 90 °C/2 min) and thermal treatments (75 °C, 4 min and 118 °C, 20 min) on tomato purée. They found a higher decrease in viscosity in thermally treated purées than in HP-treated samples compared to untreated tomato purées. They attributed this phenomenon to heat- or enzymatic degradation of pectins. Similarly, Sánchez-Moreno and others (2006) obtained a decrease in viscosity after application of thermal treatment (70 °C, 30 s and 90 °C, 1 min) while a significant increase was found in HP-treated (400 MPa/25 °C/15 min) tomato purée compared to untreated sample. These authors also obtained an increase in °Brix after thermal and HP processing. Yen and Lin (1996) studied the effects of HP treatments (400 to 600 MPa/room temperature/10 to 15 min) and thermal treatments (88 to 90 °C, 24 s) on guava purée immediately after processing and during subsequent storage 60 d at 4 °C. Immediately after processing, they obtained a decrease in viscosity and turbidity after applying thermal treatments in comparison to HP-treated and untreated guava purée. During refrigerated storage, they found a gradual decrease in the content of pectin and turbidity in untreated and HP-treated (400 MPa) purée, whereas these changes were not obtained in thermally treated and HP-treated (600 MPa) guava purée during 60 d storage at 4 °C. Show that conventional thermal treatment caused a large reduction of the viscosity compared to raw puree, whereas HP treatment at ambient temperature resulted in retention of the viscosity at 300 MPa. García-Parra and others (2011) compared the quality and shelf life of HP-processed (450 and 600 MPa/10 °C/5 and 10 min) nectarine purée with thermally processed purée (85 °C, 5 min) and their subsequent storage at 5 °C for 60 d. They found that pH was slightly lower in thermally treated purée in comparison to untreated sample and HP-treated (600 MPa/5 and 10 min) purée. Titratable acidity values were higher after thermal processing than in the highest HP treatment. The pH, titratable acidity and °Brix of the HP- or thermally treated purées did not change significantly over storage time. Jacobo-Velázquez and Hernández-Brenes (2010) did not find significant changes in values of pH immediately after application of HP (600 MPa/23 °C/3 min) to avocado paste, however a significant decrease in pH values was found during the first 20 d storage at 4 °C. Following the period of the pH decline, the values remained stable until the end of the storage (45 d).

Color. García-Parra and others (2011) did not find significant changes in lightness, redness and yellowness of nectarine purées immediately after HP treatments (450 and 600 MPa/10 °C/5 and 10 min) and thermal processing (85 °C, 5 min). In this study, they also obtained that total color differences of HP-treated nectarine purées (3.3 to 6.1) were minor and less than those of thermally treated (7.7) purées during 60 d storage at 5 °C. Similarly, Jacobo-Velázquez and Hernández-Brenes (2010) did not obtain significant alterations in color parameters (L^* , a^* , and b^* values) of HP-treated avocado paste (600 MPa/23 °C/3 min) while a significant decrease in redness and yellowness was observed at the end of the storage (45 d at 4 °C), with well visible (3.1) color differences. Patras and others (2009a,b) compared the effects of HP treatments (400 to 600 MPa/10 to 30 °C/15 min) and thermal treatment (70 °C, 2 min) on color of strawberry, blackberry,

Table 3—Effect of HP processing on physicochemical properties, bioactive compounds, and antioxidant activities of some purées/pastes.

