Chapter 3
High-Pressure Processing of Dairy Products

3.1 Milk

3.1.1 Pasteurization

Research into the application of HPP for milk preservation began when Hite (1899) demonstrated that the shelf life of milk and other food products could be extended by pressure treatment. High pressure was found to be equally effective in destroying pathogenic and spoilage microorganisms compared to heat treatment. A number of researchers have studied inactivation of microorganisms (such as *Listeria monocytogenes*, *Staphylococcus aureus*, or *Listeria innocua*) either naturally present or introduced in milk (Erkman and Karatas 1997; Gervila et al. 1997). Periodic oscillation of high pressure was very effective for the destruction of pathogens such as *Listeria monocytogenes*, *Escherichia coli*, and *Salmonella enteritidis*, and this offers a promising alternative for the cold pasteurization of milk (Vachon et al. 2002).

Higher pressures resulted in higher rates of microbial destruction, enzyme alkaline phosphatase inactivation, as well as color and flavor changes as indicated by the associated lower D-values. Further, the rate of microbial destruction was much more rapid than enzyme inactivation or color and viscosity changes. Milk subjected to a microbial 4D high pressure process at 350 MPa had a shelf life of 25 days at 0 °C, 18 days at 5 °C, and 12 days at 10 °C (Fig. 3.1, Mussa and Ramaswamy 1997). HPT (400 MPa for 15 min or 500 MPa for 3 min) of thermally pasteurized milk increased shelf life by 10 days (Rademacher and Kessler 1997). A mild heat treatment (37 °C, 240 min or 50 °C, 10 min) inhibited the recovery of *Listeria monocytogenes* in high-pressure-processed milk, and the product was safely stored for 70 days at 25 °C (Koseki et al. 2008). Raw milk pressurized at 400 MPa for 30 min at 25 °C contained < 7 log psychrotrophs/ml after storage for 45 days at 7 °C, whereas unpressurized milk contained > 7 log of these bacteria after only 15 days (Garcia-Risco et al. 1998). Application of higher pressures for longer holding time at lower temperature resulted in greater destruction of indigenous microflora and *Escherichia*

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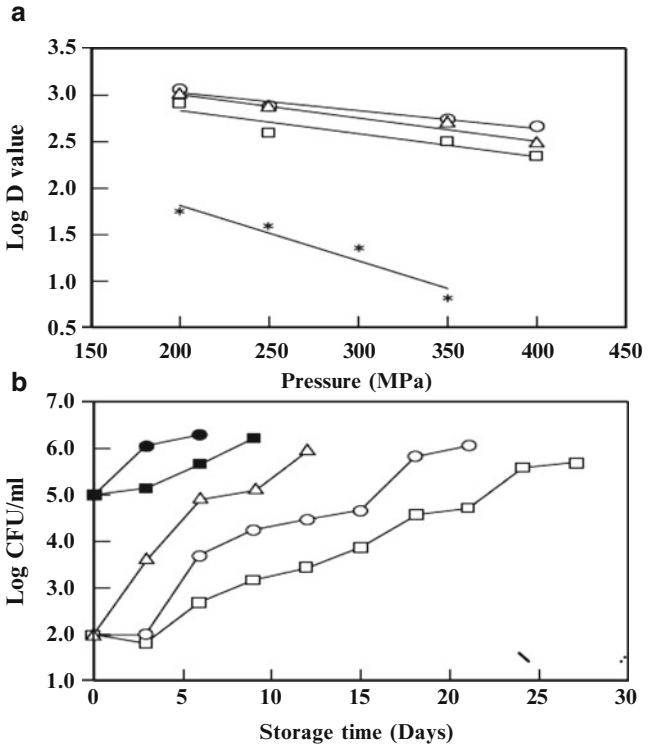

Fig. 3.1 (**a**) Decimal reduction time curves for microorganisms (*), color (○), alkaline phosphatase (Δ), and viscosity (increase; □) in milk subjected to ultra-high pressures (**b**) standard plate counts of high-pressure-processed milk (4D process 350 MPa) during storage at 0 °C (□), 5 °C (○), and 10 °C (Δ). Also shown are SPC of control samples stored at 0 °C (■) and 5 °C (●) (From Mussa, D.M., and Ramaswamy, H.S. 1997. *Lebensm. Wiss. Technol.* 30: 551–557. With permission)

coli in raw milk (Pandey et al. 2003). The Weibull model described the high pressure (400–600 MPa, 22 °C) inactivation kinetics of *Escherichia coli* and *Listeria innocua* (Buzrul et al. 2008b).

The protein fractions of skimmed milk provided protection against the injury and inactivation of *Escherichia coli* during HPT (Fig. 3.2a, Narisawa et al. 2008). Casein and lactose present in milk provided the major baro-protection effect to *Escherichia coli* in milk during HPT. Fat content in milk (0–5 %) had no significant effect on the destruction (Fig. 3.2b, Ramaswamy et al. 2009).

