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Use of Gases in Dairy Manufacturing: A Review

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Abstract

Use of gases (air, carbon dioxide and nitrogen) has been practiced in the manufacture of dairy products (i.e. ice cream, whipped cream and butter) to improve their texture, mouthfeel and shelf-life extension. Many attempts have also been made to incorporate other gases such as hydrogen, nitrous oxide, argon, xenon, and helium into the dairy systems for various product functionalities such as whipping, foaming, texture, aroma enhancement and therapeutic properties. The gases can be dissolved in aqueous and fat phases or remain in the form of bubbles stabilised by protein or fat particles. The gas addition or infusion processes are typically simple and have been used commercially. This review focuses on the use of various gases in relation to their individually physical properties along with their specific roles in manufacturing and controlling quality of dairy products. It also recaps on how gases are included in the dairy systems. The information is important in understanding of addition of specific gas(es) into food systems, particularly dairy products, that potentially provide intervention opportunities for modifying and/or creating innovative food structures and functionalities.

Keywords

Gaseous Solubility, Infusion, Stabilised bubbles, Therapeutic dairy products

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1. Introduction

The utilisation of gases plays an important role in determining shelf life extension, convenient packaging and quality control in food systems. This importance of gases has been extensively reported (Sofjan and Hartel, 2004; Aldred et al., 2008; Walsh et al. 2014) but understanding of the association between incorporated gas(es) and physico-chemical characteristics in dairy products has not been paid close attention. In fact, incorporation of air, a mixture of gases, in cream and ice cream mix is the basis for the manufacture of whipped cream and ice cream, respectively. The use of gases in dairy systems also extends to butter, cheese and milk drinks. A number of reviews have noted that incorporation of carbon dioxide can be considered as a cost effective method in improving sensory quality and rheological behaviour of dairy products (Campbell and Mougeot,1999; Hotchkiss et al., 2006; Singh et al., 2012). However, the information remains limited on the use of various gases to alter the properties of dairy products as well as methods to introduce gases into dairy systems. In addition, the solubility behaviour and related physical properties of individual gas in dairy products have not been well documented. This review summarises the past and current knowledge on usage of gases in the context of dairy manufacturing whereby further drivers for using gases as an additional tool to manipulate functional properties of food and/or to control manufacturing process can be justified.

Food products with gas bubbles have been extensively reported by the scientists whether it is a loaf bread or a bottle of champagne, but the presence of gas bubbles in dairy products is not quite always obvious. One wonders about the reaction of consumers of ice-cream if they are made aware that it contains almost fifty percent air. The use of gases had been paid little attention

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particularly on the dairy manufacturing but some researchers have worked to find out how some of the gases can prolong the shelf life of a food. Broader use of gases in dairy manufacturing has been given focus by few researchers in the past. The chemistry of milk, interaction of components within milk, processing technologies, digestibility and storage life of dairy products are extensively studied but the characteristics of the products due to the incorporation of gases in dairy systems are still limited. However, we can easily find a large number of literatures on the use of gases to extend the storage period and convenient packaging techniques. There are some reports and investigations on the use of gases as an integral part of dairy products such as whipped cream, butter, cheese and milk drinks. Campbell and Mougeot (1999); Hotchkiss et al. (2006); Singh et al. (2012) have also summarized that use of gas bubbles is a cost effective method to improve product's sensory quality and enhance rheological behaviour. However, information on the use of various gases for alteration of the properties of dairy product systems is not well documented. Thus, this paper aims to review and update the past and recent studies undertaken on usage of gases while manufacturing of dairy products.

2. Gases used in dairy products

The presence of gases as dissolved component of milk has been reported since early 1900s (Van Slyke and Baker, 1919). In addition to natural occurrence, various gases that are used individually or in a combination have been also reported in the manufacturing of dairy products. For example, air, a mixture of gases, is extensively used in frozen dessert/ice-cream manufacturing and churning of butter (Abd El-Rahman et al., 1997; Cox et al., 2007; van Aken, 2001). Carbon dioxide (CO_2) in the form of gas, supercritical fluid or solid (dry ice) is used in the manufacturing of cheese, lactose, powder and probiotic milk products. Nitrogen (N_2) gas has also been investigated in powder manufacturing. Use of nitrous oxide (N_2O) and hydrogen (H_2) in whipped cream, dairy foam and yogurt has also been reported. In addition, noble gases like helium (He), argon (Ar), neon (Ne) and xenon (Xe) have also been described in the dairy manufacturing. The use of various gases and their purposes in dairy product processing are presented in Table 1.

2.1 Air

Air is a mixture of gases consisting nitrogen (78.09%), oxygen (O_2) (20.95%), argon (0.93%), carbon dioxide (0.03%) and traces of neon, helium, methane, krypton, hydrogen, xenon and ozone (Subramani, 2012). This mixture of gases has been used as single entity to aerate dairy products such as yoghurt, butter and ice-cream. Aeration plays an important role in physical (textural) behaviour of these dairy products. Foley et al. (1990) described the relationship between firmness of butter and air content. They described when the air content of whipped butter is more than 50% of total volume this can improve spreadability of the product. Presence of air, its size distribution and amount weakens the butter structure due to the replacement effect and decreasing possibilities of interlocking fat crystals in a network. Butter when aerated produces whiter product due to dispersion of tiny air bubbles and may contain one third less amount of calorie per unit volume as well (Aldred et al., 2008).

Ice cream is a foam. It contains air as a major ingredient and bubbles of air play a major role in its sensory attributes, physical properties and stability (Pei and Schmidt, 2010). The size of the crystals in ice cream is affected by the amount of air integrated during its production. Higher the amount of air smaller the ice crystal size is (Sofjan and Hartel, 2004). Loss of gas bubbles can occur during subsequent freezing as the growing ice crystals may puncture air bubbles and this is more pronounced in case of large air bubbles (Cox et al., 2007). Thus a minimum of 70% overrun is required to disperse serum phase (Chang and Hartel, 2002). If the overrun is decreased there is increase in hardness (Pelan et al., 1997; Sofjan and Hartel, 2004). Further, meltability and stability of ice cream is related to the amount of air included. Stable air cells show slow melting character of ice cream (Pelan et al., 1997; Prindiville et al., 1999).

Cheese with sensory and marketing advantages having soft texture and light weight was obtained when small gas bubbles were dispersed in the coagulated milk (Vial et al., 2006). Yogurt with air bubbled in during manufacture had higher concentrations of acetaldehyde and diacetyl than the normal yogurt (Martin et al., 2011). This might be due to change in metabolic pathways of starter culture. There was no significant change in whey exudation in aerated and non-aerated yogurts (Martin et al., 2010). This can be partly explained by presence of branched and extensive connectivity of the protein aggregates of gel network in yogurt.

Use of air in dairy products manufacturing is limited in dairy powders and fluid milks. This is because the amount of active O_2 can cause off flavours in the dairy products. The adverse effect is prominent in dairy powders with decreased solubility and discolouration due to oxidation of fat. Several authors (Driscoll et al., 1985; Holm et al., 1927) reported milk powder stored in packaged conditions at 294.15 K under air was less desirable due to off flavour. Milk has high water activity, rich in nutrients and a very favourable pH for the microbial growth leading to spoilage. The rapid spoilage by microorganisms adversely affects sensory quality and shelf life of the products. Aerobic Gram negative psychrotropic bacteria both vegetative and spores namely *Alcaligens spp, Pseudomonas spp, Achromobacter spp, Escherichia spp, Bacillus spp and* yeasts (*Candida, Yarrowina, Geotrichum)* and moulds (*Penicillium, Mucor*) can produce

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toxins and hydrolytic enzymes in milk leading to defects (Chen and Hotchkiss, 1991; Mannheim and Soffer, 1996). Gas production by bacteria and nitrate reduction by aerobic spore formers also interfere in the production of cheese (McSweeney and Sousa, 2000). While in case of probiotic dairy products level of O_2 within package should be kept as low as possible to discard loss of viable count of probiotic organisms such as *Bacillus bifidum* and *Lactobacillus acidophilus* and to maintain the functional property of the product *(da Cruz* et al., *2007)*. To overcome adverse effect of air, inert gases are more commonly used in dairy product manufacturing.