Product	Treatment conditions	Major findings	References
Tomato purée	300 to 700 MPa/20 to 90 °C/2 min	HP treatments retained better the viscosity than thermal treatments. Lycopene, β -carotene and TC content were increased at 400 to 500 MPa while no significant changes were obtained when 700 MPa was applied	Krebbbers and others (2003)
	400 MPa/25 °C/15 min	pH, °Brix and viscosity were increased. Vit. C losses about 29%. An increase in lycopene, β -carotene and TC content was found while a significant decrease in TAC was obtained	Sánchez-Moreno and others (2006)
	400 to 600 MPa/20 °C/15 min	Lower decrease in Vit. C after HP treatments compared to thermal processing. Significant increase in TC after HP (600 MPa) while a significant decrease was obtained at 400 and 500 MPa	Patras and others (2009b)
	300 and 600 MPa/20 °C/10 to 60 min, 21 d storage at 4 °C	No significant changes in lycopene and β -carotene were found while they obtained a decrease of TAC after first week storage	Fernández-García and others (2001)
Guava purée	400 to 600 MPa/room temperature/10 to 15 min, 60 d storage at 4 °C	Decrease in pectin content and turbidity after HP at 400 MPa and subsequent storage 60 d at 4 °C. No significant changes in Vit. C and aroma	Yen and Lin (1996)
Nectarine purée	450 and 600 MPa/10 °C/5 to 10 min, 60 d storage at 5 °C	pH, titratable acidity and °Brix were not affected immediately after HP and subsequent storage. Increase in zeaxanthin+lutein after HP treatment at 450 MPa and subsequent storage 20 d at 5 °C was found an increase in TPC and TAC after HP and subsequent storage	García-Parra and others (2011)
Avocado paste	600 MPa/23 °C/3 min, 45 d storage at 4 °C	Decrease in pH and modifications in flavor during storage at 4 °C	Jacobo-Velázquez and Hernández-Brenes (2010)
Strawberry purée	400 to 600 MPa/10 to 30 °C/15 min	Vit. C losses 5% to 9%. No changes were observed in anthocyanin (cyanidin-3-glycoside and pelargonidin-3-glucoside), TAC decreased after application of HP treatments	Patras and others (2009a)
Strawberry jam	200 to 800 MPa/20 °C/20 min	Synthesis of new compounds responsible of the aroma	Lambert and others (1999)
Blackberry purée	400 to 600 MPa/room temperature/10 to 30 min	No changes in Vit. C after HP treatments	Kimura and others (1994)
Carrot purée	400 to 600 MPa/10 to 30 °C/15 min	No changes in anthocyanin (cyanidin-3-glycoside and pelargonidin-3-glucoside). TAC was higher in pressurized samples	Patras and others (2009a)
Persimmon fruit purée	400 to 600 MPa/20 °C/15 min	Increase in TC and TAC after HP treatments	Patras and others (2009b)
Kiwi jam	600 MPa/75 °C/40 min	No significant changes in carotenoids	Butz and Tauscher (2002)
Raspberry purée	50 to 400 MPa/25 °C/15 min	Carotenoid content was increased mainly due to an increase in β -carotene and β -cryptoxanthin. TAC was increased after HP	De Ancos and others (2000)
	400 to 600 MPa/Room temperature/10 to 30 min	No changes in Vit. C after HP treatments	Kimura and others (1994)
	200 to 800 MPa/18 to 22 °C/15 min, 9 d storage at 4, 20, and 30 °C	No significant changes in anthocyanin (cyanidin-3-glucoside and cyanidin-3-sophoroside) were obtained	Suthanthangjai and others (2005)

Vit. C = vitamin C; TC = total carotenoids; TPC = total phenolic compounds; TAC = total antioxidant capacity.

tomato and carrot purées. They obtained a lower loss in redness in HP-treated (400 to 600 MPa) strawberry and blackberry purées in comparison to thermal treatment. The redness of all processed (HP and thermal) tomato and carrot purées was higher than untreated samples. These authors also observed that the lightness of all processed tomato purées decreased in comparison to untreated purées, this was particularly noticeable following thermal treatment and HP (600 MPa). With regard to carrot purées, a significant increase in lightness was obtained after thermal treatment and HP treatments at 400 and 600 MPa, while a decrease was found for HP-treated (500 MPa) carrot purées in comparison to untreated samples. Moreover, they found that color differences were minor for HP-treated strawberry and blackberry purées than in thermally treated purées. Yen and Lin (1996) found marked changes in total color differences after applying thermal treatments (88 to 90 °C, 24 s) in comparison to HP-treated (400 to 600 MPa/room temperature/10 to 15 min) and untreated guava purée. During 60 d storage at 4 °C, they found higher color differences in untreated and HP-treated (400 MPa) guava purée in comparison to thermally treated and HP-treated (600 MPa) samples. Sánchez-Moreno and others (2006) obtained an increase in lightness and redness of HP-treated (400 MPa/25 °C/15 min) samples, while a decrease was obtained for these parameters when thermal treatment (70 °C, 30 s and 90 °C, 1 min) was applied in comparison to untreated purées. Moreover, a decrease in b^* values was observed for HP and thermal treatments.

