Dairy: Culinary Uses of Milk, Butter and Ice Cream

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The Complexity of Milk

Milk is a nutritionally rich food material, which has formed a significant part of the human diet for millennia. Milk is a complex physical system, with the fat content dispersed as globules in a serum within a natural emulsifier system (the protein- and phospholipid-rich milk fat globule membrane, MFGM). The serum contains two families of proteins, the majority of which is casein (80%), assembled into macromolecular structures called casein micelles. The serum dissolves other proteins and a fermentable saccharide called lactose, among other chemical species, including mineral ions, such as phosphate and calcium, that exchange with the micelles. Milk contains protein (3–4%), fat (3–5%), lactose (4.4–4.8%), and minerals, vitamins and trace nutrients (0.7–0.8%).

Due to its nutritional content and physico-chemical makeup, milk is an unstable raw material, with the large fat globules rising to give a cream layer on standing: traditionally, raw milk would have been left in a separating dish for the rich cream to rise over the course of a day, and the surplus skimmed milk would be poured off.

In addition to physical separation, the multiple sources of microbial contamination in the production environment (farms) lead to a host of safety and spoilage challenges. Hence, milk for consumption in liquid form is processed to physically stabilize it by homogenization (which reduces the size of the fat globules) or treated to make it microbiologically more stable using heat such as pasteurization (which kills vegetative bacteria, yielding a product that must be kept refrigerated) or more severe ultra-high temperature (UHT) treatment, which kills spores and results in a product that can be stored at ambient temperatures.

For 6,000 to 8,000 years, cows have been milked, and the milk has been processed into products to preserve it through different principles, such as separation, concentration or fermentation. A well-known process is the concentration of fat and proteins into cheese through coagulation with rennet. Preservation is provided by a combination of acidity (generated by bacterial cultures producing lactic acid from lactose), salt and low water activity. The diversity of cheeses is the result of differences in making conditions, cultures used, and the conditions under which the cheese is stored after manufacture to allow reactions catalysed by enzymes and micro-organisms to develop flavour and texture (i.e., ripening).

Milk has been a traditional feature of culinary uses to extents that differ greatly from country to country. Countries such as Ireland have a long tradition of consumption of ‘fresh’ pasteurized milk as a beverage with a meal, whereas in countries such as France this is not common; 95% of milk sales in France are in the form of UHT milk, which has a longer shelf life and lower price (Belgium, Portugal and Spain similarly consume >90% UHT milk). On the other hand, these countries have a culture of offering cheese after the main course, sometimes before the sweet desserts.

Milk has also been deconstructed in recent decades by a range of increasingly powerful techniques to extract its components in purified or enriched form, and a modern kitchen might include several components of milk (such as lactose, or whey proteins extracted from the fluid that arises as a by-product of cheese manufacture). These can also find applications in molecular cuisine due to the unusual techno-functional properties of components like whey proteins, which, depending on concentration, conditions like pH, and treatment, could be effective emulsifiers, gelling agents or foaming agents.

Two common uses of the recovered cream are butter and ice cream, which will be the focus of this chapter. Butter and ice cream are two traditional dairy products, which, in common with many products and dishes discussed in this handbook, have a deep scientific basis underpinning the art with which they are produced and enjoyed. In this chapter, the principles of production of both will be considered, alongside consideration of their main characteristics and culinary applications.

The Production of Butter

Butter is very simple to produce by allowing raw milk to separate under gravity, recovering the floating cream layer and then agitating it vigorously, incorporating air. This leads first to a stiffened whipped cream structure, which under continued agitation (for example, through manual rotation of a cylindrical churn) ‘breaks’, leading to the release of butter milk and butter grains of released milk fat, which are consolidated into butter, often with salt added for flavouring and preservative reasons.
This simple process has been applied in countries around the world for millennia. For example, in Ireland, samples of ‘bog butter’ have been found buried in peat bogs spanning at least 3,500 years, from the Early Bronze Age (c. 1700 BCE) to the 17th century CE (Smyth et al., 2019). Across North Africa and through the Middle East into Asia, the keeping properties of butter were more often improved by cooking-off the water, leaving a more stable ghee (or *samna*).

The scientific principle underpinning the production of butter is the inversion of the natural oil-in-water emulsified system found in milk and cream to produce a pseudo-emulsion, which includes water droplets dispersed in a semi-solid fat matrix, or even a system that behaves as a gel, depending on temperature.