Stable and fluffy foam formation is important in coffee. Cappuccino with foam can be produced from a dry mix of coffee powder and beverage creamer. The creamer is in fact a matrix comprising of carbohydrate, protein, milk fat and gas. Gases used may be N_2, CO_2 or mixture of gases. Wyss et al. (2008) patented soluble foaming beverage powder to produce white and stable foam. The air was injected under pressure (0.5 MPa to about 5 MPa) into an aqueous dairy matrix and it was rapidly dried in a spray dryer, it resulted in entrapment of gases in the matrix. This dried matrix when being mixed with liquid releases entrapped gas and consequently creates stable foam. Further, Bisperink et al. (2004) described soluble gassified creamer base can also be used to produce stable foam in milk shakes.

Air is a common gas that has been used to fabricate aerated chocolate by forcing it under high pressure into the molten chocolate mass (Sundara and Serbescu, 2014). The resulting bubbles further contribute to mild, light and creamy sensation upon consuming of the aerated chocolate. The gas dispersed in molten chocolate forms foam in which embedded in the fat phase. Previous studies found that infusion of air into chocolate can also minimise cracking of outer shells in sugar coated chocolates when being stored at elevated temperature. Thus consumer appeal for the chocolate can be maintained (Haedelt et al., 2007; Haedelt et al., 2011). During phase conversion from solid polymorphic chocolate state to the liquid the expansion in volume of chocolate can be accommodated by compressing gas bubbles. Robert (2003) described mixing of air with untempered chocolate at 302-304 K with maximum bubble size of about 25 µm to enhance the stability of chocolate during high temperature storage in hotter climate. The stability of chocolate can be related to increased amount of stable β polymorphic form of cocoa butter by induced nucleation of air. Haedelt et al. (2005) stated that use of vacuum can enhance gas hold up of milk based chocolate due to formation of large number of bubble nuclei and release of higher volume of dissolved air. Such result is due to decreasing solubility of gases while increasing vacuum in the mix. Further they noticed that there was an increase in mean bubble size at lower pressure which might be due to the coalescence of newly formed bubbles at lower pressure.

2.2 Carbon dioxide

Carbon dioxide (CO_2) gas is quite soluble in water and even further soluble in nonpolar lipids (Ma and Barbano, 2003). Solubility of different gases in water and lipids is presented in Table 2 and the solubility of CO_2 reported under various conditions in dairy systems is summarised in Table 3. Jakobsen et al. (2009) demonstrated that there is a linear relationship between carbon dioxide solubility in cheese and partial pressure. Similarly, solubility of CO_2 in milk was reported to increase with increasing pressure and decrease with increasing temperature by Tomasula and Boswell (1999). The solubility of CO_2 in dairy products decreases with increased temperature but viscosity of product affects oppositely due to slow diffusivity in the product. Pressure has effect on the solubility of CO_2 in milk and its final pH. The equilibrium solubility of gas in milk is similar to that of water at 298.15-323.15 K. Due to hindrances from casein micelles solubility of CO_2 in milk is lesser than that in water at 298.15 K. The solubility of CO_2 in milk and water is indicative of changes in the solvation of casein micelles as pH drops or pressure increases (Tomasula and Boswell, 1999). Solubility of CO_2 in whey was also reported to be proportional to change in pressure. The pH of saturated whey protein solution decreases with pressure but increases with protein concentration due to buffering capacity of whey proteins (Bonnaillie and Tomasula, 2012; Yver et al., 2011).

Proteins in solid form can absorb CO_2 gas. The amino group of protein in protonated form can reversibly react to form weak carbamate. Thus during desorption of carbamate more than 90% of CO_2 is released. But, in case of free amino acid and amines only a few percentage of CO_2 is desorbed. The interaction between CO_2 and amino acids is more like chemisorption rather than physical adsorption. The CO_2 binding sites in protein in the gas-solid phase system are ε-amino, α-amino and guanidinium groups. Changes in milk proteins caused by moderate gas injection are reversible in nature while injection of higher quantities of gas at higher temperature and pressure may cause irreversible change of milk proteins (Bonnaillie and Tomasula, 2012; Ma and Barbano, 2003; Tomasula and Boswell, 1999). At high concentrations and temperature supercritical CO_2 can denature and precipitate milk proteins. Combined effects of concentration, temperature and pressure can be used to denaturate and precipitate caseins at 7 MPa at around 311.15-313.15K while whey proteins precipitates at 31 MPa at around 343.15-353.15 K (Bonnaillie and Tomasula, 2012; Tomasula and Boswell, 1999; Yver et al., 2011). Carbon dioxide can affect milk proteins at lower pressures due to its acidifying and solvating properties,

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as it can absorb onto casein micelles after dissolution and generates carbonic acid that binds with calcium ions that internally stabilize micelles.

Fluid milk. There are various reports on natural occurrence of CO_2 in the fresh milk. The literatures report that CO_2 exists as dissolved gas, carbonic acid and bicarbonate salts depending on the pH of the aqueous phase. At pH 6.3-6.5 CO_2 exists as approximately 88 parts as dissolved gas, 10 parts as bicarbonate and 2 parts as carbonic acid (Daniels et al., 1985; Moore et al., 1961; Noll and Supplee, 1941; Smith, 1964; Van Slyke and Baker, 1919). In addition to natural occurrence CO_2 may also be incorporated in raw milk to produce carbonated milk drinks as it is colourless and odourless. This gas is more soluble in water than O_2 and can form weak carbonic acid in the medium. Such carbonated product with pH 6.2 has been found having longer storage life at refrigerated storage at 278.15 K (Amigo et al., 1995; Chang and Zhang, 1992; Rajagopal et al., 2005; Ruas-Madiedo et al., 1998). In this type of product CO_2 serves as an antimicrobial agent (Hotchkiss et al., 2006) slowing down the growth of psychrotropic microflora (Loss and Hotchkiss, 2003) and also enhances the thermal inactivation process (Hotchkiss and Loss, 2002). Psychrotropic microflora accelerates proteolysis and lipolysis which can be slowed down by adding 1500 ppm CO_2 in the raw milk (Ma et al., 2003; Lo et al., 2016). Increasing the amount of CO_2 and decreasing temperature below 278.15 K have shown to inhibit growth rate of microorganisms. The symbiotic effect of both parameters have pronounced effect due to increased solubility of the gas at lower temperature and temperature quotient (Martin et al., 2003). After injection of CO_2, O_2 level of milk is decreased due to higher solubility of CO_2 than O_2 which results in lesser oxidation of milk fat (Ma et al., 2003). Further, increased viscosity was observed when milk was carbonated with 34.32 kPa of CO_2 (Chang and Zhang, 1992).

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Yau et al. (1989) reported that carbonation had significant effect on the sensory quality of sweetened flavoured milk beverage. Increasing level from 0.6 to 1.42 volumes of CO_2 suppressed cooked milk aroma and flavour in the sweetened milk drink simultaneously boosting sourness and astringency (Lederer et al., 1991). Shah and Prajapati (2014) reported that carbonated fermented milk was acceptable after 28 days which was stored at 278.15 K. In case of symbiotic drink addition of 2 volume of CO_2 to the drink did not significantly affect the stability of probiotic bacteria (Jardin et al., 2012; Walsh et al., 2014). Along with longer shelf life and sensory acceptance of carbonated milk beverages, no significant change was noted in fat soluble vitamins especially β carotene, α tocopherol and retinol content (Ruas-Madiedo et al., 1998; Sierra et al., 1996).