Aroma and flavor. Yen and Lin (1996) did not observe changes in aroma of guava purée immediately after HP treatments (400

to 600 MPa/room temperature/10 to 15 min) and subsequent storage 60 d at 4 °C in comparison with untreated sample, nor the unpleasant flavors of heat-treated (88 to 90 °C, 24 s) purée. Lambert and others (1999) studied the impact of HP treatments (200 to 800 MPa/20 °C/20 min) on the aromatic volatile profile of strawberry purée and they found that pressure treatments of 200 and 500 MPa did not affect the aroma profile, while a significant change was observed in the HP-treated (800 MPa) strawberry purée compared to untreated sample by inducing the synthesis of new compounds. In a study performed by Jacobo-Velázquez and Hernández-Brenes (2011), they used a trained panel and a consumer panel to determine the sensory shelf-life-limiting factor of HP-treated (600 MPa/23 °C/3 min) avocado paste during 45 d storage at 4 °C. In this study, the trained panel identified sour and rancid favors as the main sensory descriptors (critical descriptors) that are able to discriminate stored from untreated samples. Consumers panel identified sour favor as the main cause for a significant decrease in the acceptability (shelf-life-limiting factors) of HP avocado paste stored at 4 °C during 45 d.

Bioactive compounds

Yen and Lin (1996) did not find significant changes in vitamin C of HP-treated (400 to 600 MPa/room temperature/10 to 15 min) and thermally treated (88 to 90 °C, 24 s) guava purée. During 60 d storage at 4 °C, they found a decrease in vitamin C content of untreated and HP-treated (400 MPa/25 °C/15 min) guava purée after 10 and 20 d storage, respectively, whereas non-significant losses in vitamin C were observed for thermally treated (88 to

90 °C, 24 s) and HP-treated (600 MPa/room temperature/15 min) guava purée until d 30 and d 40, respectively. Similarly, Kimura and others (1994) did not find significant losses on vitamin C when they evaluated the impact of HP treatments (400 to 600 MPa/room temperature/10 to 30 min) on strawberry and kiwi jams. Patras and others (2009a,b) studied the effects of HP treatments (400 to 600 MPa/10 to 30 °C/15 min) and thermal treatment (70 °C, 2 min) on strawberry, blackberry, tomato, and carrot purées. In all cases, the vitamin C degradation was lower (5 to 9%) for HP-treated strawberry purée compared with thermal treatment (21%). A significant decrease in vitamin C was observed for all treatments in tomato purées, this was particularly noticeable in thermally treated and HP-treated (400 and 500 MPa/20 °C/15 min) purées while lower losses were observed for HP-treated (600 MPa/10 to 30 °C/15 min) tomato purées. Sánchez-Moreno and others (2006) observed a decrease in total vitamin C content (about 29%) of tomato purée after HP (400 MPa/25 °C/15 min) and thermal treatment (70 °C, 30 s and 90 °C, 1 min), with no significant differences among them.