As said before, the natural dispersion of milk fat globules in milk is stabilized by the presence of the MFGM, which keeps oil and the aqueous solution separate in the aqueous milk environment. However, the agitation applied during churning mechanically ruptures this membrane, exposing hydrophobic fat; in order to minimize the instability and retained energy caused by being exposed to the aqueous environment, damaged fat globules, on collision, coalesce.

This process is usually undertaken at temperatures (10–12 °C) where the milk fat is partially liquid but still largely crystalline, and so the globules can flow, deform and coalesce, but still retain a certain solid-like character. Air is incorporated into the cream by a shear action, forming and breaking bubbles, which are initially stabilized by the adsorption of native soluble proteins to the air/water interface (Brooker, 1986). Fat globules collide, inducing aggregation and partial coalescence at the interface, to create a continuous enveloping matrix to stabilize the foam. Without sufficient solid fat content (SFC), the whipping process would cause release of the liquid fat and premature collapse of the foam. Further agitation increases the air volume, making the fat lamellae between the bubbles progressively thinner. The fat globules concentrated in the serum phase form larger aggregates, leading to distortion and eventual penetration of the MFGM by fat crystals, causing a leakage of internal liquid oils and leaving masses of coalesced fat globules that form the basis of the butter grains (Schmidt and van Hooydonk, 1980; Brooker, 1993).

This collapse is accompanied by the release of ‘butter milk’, which has a composition quite similar to that of skim milk but with a higher fat content and a high content of released MFGM material, particularly phospholipids, which give butter milk important functional properties for use in a wide array of foods (Sodoni et al., 2006) and a range of health benefits (Conway et al., 2014).

The steps in the production of butter are schematically illustrated in Figure 27.1.

### The Texture of Butter

The desirability of butter is strongly linked to its melt-in-the-mouth appeal and its performance in cooking and baking. The principal characteristic of butter that influences its use is hardness. This is primarily determined by the proportions of the fat that are liquid and solid at a given temperature, which is determined by the types of fatty acid residues that comprise the triglycerides in the fat. A higher proportion of long-chain and saturated fatty acid residues (such as palmitic acid) will give fat a higher melting point and make it harder at typical food use temperatures, whereas higher levels of short-chain or unsaturated fatty acid residues (such as oleic acid) will give lower melting points and softer butter. The greatest influence on the proportions of different fatty acid residues present is the diet of the cows, and hence the hardness of butter may differ from region to region, from country to country and even with different seasons, due to changes in availability of grass as feed (O’Callaghan et al., 2016).

The use of grass as a main component of cows’ diet also greatly influences butter colour; butter from countries such as Ireland that practise a seasonal grass-based milk production system tends to have a notably stronger golden-yellow colour (due to high levels of β-carotene) than that from countries or systems where different feeding practices dominate, e.g., 5 µg/100 ml in the
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USA (indoors) compared with 21 μg/100 ml in the UK (summer grazing) (Schönfeldt et al., 2012)

So, much of the eventual texture, especially the hardness, of butter is already set by the time milk or cream is received in a kitchen or factory, as the particular mix of fatty acid residues present will determine what percentage of the fat is solid at a particular temperature. There is still the possibility, however, of manipulating not the amount of solid fat but rather, the form of that fat. Fat, when it passes its melting temperature, will form crystals, and the ultimate self-supporting structure of butter is due to an interlocking crystal network. The exact texture then depends on the microstructure of this network, and the size and shape of crystals can influence texture. Samples of butter on a dish with exactly the same proportion of fat solid, but where in one case there are a lot of small crystals and in another a smaller amount of larger crystals, will have very different spreadability.

In industrial butter production, this is controlled by the temperature history of the cream. The cream, after separation from the milk, is pasteurized at temperatures higher than those used for milk due to the higher fat content and viscosity (min. 80 °C for 15 s) (Juffs and Deeth, 2007; IDFA., 2016). Pasteurization has the added benefit of inactivating the native milk enzyme lipoprotein lipase (LPL; EC 3.1.1.34), which otherwise could hydrolyse the fat released when the MFGM (which normally keeps enzyme and substrate apart) is broken and lead to rancidity. At pasteurization temperatures, the milk fat is completely liquid, and on cooling to churning temperatures a proportion of the fat (determined by the diet and tempering conditions) will crystallize. The key is then to control the rate of cooling, and complex profiles, which can differ at different times of the year, will be applied over several hours to tailor the exact crystalline structure in the fat and hence, the eventual butter texture (Lee and Martini, 2018; Vilgis, 2015).