Milk fat. Besides milk beverage, CO_2 is effectively used to manipulate functionality of individual milk components. For example milk fat which is a mixture of triglycerides of different molecular weights and saturations (Büyükbeşe et al., 2013) can be divided into discrete fractions using super critical CO_2. Arul et al. (1987); Bhaskar et al. (1993) separated milk fat into five to eight fractions using super critical fluid at 10-35 MPa of pressure range. This method helped in producing butter with specific carbon lengths and fractionation contributed to the production of lower cholesterol butter. Distinctive and homogeneous fat fractions with higher amounts of unsaturated long chain fatty acids is reported from super critical fluid CO_2 extraction at 10-36 MPa (Bhaskar et al., 1998; Büyükbeşe et al., 2013). Conversely, Shisiiikura et al. (1986) studied cholesterol level in butter oil by supercritical CO_2 extraction. They concluded that the butter oil extracted at 30 MPa at 313.15 K cannot be practically used for preparation of low-cholesterol butter which might be due to higher polarity of cholesterol and similar molecular weight of cholesterol and triglycerides. But they suggested using silica gel column as adsorbent to lower cholesterol level in butter oil. Recently solubility of CO_2 is investigated in anhydrous milk fat (AMF) at University of Queensland, Australia. They observed that the higher the liquid fraction (olein) is the higher the CO_2 solubility with decreasing temperature. This might be due to the presence of higher polyunsaturated fatty acids at lower temperature in liquid fraction (Personal Communication).

Dairy cream. Ma and Barbano (2003) studied the effect of injecting CO_2 at 230 mL/min on the pH and freezing points of cream at 273.15 and 313.15 K. There was a decrease in pH of cream from 6.95 to 6.6 when temperature was increased from 273.15 to 313.15 K for same level of injected total CO_2 concentration as CO_2 is more soluble in non-polar lipids.

Butter. Butter churned from carbonated cream was reported to be sour due to acidification (Prucha et al., 1931). Sherwood and Martin (1926) reported no correlation between carbonation and butter and even there was no change in composition of the product. Carbon dioxide did not show any positive result on the reduction of parameters like saponification value which might be due to the acidity developed by CO_2. Very early report of Hunziker (1924) on effect of CO_2 on butter concluded that carbonation was not an effective approach to destroy bacteria present in cream and further rendering of such cream to butter is safe for human. Churning with help of air is harmful to butter fat and it takes more time to complete churning process due to presence of highly reactive O_2. Hence use of CO_2 is more advantageous to overcome the effects of O_2 (Senn, 1944).They further claimed that the duration of whole butter making process can be completed within 2 to 9 min after addition of CO_2 in cream under pressure.

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Milk powders. On the other hand, gases can be successfully used to increase the surface area of atomized milk particles. Gas at high pressure can act as a plasticizer, lower the glass transition temperature of lactose and ultimately crystallize it at lower temperature. Although gases are ineffective medium for the transfer of heat but the solubility of atomizing gases (Islam and Langrish, 2010) can lead to superior drying of milk powder. Spray dried milk powder crystallinity can be changed by using different gases for atomizing and drying medium. Particularly CO_2 infused during atomizing and drying of milk results in larger particles and these larger particles behave more sorptive during desorption resulting in spherical and smooth surface amorphous powder. Klandar et al. (2009); Kosasih et al. (2016a, 2016b); Marella et al. (2015) have studied effect of CO_2 on the functional properties of milk powder. They found that carbonation modified casein micelle structure, leading to improved functional properties. For example, reconstituted milk powders which were carbonated during powder manufacturing have been reported to have better renettability due to change in casein micelles structure and modification of surface activity (Klandar et al, 2009). Carbonation is also used to improve the properties of whole milk powder (Kosasih et al, 2016b). It appears that powder obtained after drying the whole milk concentrate which was previously mixed with dry ice to give 2000 ppm CO_2 can improve the shelf life due to lower fat content on surface of powder particles. The carbonation was found to significantly alter the solubility, dispersibility and porosity of whole milk powder (Kosasih et al., 2016b). Dissolution of CO_2 in milk to increase the ionic calcium in serum phase followed by removal of ionic calcium by ultrafiltration was reported to improve the solubility of high protein milk powder during storage (Marella et al., 2015).

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Yogurt. Injection of CO_2 to milk during yogurt manufacturing has been reported in various publications. Addition of CO_2 extended shelf life from 30 days to 120 days of sweetened drinkable yoghurt (Choi and Kosikowski, 1985). Wright et al. (2003) calculated the threshold level of carbonation detection as 263 ppm in Swiss style yogurt.

Investigation on the effect of carbonation on the growth rate of starter culture can also be found. Lactic acid bacteria count in 0.5 kg/cm^2 carbonated yogurt was reported to be unaffected even after 80 days at 277.55 K whereas Karagül-Yüceer et al. (2001) concluded there was no such significant effect on starter culture even in a 90 days interval and such carbonated yogurts were more preferred by consumers (Choi and Kosikowski, 1985). Likewise, Karagül-Yüceer et al. (1999) reported that addition of CO_2 did not significantly influence the consumer acceptance of the yogurt. Similar findings of sensory acceptance of carbonated yogurt were reported (Gueimonde et al., 2003; Vinderola et al., 2000). They further concluded carbonation had less influence on the production of lactic acid by culture. Vinderola et al. (2000) further reported that CO_2 did not affect viability of *Streptococcus thermophilus* and *Lactobacillus acidophilus* strains in fermented milk product.

Cheese. Several works focusing on the manufacture of cheese by carbonated milk has been done previously (Calvo et al., 1993; Martley and Crow, 1996; Montilla et al., 1995; Ruas-Madiedo et al., 2002; Ruas-Madiedo et al., 1998). Cheese produced from carbonated milk require 75% less amount of rennet because of decreased pH of the milk and enhanced activity of rennet at acidic pH (Montilla et al., 1995) Less time for coagulation of milk protein was reported due to the increased level of ionic calcium in the serum phase caused by partial dissolution of colloidal calcium. But Calvo et al. (1993) had reported earlier that there is more time required due to acidification and the higher final pH in CO_2 treated samples which might be due to reduced starter metabolic activity. Others (Ruas-Madiedo et al., 1998) reported that the incorporated CO_2 had no effect on the lactic acid producing cultures. Moir et al. (1993) reported that a concentration of 10 mM CO_2 does not affect the pH of cheese. On the contrary carbonation was found to have influencing role on whey pH (Nelson et al., 2004). Whey pH was found to be lower than pH obtained from non-carbonated milk. Furthermore, the loss of fat and calcium was even more in the whey. There was no change in sensorial perception (Ruas-Madiedo et al., 2002; Ruas-Madiedo et al., 1998) and quality (Marshall, 1987) of the final cheese

Ice-cream. There are few reports that describe the effect of CO_2 on textural character and composition of ice-cream. Carbonation did not improve the textural quality (Sherwood and Martin, 1926). Study on reduction of microbial load in the ice cream mix was conducted by Valley and Rettger (1927) and they reported an apparent decrease of viable microorganisms by 39.6% in the carbonated ice cream during first twenty four hours of refrigeration.

Milk chocolates. Carbon dioxide is also found to be incorporated in milk chocolates to improve sensory character in particular (Sundara and Serbescu, 2014). Due to higher solubility of CO_2 in fat more gas is held up in chocolate mixes. This phenomenon leads to formation of large voids in the final chocolate which ultimately improved melting in the mouth and smooth texture of chocolates (Haedelt et al., 2007).

Dairy foam. Coffee beverage consists dense foam of small gas bubbles. This foam formation and its stability predict quality of cappuccino. Villagran et al. (2000) patented higher density foamable instant coffee and they reported that instant coffee foam with 0.4 g/cc density can be prepared by using 0.1-5% carbonate and bicarbonate salts. Cappuccino type foam can be

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generated by mixing water soluble alkali carbonate at an amount of 0.15-205 g per servings and the potassium salt is more preferred than sodium one due to adverse effect in flavour (Agbo et al., 1998). Use of such salts to generate CO_2 have been reported to produce soapy taste (Ledermann, 1995) in the cappuccino. Whereas Hedrick (1984) observed lesser foaming of dairy creamer in coffee when CO_2 bubbles were introduced in the mixture.