García-Parra and others (2011) compared the effect of HP treatments (450 and 600 MPa/10 °C/5 and 10 min) and thermal treatment (85 °C, 5 min) on carotenoid profile of nectarine purée and their subsequent storage at 5 °C for 60 d. They did not find significant changes in carotenoid contents after applying HP at 600 MPa while HP at 450 MPa for 5 min, while thermal treatment increased the amounts of carotenoids measured in the nectarine purée. These authors also obtained an increase in zeaxanthin + lutein after applying HP treatment at 450 MPa during 20 d storage at 5 °C, while non-significant differences were obtained at the end of the storage (60 d) for HP and thermally treated purées in comparison to untreated samples. Effects of HP treatment on rojo brillante and sharon persimmon fruit purées carotenoids (violaxanthin, neoxanthin, zeaxanthin, lutein, antheroxanthin, β -cryptoxanthin, lycopene, and β -carotene) associated with nutritional (vitamin A) values were investigated by De Ancos and others (2000). Various HP treatments (50 to 400 MPa/25 °C/15 min) were assayed. The authors found that HP treatments (50 and 300 MPa/25 °C/15 min) for rojo brillante purée and HP (50 and 400 MPa/25 °C/15 min) for sharon purée produced significant increases of 9 to 27% in the carotenoid content mainly due to an increase in provitamin A carotenoids such as β -carotene and β -cryptoxanthin. Butz and Tauscher (2002) did not find significant changes in carotenoids of HP-treated (600 MPa/75 °C/40 min) carrot purée, they attributed a protective effect of food matrix in order to prevent carotenoid degradation. Moreover, several studies are reported in the published literature showing the use of HP as a suitable processing in order to increase carotenoids extraction from tomato-based products, which would be associated with an increase in nutritional value. Fernández-García and others (2001) did not find significant modifications in lycopene and β -carotene of tomato purée after applying HP (300 and 600 MPa/20 °C/10 to 60 min) and thermal treatments (95 °C, 10 to 60 min) in comparison to untreated sample. Similar results to those found in this study were obtained by Krebbers and others (2003) when they evaluated the effects of HP treatment (300 to 700 MPa/20 to 90 °C/2 min). They did not observe significant changes on lycopene content of HP-treated (700 MPa) tomato purée. Moreover, they found an increase (58%) of lycopene content after application of HP (500 MPa/20 °C/2 min) in tomato purée. These authors also obtained an increase in lycopene, β -carotene, and total carotenoids content of 14, 20, and 10%, respectively, in HP-treated (400 MPa) purée compared to

untreated sample. In this line, Sánchez-Moreno and others found an increase in individual carotenoids such as lycopene (77%) and β -carotene (35%), and in the total carotenoid content of HP-treated tomato purée (400 MPa/25 °C/15) compared to the untreated sample. Patras and others (2009b) studied the effects of HP treatments (400 to 600 MPa/20 °C/15 min) and thermal treatment (70 °C, 2 min) on tomato and carrot purées. They found a significant increase (19 to 172%) in total carotenoids of HP-treated tomato (600 MPa) and carrot (400 to 600 MPa) purées while significant decrease was observed in thermally treated (-10%) and HP-processed (400 and 500 MPa) tomato purées in comparison to untreated samples.

Suthanthangjai and others (2005) did not find significant changes in cyanidin-3-glucoside and cyanidin-3-sophoroside of HP-treated (200 to 800 MPa/18 to 22 °C/15 min) raspberry purée stored at 4, 20, and 30 °C for 9 d. Patras and others (2009a, 2009b) studied the effect of HP treatments (400 to 600 MPa/10 to 30 °C/15 min) and thermal treatment (70 °C, 2 min) on cyanidin-3-glycoside and pelargonidin-3-glucoside in strawberry and blackberry purées. They did not observe significant changes in these compounds between pressure-treated and unprocessed purées, while a significant decrease was obtained after thermal treatment. When García-Parra and others (2011) evaluated the impact of HP treatments (450 and 600 MPa/10 °C/5 and 10 min) and thermal treatment (85 °C, 5 min) on total phenolics of nectarine purée immediately after processing and during subsequent storage 60 d at 5 °C, they found a significant increase in total phenolics immediately after applying HP at 600 MPa/10 min and during subsequent storage in comparison to untreated sample. They also found an increase in total phenolics in thermally treated purées (day 20) with a subsequent decrease at the end of the storage (day 60).