After manufacture, butter also hardens during storage due to continued crystallization during cold storage over a period of weeks or months following production (Rønholt et al., 2014), and butter may often be reworked or physically manipulated after a period of storage to soften it; this may often be combined with the point of division of a bulk of butter into smaller consumer packs. The deformation induced by the rotating propellers and perforated plates can break up crystalline structures and reduce SFC due to the applied shear (Rønholt et al., 2013). Upon cooling, the SFC increases to the original levels, but some of the Newtonian viscosity may be lost (Mazzanti et al., 2011).

Butter possesses a mild creamy flavour with a delicate odour, making it well suited as a culinary ingredient. The profile of butter includes a fine balance of short-chain free fatty acids, i.e., odorant volatile compounds associated with the hydrolysis or oxidation of triglycerides in the milk. The distribution, concentration and potency of butanoic acid (buttery, cheesy, sweaty), γ- and δ-lactones (sweet, peach, coconut), indole and skatole (mothball/faecal), phenols and hydrocarbons yield this subtle odour (Mallia et al., 2008).

Controlled fermentation with bacteria can be used to introduce a lactic acid taste with odorant diacetyl, butanoic and δ-decalactones to create the distinctive lactic or cultured butter. So subtle, in fact, is the flavour of butter that it is quite common to add herbs, spices, capers and allium for use in the kitchen. Butter is very suitable for addition of parsley, lemon and pepper (beurre maître d’hôtel), garlic cloves (beurre à la bourguignonne – Burgundy or garlic butter) or Roquefort (to make a piped topping), or it can be prepared sautéed with onions or simmered with brown sugar to make butterscotch.

The perception of the flavour of foods involves complex and multidimensional layers of gustatory sensations. Before consumption, the volatile odorant compounds associated with the food enter the nose with inhaled air and are perceived by way of the olfactory neurons (antennasal odour). In the mouth, the tongue manipulates the food to assist breakdown by mastication and forms a bolus before swallowing, while odorant molecules travel through the nasal pharynx, connecting the back of the mouth with the nose, to the olfactory neurons (retroonasal odour). During this direct contact with the food, other compounds within the food activate the taste buds on the tongue, sending signals that are perceived as taste by the brain.

These sensations can guide our eating habits; bitter and sour tastes warn of potentially spoiled, toxic or strongly acidic foods, while salty and sweet desires direct us to foods rich in saccharides, amino acids or salt. Beyond these core four tastes, other chemoreceptors on the tongue and in the mouth have been identified that can enhance our perception of the food: the savoury taste of monosodium glutamate (MSG) is detected as umami (as additional taste not elicited by any combination of the others); heat and spiciness of food are perceived as irritation or pungency; and mechanical stimulation allows touch sensors to interpret texture, whether creamy and smooth or crunchy and granular (Faurion, 1988; Finger and Kinnamon, 2011). From a dairy and nutrition perspective, recent research has identified receptors that may inform the brain of sources of mineral-rich, e.g., calcium (Tordoff et al., 2012) or energy-rich fatty foods (Besnard et al., 2016; Hartley et al., 2019). It is postulated that this may influence human eating behaviour and aid the body in finding foods containing lipid-soluble vitamins (A, D, E, K). Conversely, this association may be linked to the over-consumption of some foods by obese individuals (Gilbertson and Khan, 2014).

The combination with heat opens a further exploration of the transitions within butter odour and flavour. On heating butter with flour to 120 °C to form a white roux, a roasted odour of aldehydes, carboxylic acids and lactones is released (Kato, 2003). At higher temperatures, butter transforms into beurre noisette and beurre noir, as Amadori rearrangement associated with Maillard browning causes changes in the colour and aroma of fats, sugars and proteins, forming furans, cyclic ketoenols (sweet, fruity, floral) and nitrogen-containing pyrazines (nutty, roasted) (Shigematsu et al., 1977; Maga and Katz, 2009).