Modified atmosphere packaging (MAP) has been used to extend shelf life of dairy products. To attain desired atmosphere in the package inert gases are injected. Carbon dioxide along with N_2 gas is more commonly used. Mannheim and Soffer (1996); Singh et al. (2012); Jakobsen and Risbo (2009) have reviewed about the modified atmosphere packaging for dairy systems. The principle of this method is the replacement of air in the package with a fixed gas mixture such as CO_2, N_2 and O_2. Carbon dioxide with high barrier packaging material can inhibit psychrotrophic Gram negative bacteria and can also extend the lag phase of spoilage microorganisms thus can be regarded as main contributing factor in MAP. For example, cottage cheese inoculated with psychrotrophic bacteria packaged in MAP with 35-45% (v/v) CO_2 in headspace remains constantly fresh in appearance and there was no further growth of inoculated bacteria in the cheese (Chen and Hotchkiss, 1991). Furthermore, shelf life of milk products can also be increased due to low pH of system and reduction of O_2 level inside package which prevents further fat oxidation (Chan et al., 1993; Sherwood and Martin, 1926) and eliminates sensory quality degradation. Driscoll et al. (1985) have also reported better sensory qualities with MAP of milk powder than packaging under air. Packaged dairy products may not have sufficient headspace to accumulate gases (Jakobsen and Risbo, 2009) and thus to maximize effect of gases direct flushing before packaging can be done. Mannheim and Soffer (1996) had reported that

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flushing of CO_2 in package of cottage cheese can extend shelf life at refrigerated condition to about 150%. Further good gas barrier properties of packaging material must be selected to retain gas in the headspace of the product (Chan et al., 1993; Singh et al., 2012). Other benefits of direct CO_2 addition to dairy product package include high efficacy at low temperature due to increased solubility of gas; maintenance of freshness, nutrients and organoleptic characteristics of dairy products; easy removal after package opening and cost effective to use (Hotchkiss et al., 2006; Loss and Hotchkiss, 2003).

2.3 Nitrogen

Butter and fat spreads. Nitrogen gas has been used in butter and fat spreads. When introduced into the margarines before crystallization N_2 can whip the product to obtain softer product. Such product can easily spread at lower temperatures and can attain more attention from calorie conscious consumers (Christie et al., 1960; Massiello, 1978). Sinnamon et al. (1957) and Aceto et al. (1962) had investigated milk powder preparation process by sparging N_2 bubbles to produce better functional powder. They entrained N_2 gas in concentrated milk. Because of low solubility of N_2 in milk small and uniform bubbles were generated and this foam was dried at vacuum condition. This condition preserved foam integrity during drying and hence they obtained fresh flavoured powder which was more soluble in cold water along with improved functional character.

Milk powder. Hanrahan et al. (1962) reported that injecting N_2 gas into the milk concentrate before atomising increased production of milk powder with improved dispersibility than conventional method as the dispersed gas can create bubbles due to turbulence in the device. Change in pressure and temperature further released dissolved gas and produced fine grained foam with trapped gas bubbles. These bubbles in foam can expand during drying and increase particle size of powder resulting in better functional property. Lighter N_2 gas can effectively atomize liquid affecting their particle structure and size. Nitrogen atomized powder was found to alter sorption behaviour which might be due to higher specific heat capacity of N_2 and this change in sorption behaviour affected surface morphology of the crystals (Islam and Langrish, 2010).

Dairy creamer. The dairy creamer used in instant coffee should have good foaming capacity and this capacity was found to be better when dairy creamer was gassified with N_2 at 0.6 kg per 1000 kg of mixture (Hedrick, 1984). Wyss et al. (2008) entrapped N_2 due to its inertness in a foam matrix. Bisperink et al. (2004); Panesar et al. (1999); Zeller et al. (2010) devised powdered foamer containing entrapped N_2 gas which can provide 5 mL of gas from 1 g powder.

Yogurt. The acid production by starter culture in yogurt was found 30 min faster at 310.15 K when the level of dissolved O_2 was reduced to zero by using N_2 gas (Horiuchi et al., 2009). Rheology of N_2 gas infused yogurt was studied and they reported lower viscosity of products than oxidizing environment. Similarly, lower values of whey separation in yogurt under the influence of N_2 gas was also reported which might be due to binding of water by aggregation of exopolysaccharides (Martin et al., 2010). Effect on biosynthesis of aroma compounds in yogurt by lactic acid bacteria at different oxidoreduction potential created by gas infusion in milk was studied by Martin et al. (2011). They reported that dimethyl sulphide was found to be in lower amount in yogurts made with bubbled N_2 gas but diacetyl and pentane-2,3-dione was found in similar quantities as in standard yogurt. Change in Eh potential of the medium due to addition of gas influences aroma synthesis by lactic acid bacteria in yogurt by altering the metabolic

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pathways of lactic culture (*Lactobacillus bulgaricus* and *Streptococcus thermophilus*) (Cachon et al., 2002).

Chocolate mix. Sensory perception of chocolate is related to the bubble size and gas retention in the chocolate mix (Haedelt et al., 2005; Sundara and Serbescu, 2014). Nitrogen when incorporated in chocolate mix produced harder chocolate than the CO_2 infused one. This might be due to less gas hold up in the mix and further due to lower solubility of N_2 in the chocolate mix, chocolates were found to contain smaller diameter bubbles which affected melting characteristics of chocolate in mouth (Haedelt et al., 2007; Haedelt et al., 2011). Hachiya et al. (1994) patented a process for manufacturing chocolate with gas bubbles. According to this patent uniformly dispersed N_2 bubbles of 0.3 mm or less in chocolate will provide smooth taste. Recently, Sundara and Serbescu (2014) stated that N_2 after injecting in carrier solvents like glycerol, propylene glycol and water can be mixed with untempered chocolate to improve textural property of the chocolate. Addition of solvent increases viscosity of chocolate subsequently stabilising bubble size and robustness during further processing. This process will ultimately lead to better sensory perception. When solvent is used as carrier of gas bubbles, solvent can move to chocolate. This movement enhances heat resistance along with sensory improvement.

Cheese. Cheese can be aerated for many more reasons like cost efficiency, health benefits and reduced density per volume of the cheese. Thorson and Smith (2011) stated aeration by use of N_2 in mozzarella, cheddar and imitation cheese. Aeration of liquid mass creates gas bubbles or void spaces that are dispersed in the final cheese. The mean size of such voids was reported to be 0.1 to 1500 μm which was sufficient to give density of solid cheese in the range of 0.55-1.1 g/cc.

As discussed earlier in section 2.2, MAP in which mixture of gases are used is a useful technique for extending the shelf life and sensory quality of dairy products (Giroux et al., 2008; Martin et al., 2011). Unlike CO_2 which is highly soluble in water and fat and also have bacteriostatic properties, N_2, virtually insoluble in water and fat is used in MAP as filler gas. Use of CO_2 alone causes collapse of package due to its water and fat solubility. Thus mixture of gases is helpful in extending the shelf life. The major mechanism of N_2 against spoilage aerobic bacteria is only replacement of O_2 in the headspace (Mannheim and Soffer, 1996). Further, direct flushing of N_2 is found to improve sensory qualities of dairy products. When N_2 was flushed in anhydrous milk fat storage tank the rate of peroxide development was also reported to be reduced (Keogh and Higgins, 1986) and sweetness of irradiated orange sherbet ice-cream was found to be maintained (Hashisaka et al., 1990) when it was packaged in N_2.

2.4 Hydrogen

Authors have also reported about gases other than CO_2 and N_2 that are used in dairy manufacturing. A mixture of N_2 and H_2 bubbles in yogurt can lower whey separation and increase gel aggregation (Martin et al., 2010). They reported that in reducing condition lactic starters can produce same amount of exopolysaccharides but in more reducing environment viscosity of yogurt was lowered as viscosity depends on the solids present in the system. Similarly, such mixture of gases can be effectively used to control the aroma components in non-fat yoghurt (Martin et al., 2011) as addition of gas influences aroma synthesis in yogurt by altering the metabolic pathways of lactic starter culture (Cachon et al., 2002). To prevent the oxidative deterioration in milk products during storage, it is common to replace the normal atmosphere with mixture of inert gases. Giroux et al. (2008) described that dairy beverage

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saturated with mixture of N_2 and H_2 before heat treatment have lesser change in colour during storage period than the beverage saturated with air.