The gram-negative bacteria, in this case, were found to be more sensitive to high pressure, either alone or in combination with nisin, than gram-positive bacteria (Black et al. 2005). Later, Black et al. (2008) showed that combinations of HPT and nisin resulted in high levels of germination of *Bacillus* spores, but complete inactivation was not achieved. Further, the combination of high pressure with a bacteriocin (lacticin) was shown as a promising and natural method for increasing the

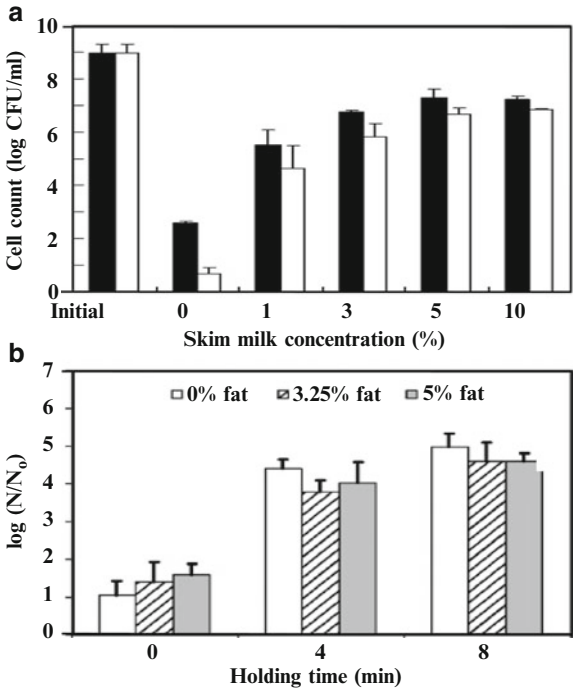

Fig. 3.2 (**a**) Effect of skimmed milk concentration on the surviving and uninjured cells of Escherichia coli by HPT at 25 °C, 250 MPa for 20 min. Black bars indicate the surviving cells and white bars indicate the uninjured cells. (**b**) A comparison of logarithmic cycle reduction of E. coli K12 in 400 MPa treated milk with different fat contents (From Narisawa, N., Furukawa, S., Kawarai, T., Ohishi, K., Kanda, S., Kimijima, K., Negishi, S., Ogihara, H., and Yamasaki, M. 2008, Intl. J. Food Microbiol. 124: 103–107; Ramaswamy, H.S., Jin, H., and Zhu, S. 2009. Food Bioprod. Proc. 87: 1–6. With permission)

efficiency and safety of HPP of milk. It resulted in a synergistic effect in controlling microbial flora of milk without significantly influencing its cheese-making properties (Fig. 3.3, Morgan et al. 2000). Other antimicrobial peptides such as lactoferrin and lactoferricin (500 μg/ml) in combination with high pressure (155–400 MPa) also resulted in enhanced microbial inactivation (Masschalck et al. 2001).

The divalent cations Ca^{2+} and Mg^{2+} protect bacteria against HP-induced inactivation because of their stabilizing effect on the cell membrane. The buffering capacity of dissociated anions, i.e., phosphate and citrate, counteracts the HP-induced decrease in pH observed in milk, which would otherwise render bacteria more susceptible to HP-induced inactivation (Huppertz et al. 2005). HPT (400 MPa, 30 min) of milk did not result in a significant variation in the content of B_1 and B_6 vitamins (pyridoxamine and pyridoxal) (Sierra et al. 2000).

Ramaswamy et al. (2010) studied the destruction kinetics of *Clostridium sporogenes* inoculated in milk subjected to different pressure, temperature, and time

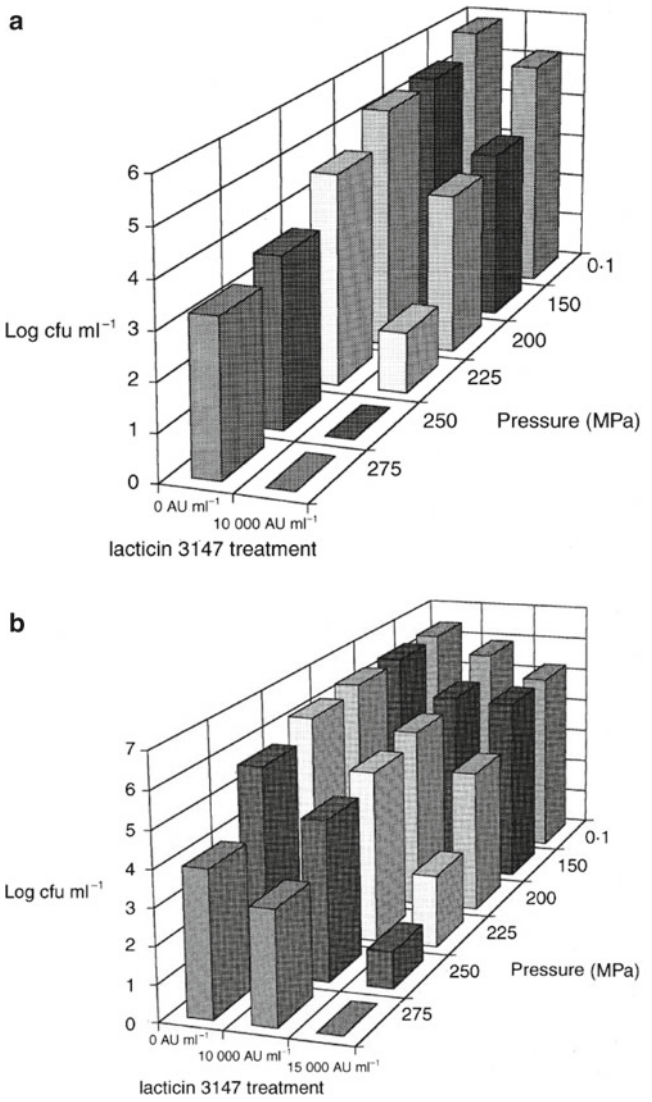

Fig. 3.3 The effect of HP and lacticin 3147 on (**a**) *Staphylococcus aureus* ATCC6538 (**b**) *Listeria innocua* DPC1770 viability (From Morgan, S.M., Ross, R.P., Beresford, T., and Hill, C. 2000. *J. Appl. Microbiol*. 88: 414–420. With permission)

combination treatments (700–900 MPa, 80–100 °C). Higher pressures and higher temperatures resulted in a higher destruction rate and a higher microbial count reduction. Vazquez et al. (2006, 2007) indicated that combination of high pressure with temperature for the processing of milk promoted the formation of few compounds leading to generation of 'cooked' milk flavor and sensory acceptance of treated milk was not very high.