The desirable nature of butter goes beyond flavour and is linked to its behaviour as it warms in the mouth – a gradual but quick melting in an almost uniquely pleasurable manner. The small solid α and β’ fat crystals in butter melt over a broad range of temperatures, softening to a liquid easily as they reach 35 °C (Devi and Kahatkar, 2017).

In baking and confectionery, the performance of butter is of utmost importance; it must provide aeration, dispersibility and...
The Science of Ice Cream

It is believed that ice cream has been produced for several centuries, with its origins ‘hotly’ debated between Italy and China and tales of Marco Polo bringing recipes with him in the 13th century. Iced desserts developed from blends of fruits and powders with crushed ice to the more complex process involving milk being cooled in vessels cooled by chilled brine while being whipped. Today, ice cream is a product that is produced and enjoyed around the world, the properties of which are dependent on a surprising amount of physics and physical chemistry.

One of the best ways to understand the science of ice cream is to visualize it down a microscope. Frozen ice cream is a complex multi-phase system, with elements as follows:

- Ice crystals, which give the product its name and character, but which must be below a certain size to prevent their being detected on the tongue while eating;
- Air bubbles, for ice cream is an aerated product (10–50% of the total volume), which give the light airy structure of ice cream, and mean the product is typically sold on the basis of volume rather than weight (CFR, 2019). These bubbles are entrapped by;
- A network of partially coalesced fat globules. The ice cream mix is homogenized, which coats fat globules in protein (the greatly increased interfacial surface area being too much for existing MFGM material to cover), but such globules do not whip and entrap air well. Thus, the mix usually includes emulsifiers (such as lecithin, provided through the inclusion of egg in the recipe), which compete successfully for access to the globule surfaces, eventually displacing the protein but giving a weaker coating, which can be damaged during whipping, giving the desired effect;

So, ice cream is a sugar-rich liquid within which air bubbles are trapped by a partially coalesced fat network and ice crystals of defined size float; part liquid, part emulsion, part foam, part frozen. It may, of course, also include flavourings and inclusions (cookie pieces, chocolate or fruit), but these are the core elements of every ice cream.

Ice cream is produced by making a mix of milk, cream (if desired to enhance the fat content), sugar, emulsifiers (perhaps egg), stabilizers (to be discussed later) and flavours, pasteurizing and homogenizing, to ensure microbial stability and create the emulsion already described. It is then held at refrigeration temperatures for several hours (referred to as ageing) to allow the emulsion to ‘sort’ in terms of displacement at the globule surfaces, fat to crystallize and stabilizer to hydrate fully.

It is then frozen in either a batch or a continuous process (the latter using a scraped-surface heat-exchanger) to remove heat, form ice crystals while mechanically disrupting them to prevent their growing too large, and whip in air to be entrapped by fat within the freezing structure. At the end of this initial freezing, the mix may be at −5 °C; it could be consumed directly (in a tub or on a cone) and is still liquid enough for inclusions to be added and mixed in. If not consumed directly, it is, however, now deep-frozen in suitable packaging to −18 °C, at which temperature the final structure emerges, and ideally stored at that temperature until consumption.

The steps in the production of ice cream are schematically illustrated in Figure 27.2.

However, ideal conditions are rarely met, and frozen storage of ice cream is often punctuated by points at which its temperature increases, even slightly, perhaps due to opening of a freezer door allowing in a small amount of warm air. Even a tiny increase in temperature allows some ice to melt, and upon the temperature decreasing again the water tends to freeze onto existing crystals, which grow as a result; crystal growth by accretion or Ostwald ripening can also occur.

The net effect of such crystal growth is a progressive movement towards the ultimate fate of all ice cream, which is a deterioration towards a state where consumers will reject the product due to perceived iciness or grittiness, as ice crystals exceed the sensory threshold. The key function of stabilizers in the ice cream mix (typically hydrocolloids such as carrageenan, guar or locust bean gums) is to delay this point of end of acceptable life as effectively as possible, by essentially building molecular cages around ice crystals or otherwise entrapping and immobilizing water, such that any water that thaws does not have the mobility to enlarge...
existing ice crystals, and acceptable structure is retained for longer.