2.5 Nitrous oxide (N_2O)

Nitrous oxide is an inert gas and had higher solubility in fat (Getz, 1948; Yokozeki and Shiflett, 2011) compared to other gases. This property can be utilized in chocolate making process to improve sensory property (Sundara and Serbescu, 2014). When infused in chocolate this gas produced more aerated, softer and less creamy milk chocolate with larger voids in the chocolate bar along with good sensory perception by consumer (Haedelt et al., 2007). It is also used to gassify the mixture of coffee foamer before spray drying and such dried particles were used to produce stable foaming creamer used in cappuccino (Hedrick, 1984).

Nitrous oxide has great solubility in fat. Thus, it can aid whipping process due to better interaction with fat. Hence obtained overrun of whipped cream was better than the normally aerated cream. Nilsen and Zamzow (1967); Diller and Brooklyn (1939); Nakai et al. (2010) reported production of whipped cream by dissolving cream in pressurized N_2O gas in a closed vessel. Authors have reported that sweet whipped cream with better texture and mouthfeel can be produced by using N_2O but when used singly, gas tend to produce acidic and unpleasant taste in the cream. So, a mixture of gases N_2 (30-40%), N_2O (40-50%) and CO_2 (15-25%) was utilized to produce better whipped cream free from unpleasant taste at lower cost by Diller and Brooklyn (1939). The N_2O is readily soluble in butter fat but is expensive to use and even it is analgesic to some consumers (Finley, 2014). In addition to advantages of N_2O, some disadvantages are of taken as a great concern by manufacturers. This includes asphyxiation caused by use of N_2O.

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This gas is a strong greenhouse emission having 20 times more global warming potential than CO_2. Use of this gas should be properly labelled to aware consumer (Finley, 2014).

2.6 Argon

Argon gas has no narcotic effect and is listed as generally recognised as safe (GRAS) by FDA. Hence use of Ar is advantageous in producing foamy and creamy beverage instead of other noble gases. Finley (2014) reported the use of argon gas to manufacture foamy beverage and this gas can overcome the previously mentioned adverse concerns of N_2O. Added Ar gas can solubilise in lipid and water of the beverage. The quantity of Ar gas incorporated is functions of temperature and pressure. Increasing pressure and decreasing temperature can increase mixture capacity to hold argon. Effective mixing of Ar was reported at 274.15- 278.65 K and 400-600 kPa. The portion dissolved in lipid is responsible for foaming and creamy character development in the product. Prior to consumption when pressure is released dissolved smaller Ar bubbles will expand producing foamy and creamy head lasting about 30 min. Thus addition of argon enhances appearance and mouth feel of non-carbonated dairy beverages. Aftel et al. (1996) suggested that substitution of air with Ar in drop nozzle could result in larger droplet size of atomised particles. This is due to higher density of argon and can be very much useful to atomise concentrated milk during spray drying. The patent by Clark and Clark (2012) provides information of using the Ar along with N_2 and CO_2 to suppress the growth of bacteria and spores in dairy nutrient beverages. They stated that such gases can displace the O_2 and buffer the pH which can control the growth of aerobes. Furthermore, use of composite gas mixture can enhance sensory properties such as mouth feel and body of beverage and additional aid in the stabilization of casein and lactalbumin (Clark and Clark, 2012). Gases can be injected in the liquid at a

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pressure at 3-4 MPa and temperature of 273.15-276.15 K for 3-5 min. Because of its low solubility Ar can be recovered by raising the temperature to 282 K in a vacuum centrifuge. As Ar does not react to form other compounds in a system, it is effective on displacing O_2 and can create anaerobic environment. Presence of N_2 and Ar along with CO_2 in mixture of gases in the beverage can reduce the required amount of CO_2 to produce same effect by CO_2 alone.

Argon when injected during manufacturing of chocolate was found to alter the sensory characteristics. Texture of chocolate was found to be harder when compared with chocolates infused with other gases (Haedelt et al., 2007). This might be due to less gas hold up in the untempered mix and formation of smaller bubbles due to low solubility in fat phase.

Argon gas is also believed to have functional property and this gas when orally administered can be used in treatment and prevention of disease related to brain injury (Huang et al., 2014; Nowrangi et al., 2014). The low cost and highly available Ar can be considered as a promising neuroprotectant (Ezzeddine, 2011) and from these traits research on addition of such noble gas in dairy products should be promoted in future.

2.7 Xenon:

Xenon has unique character that includes rapid diffusion across biological barriers, complete passage across cell membrane and has neuro protective and myocardial protective effects. By altering molecules involved in neuronal ischemic tolerance xenon can protect against ischemia (Baumert et al., 2005; Ezzeddine, 2011). As chemically neutral Xe can dissolve in fat and these novel traits are utilized by scientists to produce functional dairy products in the treatment of chronic diseases such as neuralgia, migraine, myocardial infarction, Alzhemeir’s disease etc. Xenon dissolved in dairy products can transit to surface of mucous membrane of the internal organs in the body followed by successive penetration into cell via cell membranes and actively manifesting curative properties in the human body (Nowrangi et al., 2014). Huang et al. (2014) have also suggested to encapsulate Xe gas with water soluble cyclodextrin in the production of nutraceutical beverage. Such product in a unit dosage in an amount of 0.1-200 mg can be administered to the patient (Huang et al., 2014). Therapeutic formulations based on dairy products should be encouraged to find better results of xenon.

2.8 Helium

A transparent and attractive package film that tightly fits the perishable food was used by many food packaging industries to avoid effects of O_2 particularly. French (1967) patented a novel method of packaging an object within plastic film utilizing He gas. They stated that packaging in a suitable wrap with entrapped helium gas result in attractive and tightly fitted film around product. As the diffusivity of helium from the package is reported to be higher than other gases and even solubility of He gas in water and fat phase is very low so this technique can be utilized in cling packaging of regular shaped perishable dairy products like cheese and butter. Peppermint ice-cream when flushed with helium at 10-15 L/min and packaged before 40 kGy irradiation is described to improve sensory quality particularly retention of flavour in the product (Hashisaka et al., 1990). They stated that gas helped to maintain overall acceptability and also helped to minimize the off flavour in ice-cream.

3. Methods of introducing gases in dairy systems

There are various ways of incorporating gas in the foods such as fermentation, whipping, shaking, mixing, pressurisation, steam generation, entrapment, injection, extrusion, puffing, vacuum expansion etc. The gas is retained in bubbles or in dissolved forms in aqueous and lipid

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phases. Above saturation (solubility) the gases are retained in bubble form. Bubble can be regarded as a gas liquid mixture of spherical shape with minimum possible interface. The energy associated with interfacial area gives rise to surface tension and this force is necessary to hold the bubble. The contribution of bubble to the dairy products depends on physical behaviour of bubble such as size of bubble, rising, bursting and solubility. There is pressure differential between the interfaces due to surface tension and this change in pressure in fact determines the size and the smaller bubbles have higher internal pressure (Campbell and Mougeot, 1999). Solubility of gas in outer liquid is also pressure dependent. Furthermore, solubility in dairy system is a complex phenomenon to understand as it is affected by various intrinsic and extrinsic factors of dairy products. Major factors contributing for solubility of gas can be listed as milk components and their quantities, pH, physical state and temperature (Chaix et al., 2014; Ma and Barbano, 2003).

In case of dairy products gases can be introduced and retained by whipping, pressurisation, sparging, fermentation, chemical addition and using gas hydrate (Campbell and Mougeot, 1999; Irving, 1970; Niranjan and Silva, 2008). Table 4 illustrates the methods of gas introduction in the various dairy systems. The method of gas inclusion should be carefully selected as the aerated products are thermodynamically unstable and included insoluble bubbles must be adequately stabilised using surface active agents as the stability affects further rheology and texture of the product (Campbell and Mougeot, 1999).