Huppertz et al. (2005) reviewed the effect of HP on the range of bacteria naturally present (total microflora, aerobes, aerobic mesophiles, psychrotrops, coliforms) and exogenously added (*Escherichia coli*, *Listeria monocytogenes*, *Listeria innocua*, *Staphylococcus aureus*, and *Salmonella enteritidis* etc.) in milk. Further, Trujillo et al. (2002); Huppertz et al. (2002, 2005), and Chawala et al. (2010) reviewed the effect of HP on properties and contents of milk.

3.1.2 Whey Protein

High pressure up to 300 MPa did not result in significant decrease in β-lactoglobulin in whey, whereas further increase in pressure resulted in decreased β-lactoglobulin (Pandey and Ramaswamy 1998; Brooker et al. 1998). HPT (200–600 MPa) prior to enzymatic hydrolysis of whey protein concentrate with proteinase led to a decrease in β-lactoglobulin, but α-lactalbumin did not change, whereas heat treatment in place of HPT resulted in decrease in both the proteins (Nakamura et al. 1993). The decrease in β-lactoglobulin was attributed to the exposure of side chains of buried amino acids to solvent (Alvarez et al. 2007). Denaturation of β-lactoglobulin took place at pressures as low as 200 MPa and the extent of which was found to increase with an increase in holding time and treatment pressure. Also, α-lactalbumin was denatured only at pressures 400 MPa, and no effect of milk solids concentration was observed (Anema 2008a, b). A pressure treatment of 500 MPa at 25 °C denatures lactoglobulin, whereas denaturation of immunoglobulins and lactalbumins occurs only at the highest pressures, particularly at temperatures above 50 °C (Felipe et al. 1997). An increase in the temperature of the HPT up to 60 °C did not induce β-lactoglobulin denaturation at 100 MPa, but at higher pressures denaturation increased with increasing temperature. At the same time, almost 60 % of α-lactalbumin was denatured by treatment at 400 MPa and 60 °C (Fig. 3.4, Lopez-Fandino and Olano 1998).

High pressure (100–300 MPa) combined with selected food-grade proteinases can be used as a treatment to remove the antigenicity of whey protein hydrolysate enabling its use as ingredients of hypoallergenic infant formulas (Penas et al. 2006). Pepsin and chymotrypsin under high pressure (400 MPa) produced hydrolysates in which α-lactalbumin and β-lactoglobulin were totally proteolyzed resulting in large and hydrophobic peptides. Such hydrolyzates showed reduced antigenicity, human IgE-binding properties, improved heat stability, and superior emulsion activity (Chicon et al. 2009). HPT of whey protein concentrate increased the number of binding sites which led to certain modifications in proteins, enhanced hydrophobicity, and showed promising results for improving functional properties of foods (Liu et al. 2005).

3.1.3 Milk Enzymes

Milk enzymes were much less sensitive to pressure. Only alkaline phosphatase and proteinases were completely inactivated at 1,000 MPa. A small increase in the

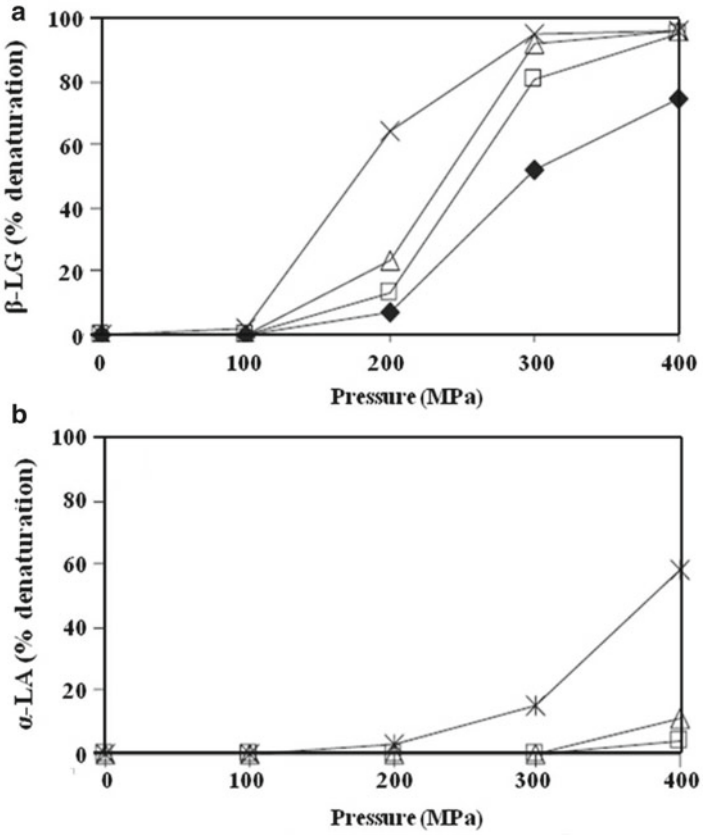

Fig. 3.4 (**a**) Effect of pressurization on milk at 25 °C(♦), 40 °C (□), 50 °C (Δ), and 60 °C (×) for 15 min on the percentage of denaturation of (**a**) β-LG (β-*lactoglobulin*) and (**b**) α-LA (α-*lactalbumin*) (From Lopez-Fandino, R., and Olano, A. 1998. *Intl. Dairy J.* 8: 623–627. With permission)