Ice cream has been a popular basis for experimentation and innovation within the field of molecular cooking. For example, freezing using liquid nitrogen results in extremely fast freezing (due to a very large temperature difference between the freezing medium and the mix), leading to very small ice crystals and a structure dominated by the perception of creaminess due to the fat present. Fast freezing using liquid nitrogen can also result in a product with a hard-frozen outside crust and a creamy semi-liquid interior. Freezing with liquid nitrogen also allows the possibility of inclusion of alcohol in an ice cream mix, which otherwise would undesirably interfere with the freezing properties of the product due to the low freezing point of ethanol.

Ice cream flavours can also be manipulated to contain counter-intuitive flavour combinations, and savoury ice creams are available in some restaurants (such as a frozen crab bisque or egg and bacon ice cream at The Fat Duck); inclusion of spicy ingredients such as chilli can result in an unusual mix of sensations of heat and cold on consumption. Ice cream can also be dried into a powder as an ingredient of desserts (a Pacojet system, which micro-purées frozen materials, is used commonly for this purpose) or freeze-dried into a solid form which does not require frozen storage (so-called astronaut ice cream).

A key consideration in evaluating their structure is the properties of milk fat, which is entirely solid at <-10 °C and entirely liquid at >50 °C. Between these temperatures, part of it is solid, and part is liquid. For example, using melting curves (plus nuclear magnetic resonance (NMR) analysis), one can say that about 70% is liquid at room temperature (Bouteille et al., 2013).

Then there is the question of how the liquid and the solid are distributed in systems like ice cream and butter. If the liquid is enough to make a continuous liquid phase intermixed within a continuous solid matrix, then we could use the Dispersed System Formalism term:

$$D_3(O) \times D_3(S)$$

However, if the solid is less than 5% (the limit for having a continuous solid network), then we can have a dispersion:

$$D_0(S)/D_3(O)$$

Moreover, the issue of the water phase has to be considered, which adds complexity because, for some temperatures, we can imagine dispersions of water and liquid fat in the solid, or other possibilities. As mentioned earlier, butter is often described as a water-in-oil emulsion, but technically it is not an emulsion but rather a pseudo-emulsion, as the water droplets are not individually covered in an emulsifying barrier layer but are entrapped in the semi-solid fat matrix by physical dispersion.

When the butter is consumed, the first phenomenon that happens in the mouth will be melting (leading to cooling, as latent heat of fusion for the fat crystals is absorbed) followed by rapid coalescence of the water droplets (there being no barrier to this happening once the fat liquefies) and a perceptible sudden rise in perception of salty flavour, in the case of salted butter, as pools of salted water react with the relevant receptors on the tongue.

**Structural Considerations for Butter and Ice Cream**

Butter and ice cream are, as explained earlier, complex entities, and also ancient products, but consideration of their physical characteristics leads to possibilities for future innovation.

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**FIGURE 27.2** Schematic illustration of the transition from ice cream mix (a) to homogenised mix (b), and after aeration and freezing, to a semi-frozen foam (c) and final hardened ice cream (d).
For ice cream, there are many different possibilities, but if there are air bubbles (D₃(G)), dispersed fat (D₃(O)) and dispersed solids (D₃(S)) (for example ice crystals, fat crystals or egg solids), and a continuous dispersing liquid (concentrated sugar syrup) D₃(W), we can have

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[D₃(G) + D₃(O) + D₃(S)]/D₃(W)
\]

However, this will be highly changeable with temperature, since the relative proportions of frozen and unfrozen phases will change, such as in the case of heat shock (leading to partial melting and later refreezing of ice crystals).

As with butter, consumption results in rapid melting in the mouth, and the absorption of latent heat to fuel the melting of both ice and fat crystals results in a pleasurable cold sensation, followed by a rapid release of flavour and sweetness as the system reverts to a liquid and highly mobile state.

Conclusion

Ice cream and butter are two traditional dairy products, which can be produced on scales from the large to the small and are staples in many cuisines and culinary traditions. While the principles of their production are relatively simple, this is underpinned, as is the case for so many food products, by complex science. In both cases, the key principle is destabilization of an emulsion and its reconstruction in a modified form that gives specific textural characteristics. In addition, key attributes of both products relate to melting, in one case of fat and in the other of ice crystals, and the stability and eating experience of both are dependent on control of this process. Understanding these principles allows fine control of their use in culinary settings, as well as innovating new recipes and experiences based on their integration into other dishes, sauces and desserts.

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