3.1 Mechanical whipping

This type of method includes agitation, shaking, entrapping, and mixing of gas in the product. Low viscous products entrap bubbles as in milk drinks, yogurt, milk chocolates and low fat

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cream where presence of protein and fat helps in incorporation of the bubbles. Large bubbles may rise and separate from the system during shaking thus size distribution is important point to consider. Due to whipping, viscosity of products increases as new surfaces are created due to incorporation of bubbles and subsequent adsorption of milk components on the surface. A three-stage mechanism was stated by van Aken (2001) to describe the process of air inclusion in the dairy system. The first one is formation of protein stabilized foam followed by coating with fat globules and finally dynamic process of bubble break-up and coalescence of fat to form aggregates. This process of breaking and coalescence adjusts bubble size to close packing of gas bubbles only if there is sufficient amount of gas and fat. Due to high packing densities of gas bubbles, there is no further gas inclusion. This process stabilizes air in the form of foam.

The structure of ice-cream shows partially crystalline fat globules and casein micelles as particles in solution of sugar, whey protein. The surface of the fat globule demonstrates the competitive adsorption of different types of milk proteins. As shown in Figure 1(a) ice-cream contains ice crystals, air and partially coalesced fat globules. Such fat agglomerates adsorb to the surface of air which are surrounded by protein and emulsifiers. They further create a network through lamellae between them. The presence of ice crystals and serum phase also help to stabilize air cells (Pelan et al., 1997; Sofjan and Hartel, 2004). Regarding whipping cream when air is initially incorporated, high surface tension at air-water interface results in the adsorption of fat globules followed by protein. Partial loss of fat globule membrane and spreading of fat at interface take place. Further coalescence, size reduction and collapse may occur. As shown in Figure 1(b) when whipping is complete air bubbles are completely surrounded by a continuous layer of coalesced fat globules (Brooker et al., 1986).

Thorson and Smith (2011) stated that any of a variety of commercially available mixers or mixing devices may be utilized as an aeration device. Further, they emphasized devices that can be operated at high shear rates as useful. Some examples they included are traditional mixing or blending equipment equipped with motor driven stirrers having various configurations, e.g., paddle, helix, etc., batch high shear mixers, inline high shear mixers, ultrahigh shear inline mixers, pin-type aeration device, ultrasonic mixers, pipeline static mixers, hydraulic shear devices, rotational shear mixers, rotor stator mixers, inline shear mixers, jet mixers, venturi-style/cavitation shear mixers, microfluidizer shear mixers and high-pressure homogenization shear mixers.

3.2 Sparging or Injection

This method includes pumping under pressure and sparging gas in the system. This technique is commonly practiced in butter, ice cream, coffee foam and cream. Commonly used spargers are presented in Figure 2. As soon as sparging occurs foam collapses and bubbles conglomerate into swelling. Depending on the temperature and properties of gas a part of the gas will dissolve in water or in lipid. Ma and Barbano (2003) provided an example of CO_2 injection system of stainless steel tube with an internal diameter of 0.08 cm. This tube can be inserted to the milk through a tee fitting immediately after feeding valve. Sixty seconds of contact time between milk and gas at 34.47 kPa were conducted, the levels of carbonation can be regulated by controlling the level of flowrate. With a pressure of several atmospheres of gas and stirring, the cream in the milk can also be converted into foam (Senn, 1944). Ahmed et al. (1989) reported a method of carbonating of liquid dairy product to a high level of CO_2 (1.5 volumes of gas dissolved). The product is first heated at 345.15 K for 30 min to partially denature proteins which was followed by cooling to below 284.15 K. They described by then placing a mix to be carbonated in a carbonator initially feeding gas through the dip tube at 89.6 kPa for 15 min and then elevating pressure to 158.5 kPa for about 20 min with continuous agitation. Bruins et al. (1985) described about injecting air stream in dairy emulsion in a conduit via the help of sparger of 0.5 to 100 microns size which shear off air bubbles formed on the surface of sparger. Haedelt et al. (2011) mentioned that chocolate can be aerated by injecting gas in a continuous fat phase at 0.3-0.8 MPa followed by expansion of bubbles at lower pressure (1-8 kPa) at 288-292 K.

3.3 *In situ* generation

This method can also be said as biological or chemical leavening. Fermentation and inclusion of its by-product (gases) in the product can be found in cheese, yogurt, butter and cappuccino. Lactic acid bacteria are commonly used as starter culture for fermentation. Particularly hetero fermentative LAB including *Leuconostoc spp.* and *Lactobacillus spp* can ferment glucose to lactic acid, ethanol and CO_2. Besides glucose, other LAB like *Leuconostoc mesenteroides subspp cremoris* and *Lactococcus lactis* subspp *lactis* biovar *diacetyllactis* are utilized to produce gas from citrate, gluconate and amino acids in the manufacture of buttermilk, sour cream and cultured butter (Beresford et al., 2001; Marshall, 1987; McSweeney and Sousa, 2000) and such gas production by LAB is important for the subsequent flavour development in ripening of mould ripened cheeses as well as for the formation of eye holes in Swiss cheese (Martley and Crow, 1996). Sodium and potassium salts like carbonate, bicarbonate are also added to generate carbon dioxide in the product as cappuccino foamer (Agbo et al., 1998; Hedrick, 1984; Lederer et al., 1991).

3.4 Gas hydrates

Gas hydrates, a three dimensional structure of water molecule which cavities are filled by gas molecules, (as illustrated in Figure 3) are also successfully used to produce bubbles in the dairy products particularly in frozen dessert and milkshake. When gas is subjected to high pressure (3.5 MPa) and reduced temperature (below 268.15 K), then a solid gas-water clatharate known as gas hydrate is formed. These hydrates are unstable at atmospheric conditions. When gas hydrates are generated in frozen desserts excess of water is used to produce so that composite of gas hydrate crystals is ice. This composite structure of ice acts as a microscopic particles and prevents from collapsing. On warming the ice layer around the gas hydrate crystal melts and gas hydrate releases gas (Telford et al., 2010). Commonly used gases for hydrate formation are H_2, CO_2, CH_4, Ar, Xe. Kr, Ne, N_2O etc. In appearance they look alike snow or ice (Cebula et al., 2013). This type of hydrates can be created with dairy ingredients to give gas bubbles in the final product (Bee, 1988; Gupta and Dimmel, 2003). Bee (1988) suggested that 12% w/w CO_2 gas in the frozen milk product could be obtained by using gas hydrate. Authors (Bee, 1990; Irving, 1970) had reported that various gas hydrates (CO_2 and N_2O) can be used to manufacture milkshake. Furthermore, they claimed that CO_2 hydrates when used in milk shake results in acidic taste and less attractive overall impression than N_2O hydrates. Thus, N_2O hydrates are preferred in milk shake.

4. Conclusions

Gases such as air, CO_2, N_2, H_2, N_2O, Ar, Xe and He have been used in the dairy system manufacturing process. This review highlighted gaseous solubility in the dairy products and the practice of adding the bubbles of gases for improving the product quality in the dairy product manufacturing. Aerated dairy products are diverse in nature. Although gases are found to be

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components of raw milk, various gases are found to be added externally to enhance milk and milk products keeping quality. Amount of gas, solubility of gas and dispersion of gases in the milk system can affect the character of milk products. These characteristics are in fact related to the individual gas properties. Furthermore, incorporated gases have been reported to affect shelf life, rheology, sensory attribute and foaming characteristics of dairy systems. Carbon dioxide has been extensively reported in dairy systems even noble gases like Ar and Xe are also found to be promising to use in dairy products as a functional ingredient. Additional research should be conducted on the efficient utilization of such gases for the characterization of the innovative food structures and functionalities.