lactoperoxidase activity due to antagonistic effect of HP and temperature was noted, which indicated that pressure treatment might lead to preservation of the lactoperoxidase activity, thereby maintaining the antimicrobial potency of milk (Ludikhuyze et al. 2001). HPT for a short time was reported to enhance activity of lipoprotein lipase and glutamyl transferase of milk. But, long-time (100 min) pressure treatment did not bring about any inactivation of lipase, while glutamyl transferase followed first-order inactivation kinetics (Pandey and Ramaswamy 2004).

Felipe et al. (1997) showed that HPT (500 MPa, 10 min, 25 or 50 °C) did not change the activity of alkaline phosphatase in goats' milk. Xanthine oxidase was proposed as an indicator of the HPT of milk. It was resistant to high-pressure exposure at 400 MPa at 25 °C and, at higher pressures; it was inactivated following first-order kinetics (Olsen et al. 2004). Ludikhuyze et al. (2000) studied the effect of high pressure on alkaline phosphatase to use it as an indicator of HPT. It was concluded that alkaline phosphatase could be an indicator of the absence of nonsporogenic

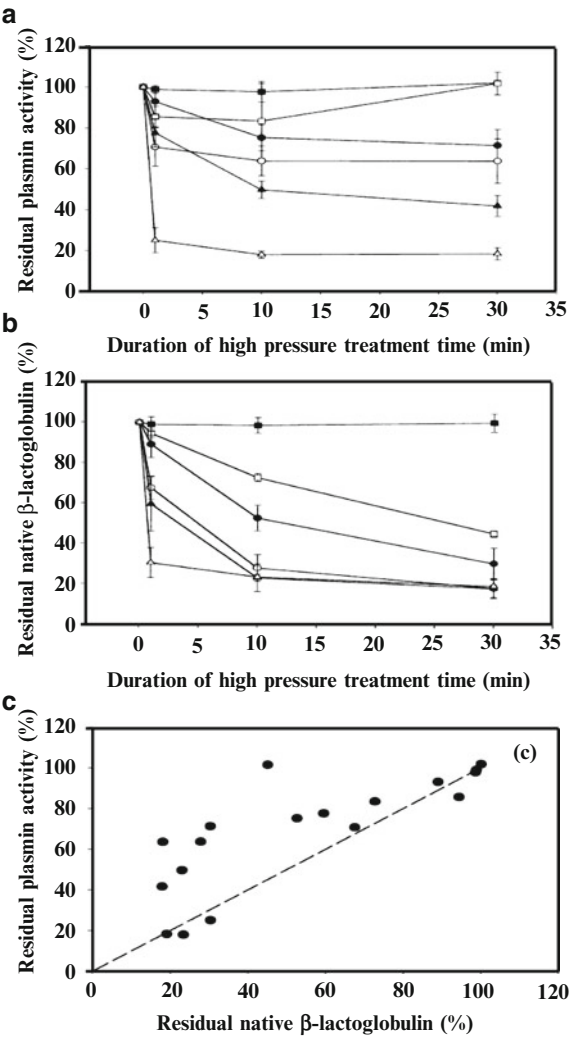

Fig. 3.5 Residual native (**a**) plasmin, (**b**) β-lactoglobulin concentrations in milk determined immediately after HPT at 50 MPa (■), 300 MPa (□), 400 MPa (●), 500 MPa (○), 600 MPa (▲), and 800 MPa (Δ), for a range of times, relative to untreated control milk, (**c**) plot of the relationship between residual plasmin activity (%) and native β-lactoglobulin (%) (From Scollard, P.G., Beresford, T.P., Needs, E.C., Murphy, P.M., and Kelly, A.L. 2000. *Intl. Dairy J.* 10: 835–841. With permission)

pathogens, but an acceptable level of residual activity should be adequately defined to avoid overprocessing.

Scollard et al. (2000) indicated that β-lactoglobulin was denatured and plasmin activity was decreased at pressures higher than 300 MPa and 400 MPa, respectively. The loss of activity was not well correlated with β-lactoglobulin denaturation (Fig. 3.5). HPT influenced proteolysis in milk. During the storage of treated milk, treatment at 50 MPa had little effect on proteolysis, but at 300–400 MPa proteolysis was increased, possibly due to changes in micelle structure facilitating increased availability of substrate bonds to plasmin; whereas after 500 MPa, the proteolysis during storage of milk was less than that observed in raw milk. García-Risco et al. (2000) also demonstrated that HPP at higher temperatures considerably increased plasmin inactivation.

A synergistic effect of temperature and high pressure was observed in the range of 300–600 MPa, whereas an antagonistic effect was observed at 600 MPa, most likely due to stabilization of enzymes by disruption of disulfide bonds (Borda et al. 2004a, b). The combined effects of high pressure (300–600 MPa, 40–60 °C) and homogenization resulted in inactivation of protease activity in milk, which extended its shelf life (Sainz et al. 2009).