Total antioxidant capacity

De Ancos and others (2000) studied the effects of HP treatments (50 to 400 MPa/25 °C/15 min) on the antioxidant capacity of persimmon fruit purées, measured as free radical-scavenging capacity. They obtained an increase in the free radical scavenging capacity of the HP-treated (150 MPa/25 °C/15 min) rojo brillante fruit purée and HP-treated (150 and 300 MPa/25 °C/15 min) sharon fruit purée. In other study, Patras and others (2009a, 2009b) evaluated the impact of HP treatments (400 to 600 MPa/10 to 30 °C/15 min) and thermal treatment (70 °C/2 min) on antioxidant capacity of strawberry, blackberry, tomato, and carrot purées. They found a significant increase in antioxidant capacity for all HP-treated blackberry purées (29 to 68%), tomato purées (8 to 27%) purées and HP-treated (500 and 600 MPa/20 °C/15 min) carrot purées (22 to 37%) while a decrease was found for all HP-treated strawberry purées (14 to 19% losses) in comparison to untreated samples. In general, antioxidant capacity of HP-treated purées was significantly higher than in thermally processed purées. García-Parra and others (2011) studied the effects of HP-treated (450 and 600 MPa/10 °C/5 and 10 min) nectarine purées and compared them with thermally treated purée (85 °C, 5 min), and stored them at 4 °C for 60 d. They found significant higher values of antioxidant capacity immediately after HP treatment in comparison to untreated purée. During 20 d storage, the higher antioxidant capacity was obtained in thermally treated purée, however, the highest antioxidant capacity at the end of storage (day 60) was found in the HP-treated purée at 600 MPa/10 min. When Fernández-García and others (2001) evaluated the impact of HP treatments

Table 4—Effect of HP processing on fat, fatty acid profile, lactose, and mineral balance of milk.

Product	Treatment conditions	Major findings	References
Bovine and goat whole milk	200 to 400 MPa	No changes in the size of the fat globules	Buffa and others (2001), Huppertz and others (2003), Ye and others (2004)
Bovine whole milk	400 to 500 MPa/0 to 20 min	Alterations in the size and distribution of fat globules	García-Amezquita and others (2009)
Whole ewe milk	100 to 500 MPa/4 to 50 °C/15 to 30 min	Alterations in the size and distribution of fat globules. Free fatty acids levels lower than untreated	Gervilla and others (2001)
Human milk	400 to 600 MPa/22 to 27 °C/5 min	No changes in free fatty acid levels	Moltó-Puigmartí and others (2011)
Whole milk	200 MPa/−4 °C/10 to 30 min	Short-chain free fatty acid content increased as treatment time increased	Kim and others (2008)
Whole cow milk	100 to 400 MPa/25 °C/10 to 60 min	No changes in lactose	López-Fandiño and others (1996)
Bovine Milk	200 to 400 MPa	Increase in phosphate concentration	Schrader and others (1997), Schrader and Buchheim (1998), López-Fandiño and others (1996), Zobrist and others (2005)

(500 and 800 MPa/20 °C/5 min) on antioxidant capacity (TEAC) of tomato purée immediately after processing and during subsequent storage 21 d at 4 °C, they observed a significant decrease in total antioxidant capacity of HP-treated tomato purée after the first week of storage. Sánchez-Moreno and others (2006) observed a significant decrease in the antioxidant capacity (DPPH) of tomato purée immediately after application of HP treatment (400 MPa/25 °C/15 min) and thermal treatments (70 °C, 30 s and 90 °C, 1 min). They correlated this decrease of antioxidant capacity with vitamin C loss.

Milk

Milk was the first product to be treated with high pressure (Hite, 1899), and numerous studies have been conducted concerning the changes that HP may induce in this product. However, few studies are reported in the published literature. Some of these studies are listed in Table 4.

Physicochemical properties

Kim and others (2008) did not observe changes in the pH or viscosity of whole milk after HP treatment (200 MPa/−4 °C/10, 20, and 30 min), but other authors found an increase in pH that depended on treatment pressure and time (Schrader and others 1997; Schrader and Buchheim 1998; Huppertz and others 2004; Zobrist and others 2005). With regard to sensory properties, García-Risco and others (2000) suggested that the application of HP (400 MPa/40 to 60 °C/15 min) maintained or improved the organoleptic quality of milk.