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Table 1 Gases used in the manufacturing of dairy products

Gas	**Used Product**	**Purpose**	**Reference(s)**
Air	Butter	Fat coalescence; phase conversion; better overrun	Foley et al. (1990); van Aken (2001); Aldred et al. (2008)
	Cheese	Enhance softness	Vial et al. (2006)
	Chocolate	Improve stability	Robert (2003); Haedelt et al. (2005); Haedelt et al. (2007); Sundara and Serbescu (2014)
	Dairy Foam	Stabilize foaming	Wyss et al. (2008); Bisperink et al. (2004)
	Ice cream	Increase softness, melting properties, control the size of ice-crystals; increase overrun	Pelan et al. (1997); Sofjan and Hartel (2004); Pei and Schmidt (2010); Prindiville et al. (1999); Cox et al. (2007)
	Yogurt	Improve aroma compounds	Martin et al. (2011); Martin et al. (2010)
Carbon dioxide	Butter	Improve functionality; enhance overrun; reduce time	Prucha et al. (1931); Sherwood and Martin (1926); Christie et al. (1960); Senn (1944); Shisiiikura et al. (1986)

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	Cheese	Enhance rennetability; eye formation	Calvo et al. (1993); Montilla et al. (1995); Nelson et al. (2004); Ruas-Madiedo et al. (2002); Ruas-Madiedo et al. (1998); Vial et al. (2006); Marshall (1987)
	Cappuccino/ coffee foam	Generate foam	Villagran et al. (2000); Hedrick (1984); Wyss et al. (2008)
	Chocolate	Improve sensory	Haedelt et al. (2007); Sundara and Serbescu (2014)
	Fat fractionation	Extraction of fat fractions, enhance the process	Arul et al. (1987); Bhaskar et al. (1998); Bhaskar et al. (1993); Büyükbeşe et al. (2013); Ma and Barbano (2003)
	Ice cream	Improve texture	Sherwood and Martin (1926); Valley and Rettger (1927)
	Milk beverage	Improve sensory quality; reduce growth rate of microbes	Lederer et al. (1991); Yau et al. (1989); Jardin et al. (2012); Walsh et al. (2014); Shah and Prajapati (2014); Ahmed et al. (1989)
	Milk Powder	Plasticizing effect;	Islam and Langrish (2010); Klandar et al.

		Improve solubility	(2009); Kosasih et al. (2016a, 2016b); Marella et al. (2015)
	Raw milk	Extend shelf life; antimicrobial effect; delay fermentation	Amigo et al. (1995); Lederer et al. (1991); Ma et al. (2003); Martin et al. (2003); Prucha et al. (1931); Rajagopal et al. (2005); Ruas-Madiedo et al. (1998); Hotchkiss and Loss (2002); Lo et al. (2016)
	Yogurt	Improve sensory quality and extension of shelf life	Gueimonde et al. (2003); Vinderola et al. (2000)
Nitrogen	Anhydrous milk fat	Improve oxidative stability	Keogh and Higgins (1986)
	Butter	Reduce calorific value	Christie et al. (1960); Aceto et al. (1962); Sinnamon et al. (1957)
	Cheese	Improve physical property	Thorson and Smith (2011)
	Chocolate	Improve sensory property	Hachiya et al. (1994); Haedelt et al. (2007); Haedelt et al. (2011) Sundara and Serbescu (2014)
	Cappuccino	Encapsulate foamer	Hedrick (1984); Bisperink et al. (2004);

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		ingredient, assist foam formation	Wyss et al. (2008); Panesar et al. (1999); Zeller et al. (2010)
	Margarine	Enhance consistency	Massiello (1978)
	Powder	Improve drying	Hanrahan et al. (1962); Islam and Langrish (2010);
	Yogurt	Enhance shelf life	Horiuchi et al. (2009); Martin et al. (2011); Martin et al. (2010); Cachon et al. (2002)
Hydrogen	Beverage	Improve sensory	Giroux et al. (2008)
	Yoghurt	Control syneresis, aroma compounds	Martin et al. (2011); Martin et al. (2010)
Nitrous oxide	Coffee foam and cream	Assist whipping process	Nakai et al. (2010); Nilsen and Zamzow (1967); Getz (1948); Diller and Brooklyn (1939)
	Chocolate	Enhance sensory character	Haedelt et al. (2007); Hedrick (1984)
Argon	Beverages	Suppress bacterial growth, neuro-protectant component	Clark and Clark (2012); Huang et al. (2014); Nowrangi et al. (2014)

	Coffee Foam	enhance foaming	Finley (2014)
	Chocolate	Enhance Sensory	Haedelt et al. (2007)
	Milk powder	Increase droplet size	Aftel et al. (1996)
Xenon	Milk beverage	Functional component improvement	Huang et al. (2014)
Helium	Frozen dessert	Package forming; flavour retention	French (1967); Hashisaka et al. (1990)

Table 2: Solubility of gases in water and fat phase at 298.15 K and 101.325 kPa

Gas	**Ostwald solubility* coefficient in**		**Solubility in Mol.kg^{-1}.Pa^{-1}**		**References**
	Olive oil	**Water**	**Olive oil**	**Water**	
N_2	0.07433	0.015935	3.0074×10^{-8}	6.4473×10^{-9}	Gevantman (2000); Battino et al. (1968); Snedden et al. (1996)
CO_2	1.41349	0.8131675	5.7189×10^{-7}	3.2900×10^{-7}	Battino et al. (1968); Yokozeki and Shiflett (2011); Yeh and Peterson (1963); Snedden et al. (1996)
He	0.01757	0.009245	7.1088×10^{-9}	3.7405×10^{-9}	Battino et al. (1968); Yokozeki and Shiflett (2011); von Antropoff (1910)
H_2	N/A	0.03496	N/A	1.4152×10^{-8}	Gevantman (2000)
N_2O	1.8	0.607	7.2828×10^{-7}	2.4559×10^{-7}	Gevantman (2000); Yeh and Peterson (1963); Battino et al. (1968); Gabel and Schultz (1973); Snedden et al. (1996)

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Ar	0.14953	0.031298	6.0499×10^{-8}	1.2663×10^{-8}	Battino et al. (1968); Gevantman (2000); von Antropoff (1910)
Xe	2.0725	0.1004	8.3853×10^{-7}	4.0622×10^{-8}	Yeh and Peterson (1963); Gevantman (2000); von Antropoff (1910)
Ne	0.02139	0.01113	8.6544×10^{-9}	4.5032×10^{-9}	Battino et al. (1968); Gevantman (2000); von Antropoff (1910)

*Ostwald solubility coefficient denotes a ratio for volume of gas absorbed by the volume of solvent. Conversion factor for different solubility indices are taken from Sander (1999)

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Table 3: Solubility of CO_2 in dairy products at different conditions

Products	Solubility ($mol.kg^{-1}.Pa^{-1}$)	Conditions	Reference(s)
Butterfat	$3.8\text{-}3.9 \times 10^{-7}$	0-22°C	Ma and Barbano (2003)
	$3.3\text{--}3.6 \times 10^{-7}$	0°C (5.7-24.6%) fat	
Semi hard Cheese	$2.8\text{-}3.2 \times 10^{-7}$	7°C (5.7-24.6%) fat	Chaix et al. (2014);
	$2.6\text{-}2.9 \times 10^{-7}$	10°C(5.7-24.6%) fat	
	$2.4\text{-}2.7 \times 10^{-7}$	16°C(5.7-24.6%) fat	Jakobsen et al. (2009)
Soft cheese	$2.1\text{-}2.3 \times 10^{-7}$	20°C(5.7-24.6%) fat	
	$7.8 \times 10^{-7}\text{-} 4.9 \times 10^{-8}$	8°C	
Simulated yogurt	$2.2\text{-}3.3 \times 10^{-7}$	3.3-17°C	Taylor and Ogden (2002)

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Table 4 Methods of gas inclusion in dairy systems