3.1.4 Casein

HPT at 100–200 MPa had little influence on average casein micelle size at ambient temperature, whereas 250 MPa for more than 15 min increased the micelle size, and at a pressure higher than 300 MPa reduces micelle size by less than 50 %. HP-induced increase in micelle size at 250 MPa is greater after a longer treatment time and at a higher treatment temperature and higher milk pH, as well as when the original untreated micelles are larger. Increases in micelle size at 250 MPa are probably due to the formation of large aggregates from HP-disrupted casein micelles (Huppertz et al. 2008; Anema et al. 2005a). HP-induced disruption of casein micelles and dissociation of casein from the micelle were due to solubilization of micellar calcium phosphate, as well as the disruption of intramicellar hydrophobic and electrostatic interactions (Regnault et al. 2004).

HP-induced micellar dissociation resulted in the breaking of linkages between casein and inorganic constituents. Besides, HP also exerts a disruptive effect on hydrophobic interactions that allowed the loss of casein clusters, stabilized through colloidal calcium phosphate, from the casein micelle (Needs et al. 2000a). HPT of acidified milk ($pH \leq 6.0$) led to intensive destruction of the colloidal structure and an increase in the content of nonsedimentable casein (Arias et al. 2000), whereas at neutral or alkaline pH the solubilization of colloidal calcium phosphate is limited, which helps to maintain the colloidal structure (Anema et al. 1997).

Initially, application of HP (250–300 MPa) led to a rapid micellar disruption, which was found to be reduced by cross-linking of the casein micelles through transglutaminase prior to pressure treatment (Huppertz and Smiddy 2008). Pressurization of milk in the range of 150–300 MPa favored the formation of a large number of small micelles that coexisted with a fraction of large micelles and appeared perfectly spherical with smooth and well-defined surfaces which originated due to secondary adsorption of casein (Knudsen and Skibsted 2010).

3.2 Cheese

HP resulted in casein micelle disruption, whey protein denaturation, increase in milk pH and cheese yield, and reduction in rennet coagulation time, which indicates its significant potential in the cheese-making process (O'Reilly et al. 2001; San-Martin et al. 2006).

3.2.1 Shelf-Life Extension

HPP can be utilized as an effective tool to extend shelf life while maintaining the quality attributes of this product. HPP (400–500 MPa) of goat milk cheese (inoculated with 10^8 CFU/g) showed no surviving *Escherichia coli* even after 15, 30, or 60 days of storage at 2–4 °C (Capellas et al. 1996). Application of HP substantially reduced the microbial load in Cheddar cheese, with 400 MPa for 20 min at 20 °C being sufficient to reduce the numbers of viable *Escherichia coli* and *Penicillium roqueforti* by 7- and 6-log-unit cycles, respectively, and to reduce the levels of *Staphylococcus aureus* by 3-log-unit cycles (O'Reilly et al. 2000).

HPT (400–700 MPa) was effective in reducing *Listeria monocytogenes* in gorgonzola cheese rinds (Carminati et al. 2004) and Turkish white cheese (Evrendilek et al. 2008) without significantly changing its sensory properties. HPT also resulted in total reduction in molds, yeasts, and Enterobacteriaceae counts for the cheese samples produced from raw and pasteurized milk. HPT (500 MPa, 10 min) significantly reduced the level of *Listeria monocytogenes* in the raw milk and so allowed the production of safer nonthermally processed camembert-type soft cheese (Linton et al. 2008).

Delgado et al. (2011a) demonstrated that HPT increased the food safety of raw goats' milk cheeses without affecting the original aroma of the cheese. Arriagada et al. (2012) showed that cheese treated at 300 and 400 MPa and stored at 4 °C had a shelf life of 14 and 21 days, respectively, compared to 7 days in untreated cheese.

3.2.2 Rennet Coagulation

Rennet coagulation time was not dependant on the pressure in the lower range (< less than 150 MPa), whereas at higher pressures (200–400 MPa) it decreased (Needs et al. 2000a). The decrease was due to HP-induced association of whey proteins with casein micelles. Further, increase in pressure (500–600 MPa) resulted in increased rennet coagulation time (Needs et al. 2000a). Rennet coagulation time of pressure-treated (500 MPa) milk was higher than pasteurized milk (72 °C, 15 s, Trujillo et al. 1999a).

HPT (400 MPa) of pasteurized milk resulted in decreased rennet coagulation time. At 600 MPa, the rennet coagulation time was found to decrease along with decrease in pH, initial counts of nonstarter lactic acid bacteria, protein and fat content. The treatment increased incorporation of β-lactoglobulin leading to increased yield (Voigt et al. 2010). Freshly prepared rennet-coagulated soft cheese subjected to HPT (291 MPa and 29 min) resulted in increased fat content (due to decrease in moisture), reduced lipid oxidation, acidity, and adhesiveness, whereas, hardness, and yellowness was found to increase (Okpala et al. 2010). Katsaros et al. (2010a) applied the protease actinidin (from *Actinidia chinensis*) as the milk clotting agent, and HP to control excessive proteolysis for the production of fresh

cheese without affecting the texture and sensory characteristics. Plant proteases can be a viable approach provided that excessive proteolysis after structure formation is regulated.

3.2.3 Yield

HPT induced denaturation of whey proteins and their association with casein, which resulted in increased cheese yield. HPT of milk may allow moisture to be trapped or held in cheese due to aggregation of casein molecules and fat globules leading to increased yield and higher moisture content of cheese (Drake et al. 1997). Reduced hardness of Cheddar cheese made from HP-treated milk was due to association of whey protein with casein in pressurized milk (Pandey and Ramaswamy 1998). The yield of cheese from HP-treated and subsequently heated milk was greater than that from unheated and unpressurized milk (Arias et al. 2000; Huppertz et al. 2005, 2008). Molina et al. (2000) refer to the increased yield of pressurization of pasteurized milk due to improvement in the coagulation properties of proteins. Alonso et al. (2011) reported on the suitability of frozen pressurized curd made from raw ovine milk for Hispanico cheese manufacture without altering its flavor characteristics but increased the yield of the ripe cheese.