In some studies, authors observed that the application of HP treatment destabilized casein micelles and also increased the dynamic viscosity of milk, whereas it reduced the turbidity and lightness of skim milk, normally in the range 200 to 400 MPa (Shibauchi and others 1992; Desobry-Banon and others 1994; Regnault and others 2004). The decrease in the turbidity of the milk was related with an increase in the transmittance of light in pressurized skim milk, and the treated skim milk became almost transparent. This effect increased as pressure applied and treatment time increased. However, whole milk did not show changes in turbidity, probably because of the fat globules (Shibauchi and others 1992).

Gervilla and others (2001) applied HP (100 to 500 MPa/4, 25 and 50 °C/10 min) and observed a decrease in the value of lightness and an increase in redness and yellowness as the pressure applied to the milk increased. These results are similar to those obtained, also in whole milk, by Kim and others (2008).

Bioactive compounds

With regard to the vitamins in milk, Sierra and others (2000) did not observe significant losses of vitamins B₁ and B₆ in whole milk after applying HP (400 MPa/25 °C/30 min), whereas Kim and others (2008) observed a significant decrease in the values of vitamin C, niacin, and riboflavin in the HP-treated samples as treatment time increased in comparison with fresh milk. However, Molto-Puigmartí and others (2011) did not find significant differences in the levels of vitamin C and tocopherols in HP-treated (400 to 600 MPa/22 to 27 °C/5 min) and fresh samples of human milk.

Fat content and fatty acid profile

There are also studies on the fat fraction of milk. Some authors have observed that the size of the fat globule is not significantly affected by HP treatment (Buffa and others 2001; Huppertz and others 2003; Ye and others 2004), but some whey proteins are denatured after HP treatment of whole milk. This contrasts with other research, which suggests that pressures above 500 MPa produce some alterations in the size and distribution of the fat globule in whole milk (Gervilla and others 2001; García-Amezquita and others 2009).

With regard to the fatty acid profile, Gervilla and others (2001) observed free fatty acid levels lower than those of untreated whole sheep milk. On the other hand, Molto-Puigmartí and others (2011) did not find significant alterations in fatty acids in the HP-treated human milk (400, 500, and 600 MPa/22, 24.5, and 27 °C/5 min) in comparison with fresh milk. Furthermore, Kim and others (2008) also did not observe changes in short-chain free fatty acid contents after applying HP treatment when the treatment time was less than 20 min, but the values did increase at 20 and 30 min, which they attributed to the possible activation of lipolysis.

Lactose

López-Fandiño and others (1996) studied the effect of HP on lactose in whole cow milk. They observed that after pressurization (100 to 400 MPa/25 °C/10 to 60 min) there was no degradation of lactose, which suggests that there is no Maillard reaction or isomerization of lactose after HP.

Mineral balance

With regard to minerals, two basic alterations in the mineral balance of milk have been observed as a consequence of HP: the distribution of minerals and the level of ionized minerals, especially

calcium. Some of the major minerals or salts in milk, primarily calcium and phosphate, are distributed in a complex three-phase equilibrium. Calcium is found in ionized or non-ionized form in the milk serum, as well as associated with the casein micelles in the micellar calcium phosphate form. Various studies show that HP treatment (200 to 400 MPa) increases the concentration of ionic calcium in milk as well as the level of total calcium and phosphate in the serum phase of milk, with a maximum effect at 300 MPa (Schrader and others 1997; López-Fandiño and Olano 1998; Schrader and Buchheim 1998; Zobrist and others 2005). These studies also reported that the increase produced in the concentration of calcium and phosphate was rapidly reversible after HP treatment, particularly when the milk is stored at a temperature above 10 °C.

Conclusion

After observing the results obtained by the various authors who have studied the behavior of fluid foods when HP is applied, it can be concluded that the behavior of bioactive compounds and certain physicochemical parameters, especially color, differ because of the HP treatment intensity applied and also according to the food matrix to which it is applied, making it necessary to study each matrix separately.

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