Method of inclusion	**Products**	**Reference(s)**
Mechanical whipping	Cream, frozen desserts	Massiello (1978); Abd El-Rahman et al. (1997); Nakai et al. (2010)
Pressurisation	Coffee foam, whipped cream, cheese, powder	Hedrick (1984); Wyss et al. (2008); Diller and Brooklyn (1939); Islam and Langrish (2010); Ahmed et al. (1989)
Fermentation	Cheese, yogurt, cultured butter	Horiuchi et al. (2009); Beresford et al. (2001); McSweeney and Sousa (2000); Marshall (1987)
Sparging	Milk, Whipped Cream, coffee foam, yogurt, powder	Hotchkiss and Loss (2002); Bisperink et al. (2004); Panesar et al. (1999); Zeller et al. (2010); Chang and Hartel (2002); Wright et al. (2003); Kosasih et al. (2016a, 2016b)
Mixing	Beverages, Ice cream, Butter, Cheese, Chocolate	Rajagopal et al. (2005); Lederer et al. (1991); Walsh et al. (2014); Ruas-Madiedo et al. (1998); Robert (2003)
Super critical fluid	Butter, Cream, fat	Arul et al. (1987); Bhaskar et al.

	extraction	(1993); Shisiiikura et al. (1986)
Chemical salt addition	Coffee foam	Villagran et al. (2000); Agbo et al. (1998); Ledermann (1995)
Gas hydrates	Frozen dessert, Milkshake	Bee (1988, 1990); Cebula et al. (2013); Gupta and Dimmel (2003); Irving (1970)

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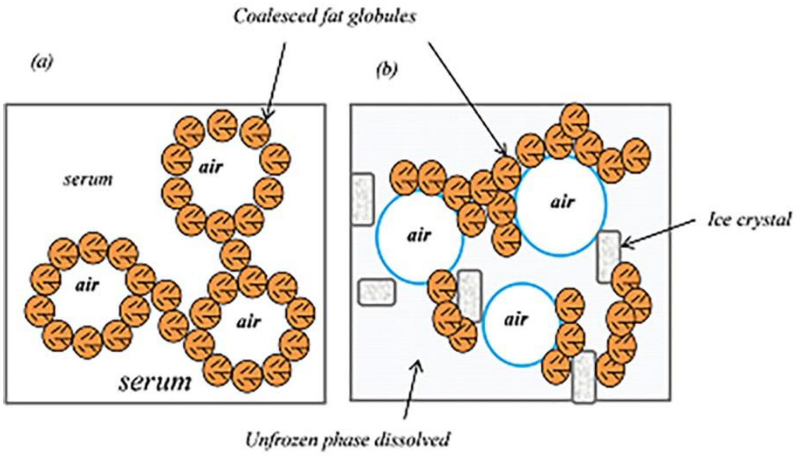

Figure 1 Schematic presentation of aerated products: (a) ice cream and (b) whipped cream (adapted from Sofjan and Hartel (2004) and Brooker et al. (1986))

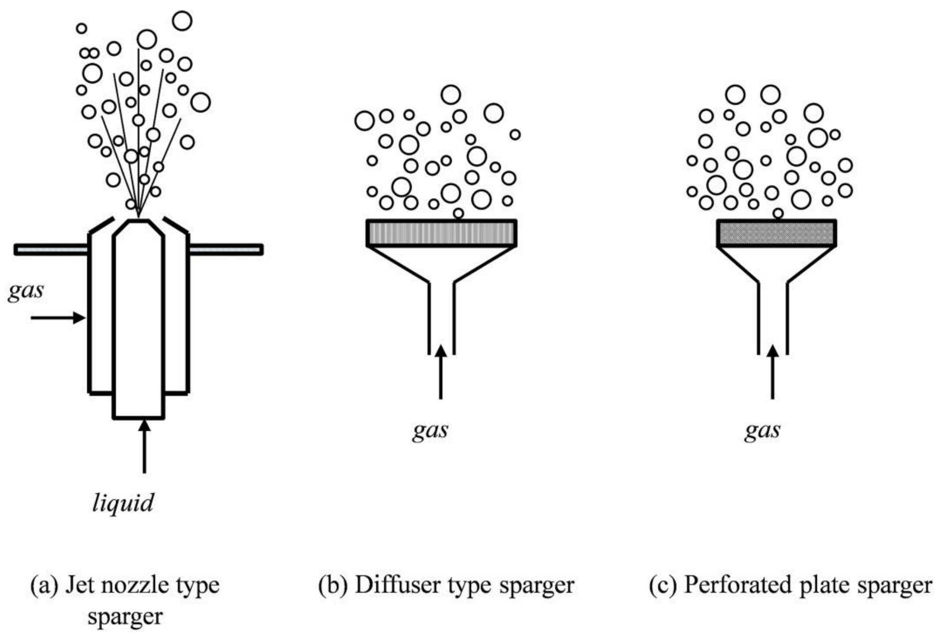

Figure 2 Illustrations of gas sparging system: jet nozzle type (a), diffuser type (b) and perforated plate type spargers (c) adapted from Zehner and Kraume (2000)

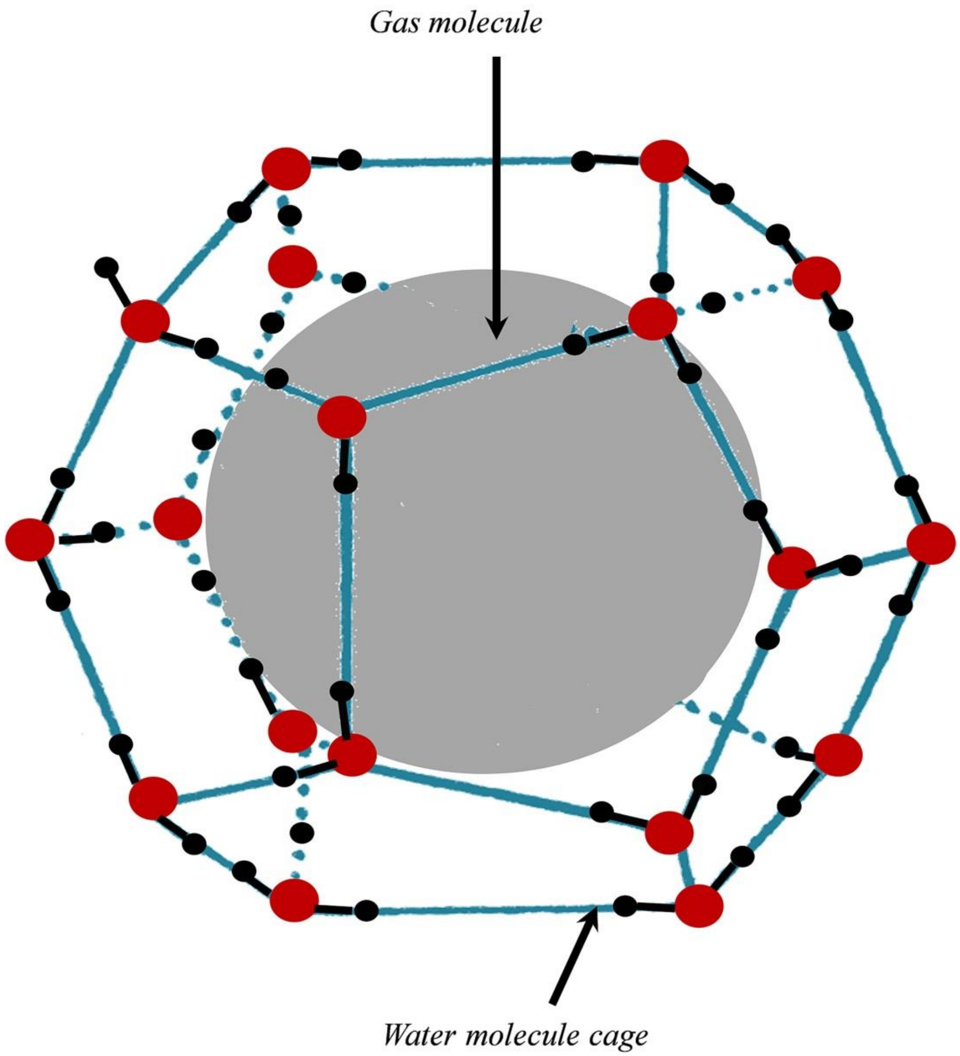

Figure 3 Illustration of arrangement of a gas hydrate molecule

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