3.2.4 Ripening

HP induces changes in biochemical processes such as glycolysis, lipolysis, and proteolysis during ripening of cheese leading to reduction in ripening time and quality improvement. The rate of ripening of commercial cheddar cheese due to HPT accelerated the degradation of α_{S1}-casein and accumulation of α_{S1}-1-casein (O'Reilly et al. 2001). HP-treated (500 MPa) goats' milk had higher pH and salt content, matured more quickly, and developed strong flavors (Trujillo et al. 1999b).

The odor of La Serena cheese during ripening made from raw Merino ewe's milk after the second day of HPT (300 or 400 MPa, 10 min) was scarcely affected; but after 50 days the volatile compound profile or the sensory characteristics were the same as those of the controls (Arques et al. 2007). Similarly, Juan et al. (2008) showed that HP (300 MPa, 10 min) on the day of manufacture resulted in decrease in α_{s1}- and β-casein and increase in water-soluble nitrogen and free amino acids, which resulted in decrease in scores for taste, odor, and aroma quality compared to controls, whereas after 15 days of ripening the scores were similar to the controls. The samples had more homogeneous protein network, less crumbly texture, and highest percentage of short-chain fatty acids.

HPT (200 or 500 MPa, 15 min, 20 °C) on the 15th day of ripening of ovine brined cheese indicated that the treatment at 200 MPa did not affect the counts of total aerobic mesophilic bacteria, thermophilic lactococci, thermophilic lactobacilli, and nonstarter lactic acid bacteria throughout ripening, whereas the treatment at 500 MPa

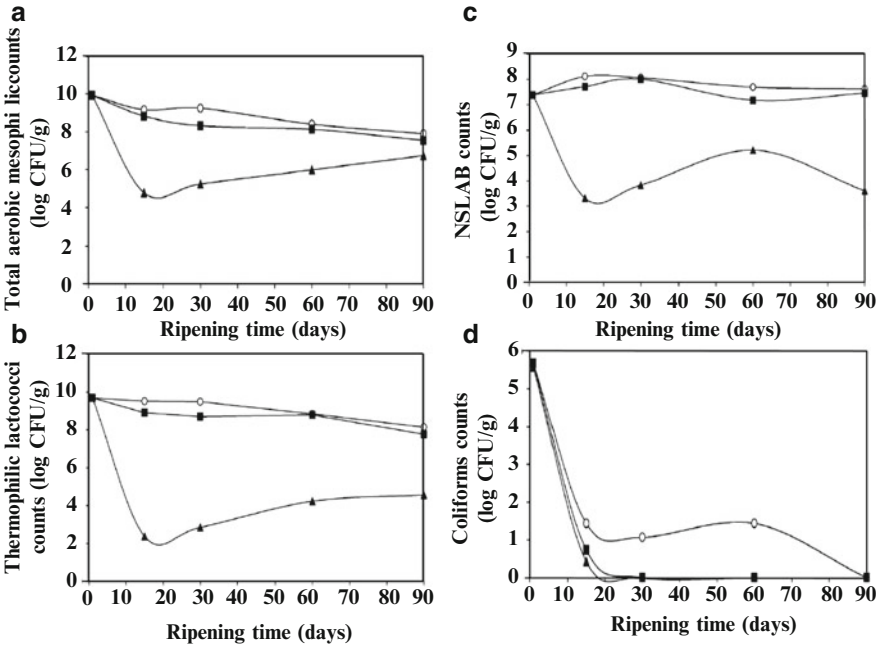

Fig. 3.6 Counts of (**a**) total aerobic mesophilic bacteria, (**b**) thermophilic lactococci, (**c**) non-starter lactic acid bacteria (*NSLAB*), (**d**) coliforms in ovine brined cheese during ripening: untreated (-○-), HP-treated at 200 MPa (-■-) or at 500 MPa (-▲-) for 15 min (From Moschopoulou, E., Anisa, T., Katsaros, G., Taoukis, P., Moatsou, G. 2010. *Innov Food Sci Emerg* 11: 543–550. With permission)

resulted in significant reduction. Coliforms were reduced faster at nondetectable levels in HP-treated cheeses than in control cheese (Fig. 3.6, Moschopoulou et al. 2010).

Delgado et al. (2011b) studied the effect of HPT (400 or 600 MPa, 7 min) on volatile compounds applied to raw-milk goat cheese at different stages of ripening (1, 30, or 50 days). HPT applied at the beginning of maturation decreased the relative abundance of most volatile compounds, but enhanced the formation of ketones and other compounds. Changes were less intense when treatment was applied at the end of maturation. Camembert cheese manufactured from HP-treated (500 MPa, 10 min) bovine milk caused an increase in moisture content and decrease in protein content and plasmin activity. The treatment resulted in an altered cheese composition and ripening pattern, but with an acceptable sensory quality (Voigt et al. 2011). Besides, it resulted in the elimination of a number of risk factors, but the quality characteristics of the cheese were similar to the cheese made from untreated raw milk. The treatment resulted in increased proteolysis and higher levels of free fatty acids in cheese and the product was whiter, less hard, gummy, and chewy compared to control cheese (Voigt et al. 2012). HPT (50–400 MPa, 5–15 min) of white cheeses ripened in brine for 60 days indicated that the treatment did not affect moisture,

protein, and fat contents. A lower HP level (50 and 100 MPa) resulted in no changes in microstructures, while at higher levels (200 and 400 MPa) resulted in denser and more uniform structure (Koca et al. 2011).

3.3 Yogurt

HPT (200–300 MPa at 10–20 °C) of packaged yogurt neither modified the yogurt texture nor reduced the number of viable lactic acid bacteria; but it prevented the development of acidity. The pressure above 300 MPa resulted in overacidification and the number of viable lactic acid bacteria was reduced (Tanaka and Hatanaka 1992).

Acid-set gels prepared from HP-treated (100–600 MPa, up to 1 h) milk improved texture (rigidity and resistance to breaking) and syneresis resistance of the gels, which in turn resulted in viscosity improvement of yogurt-type products (Johnston et al. 1994). High water retention was only maintained in yogurts made from HP-treated milk and the firmness increased with an increase in pressure and the product was found to be stable during storage at 4 °C for 20 days (Ferragut et al. 2000). Lower values of fracture stress were observed in set yogurts made from milk treated at 600 MPa for 15 min compared to heat-treated milk (Needs et al. 2000b). The use of a mixture containing only 10 % of pressure-treated milk resulted in a creamy product that maintained the taste of conventional yogurt (Trujillo et al. 2002). Reps et al. (1999, 2001) showed that prolongation of the shelf life of yogurt by HPT can be obtained by complete inactivation of lactic acid bacteria.

HPT (550 MPa) of yogurt maintained desirable sensory characteristics longer than controls during storage for 4 weeks at refrigerated (4 °C) or room (20 °C) temperature. The pressure treatment prevented the postacidification of the product. The number of bacteria in the HP-treated yogurt stored at 4 °C was maintained at less than the therapeutic minimum level of 10^6 CFU/ml (Jankowska et al. 2005). The pressure treatment (550 MPa, 4 °C, 10 min) could be used to produce shelf-stable thicker and smoother fruit yogurt. No microbial spoilage took place in HP-processed sample even after 60 days of storage at 4.4 and 25 °C. Moreover, the count of lactic acid bacteria decreased to <10 CFU/ml (Walker et al. 2006). Stirred yogurt made from reconstituted HP-treated (100–400 MPa, 25–90 °C, 10 min) skim milk prior to inoculation with yogurt culture showed that fermentation time was not affected by treatment. HPT of skim milk at lower temperature (25 °C) before or after heat treatment gave yogurts of similar viscosities to that of heat-treated milk, whereas lower viscosities were obtained when yogurts were made from HP-treated milk at elevated temperatures due to changes in interactions and structures of protein in the milk samples (Udabage et al. 2010).

A combination of transglutaminase and HPT of milk (when applied individually or in combination) proved to be an alternative treatment to produce yogurt with improved textural and sensorial characteristics. The samples made from HPT in combination with transglutaminase-treated milk exhibited higher firmness and

lower whey separation, while the sample made from HP-treated milk with or without subsequent transglutaminase treatment exhibited a creamier perception (Tsevdou et al. 2012).

3.4 Reconstituted Milk

HPT (up to 500 MPa) reduced the turbidity of reconstituted skim milk for all combinations of pH (5.5–7.5) and temperature (5–40 °C) due to micelle dissociation (Orlien et al. 2010). HP-treated reconstituted skim milk (200–600 MPa, 5–30 min) on acidification resulted in the formation of week gel due to formation of restructured colloidal particles which were not stable to acidification because of the inability of redistributed κ-casein to stabilize these particles (Anema 2010).

HPT (200 MPa, 40 °C) applied to the milk protein concentrate before spray drying improved solubility (85 %) of the dried powder, which did not change even after 6 weeks storage at ambient temperature. The improved solubility was attributed to the altered surface composition arising from an increased concentration of nonmicellar casein in the milk due to HPT (Udabage et al. 2012).

3.5 Ice Cream

HP (300 MPa, 15 min) enhanced the foaming properties of whey protein concentrate, which was added to low-fat ice cream to improve body and texture. Due to the impact of HP on the functional properties of whey proteins, the ice cream mix containing the whey protein exhibited an increased overrun and foam stability and hardness than ice cream produced with untreated whey protein (Fig. 3.7, Lim et al. 2008a, b).

3.6 Other Dairy Products

Waite et al. (2009) indicated that HPP (600 MPa, 3 min) of ranch dressing (combination of buttermilk, salt, garlic, onion, herbs, and spices, pH 4.4) resulted in decrease in *Pediococcus acidilactici* (the most pressure-resistant spoilage organism) by ≥ 6.4 log CFU/g. On the other hand, treatment at 600 MPa for 5 min prevented microbial spoilage throughout the storage period for 26 weeks at 4 °C and 26 °C without adverse changes in pH and emulsion stability (Fig. 3.8).

Sahu (2010) optimized the levels of HP (200–400 MPa), pressurization time (0–100 min), and coagulation temperature (30–70 °C) for the preparation of *chhana* (Indian cottage cheese). HPT at 280 MPa, pressurization time of 47 min, and coagulation temperature of 52 °C were found to be optimal for minimum lag, inflexion,

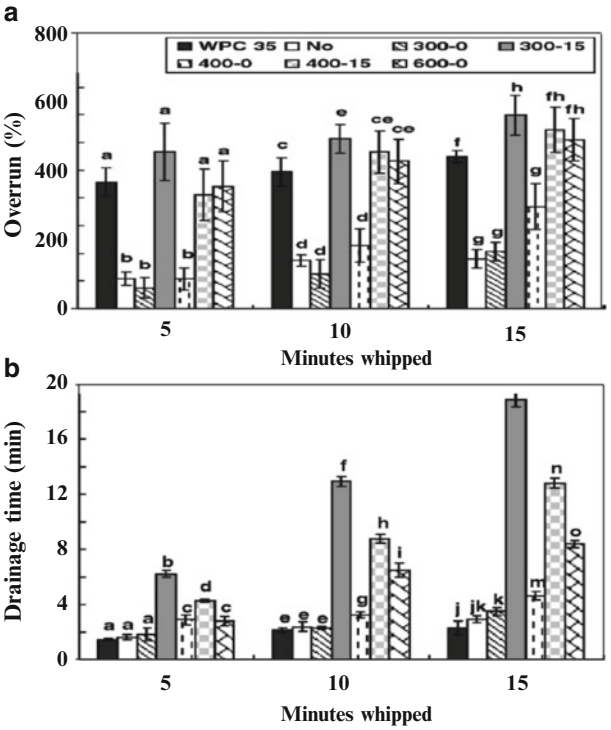

Fig. 3.7 Effect of whipping time on (**a**) overrun and (**b**) drainage time (foam stability) (WPC35 commercial whey protein concentrate, No = Control, 300-0 = 300 MPa for 0 min, 300-15 = 300 MPa for 15 min, 400-0 = 400 MPa for 0 min, 400-15 = 400 MPa for 15 min, 600-0: 600 MPa for 0 min) (From Lim, S.Y., Swanson, B.G., Clark, S. 2008a. *J. Dairy Sci.* 91: 1299–1307. With permission)

and coagulation time of 0.0028, 5.19, and 3.87 min, respectively. Oh et al. (2009) showed that gelatinization of waxy rice starch in skim milk was retarded due to the presence of soluble milk minerals and lactose. Milk proteins (casein and whey protein) did not affect the degree of pressure-induced gelatinization. Al-Nabulsi et al. (2012) indicated that coagulant-induced milk gel produced by HPT (483 MPa) had higher storage modulus (G*) and firmer gel at cutting compared to heated milk. Increasing the pressure to 676 MPa caused a reduction in *G**, less firm gels, and an increase in milk turbidity.

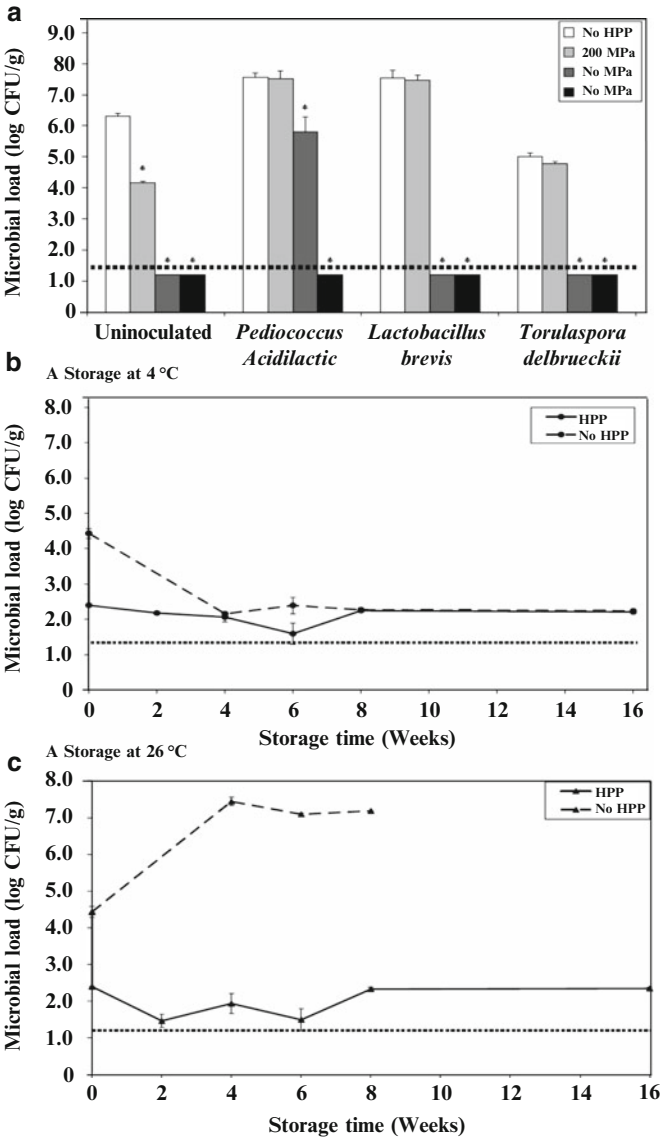

Fig. 3.8 (**a**) Efficacy of HPP (200–600 MPa, holding time 3 min) against natural microbiota of ranch dressing (uninoculated) and the inoculated spoilage bacteria, *Pediococcus acidilactici* OSY-JW1, *Lactobacillus brevis* OSY-JW1, and *Torulaspora delbrueckii* OSY-JW1. *Dashed line* indicates recovery method's detection limit. (**b**, **c**) Microorganisms recovered on MRS agar from ranch dressing (pH 4.4) with or without HPT (600 MPa, 5 min) with extended storage at 4 °C or 26 °C (From Waite, J.G., Jones, J.M., Turek, E.J., Dunne, C.P., Wright, A.O., Yang, T.C.S., Beckwitt, R., Yousef, A.E. 2009. *J. Food Sci.* 74: M83–M93. With permission)