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1 Introduction

The initial application of biotechnology to cheese manufacturing undoubtedly occurred during the first accidental souring and clotting of milk to form a rudimentary curd. All subsequent research and development efforts have characterized and refined that prehistoric use of microbial metabolism, enzymology and process engineering. Historical descriptions of cheese manufacturing are sketchy, but drawings in a Ramesid tomb (100 BC) show goats being led to pasture and skin bags hanging from poles (SCOTT, 1986). Contamination of milk with acid-producing bacteria undoubtedly led to curdling and the subsequent motion in the bags produced curds and whey, both of which were consumed out of necessity and preference. Cheese, whey and fermented milks offered a logical alternative protein source to meat which would require slaughtering of an essential animal. The subsequent evolution of usage, characterization and development of lactic acid bacteria was reviewed by TEUBER (1993a).

Although not documented, it seems reasonable that use of milk-clotting enzymes originated from an observation of clotted milk in the stomach of suckling animals. Our perceptive prehistoric ancestors could have related that transformation of milk to a substance in the stomach with subsequent evolution to practices of dipping stomach linings into milk to cause clotting. The stomachs of hares and kids served as sources of milk-clotting enzymes, but extracts of plant materials such as thistle flowers, fig tree, and saffron seeds also were used as clotting agents. The successful use of plant extracts probably relates to the prevalence of ewe’s and goat’s milk cheese which would not become bitter as would that from cow’s milk.

Early records indicate that foods such as cheese and bread were staples as early as 6000 to 7000 BC in the Fertile Crescent located in present-day Iraq (SCOTT, 1986). Cheese was a favored food of ancient royalty; 13 of the 500 cooks serving the Persian king Darius were experts in cheesemaking and cheese is thought to be amongst the remains in the tomb of Pharaoh Horus. Although goats and sheep were the preferred animals, a Sumerian frieze dating between 3500 and 3000 BC shows cows being milked and the subsequent curdling of milk (HARRIS, 1984). The spread of cattle husbandry and the concomitant cheesemaking was fostered by the migrant Vikings.

Advances in cheesemaking were stagnant during the Dark Ages except for Scandinavia and the isolated West coast of Ireland (HARRIS, 1984). Subsequent evolution of cheese production took place through individuals, farmer cooperatives and monasteries with the Po Valley in Northern Italy becoming one of the principal commercial cheese exchanges in Europe. Interest was rekindled in agricultural technology in the sixteenth century. One of the first treatises in that era by an Italian, Agostino Gallo, indicated that cow’s milk had replaced that from sheep and goats in the production of cheese. The Age of Enlightenment fostered technological developments and the consolidation of cheesemaking into commercial enterprises. This trend accelerated during the nineteenth century with VON LIEBIG, PASTEUR, METCHNIKOV and TYNDALL establishing scientific bases for cheese fermentation, microbiology and pasteurization. Several developments were especially important in the rationalization of cheese manufacturing: use of heat to destroy microorganisms by PASTEUR in 1857 evolved into specific processes (including pasteurization) and equipment to heat milk before cheese manufacturing, the introduction of pure cultures of lactic acid bacteria by STORCH in 1890 and ORLA-JENSEN in 1919, refinement of extraction of rennet from calf vells and standardization of the extract by HANSEN in 1870 and the development of the acidimeter by LLOYD in 1899 to objectively measure acid production by lactic acid bacteria during cheese manufacturing (SCOTT, 1986).

The advent of international trade, development of railway systems, the Industrial Revolution and urbanization of the population fostered improved processes and facilities, and the consolidation of cheesemaking operations and marketing systems. Cheese manufacturing plants that purchased milk from farmers arose throughout Europe and the United States during the nineteenth century. This
specialization naturally led to systematic control of the biology, chemistry and composition during cheesemaking and automated systems of handling the ingredients and the resulting cheese (Olson, 1970, 1975). Presently, highly automated manufacturing plants are capable of converting millions of liters of milk per day into cheeses that constitute major varieties on the world market; Cheddar, Gouda, Mozzarella, Swiss, Camembert and Brie are some examples. However, the cheese industry is still heterogeneous and includes some varieties being made by family units with techniques not greatly different from those used in the early origins of cheesemaking.

2 Cheese Types

It is not surprising, with the development of the cheese industry, when travel and communications were relatively limited, that a large number of cheese varieties would evolve. The exact number of cheese varieties would be impossible to determine and probably meaningless to ascertain. It is estimated that 2000 different varieties have been developed; 400 varieties have been described (Walter and Hargrove, 1972). This diversity of products hampers defining cheese. The Food and Agricultural Organization devised a Code of Principles which included the following definitions of cheeses. Cheese is the fresh or matured product obtained by the drainage (of liquid) after the coagulation of milk, cream, skimmed or partly skimmed milk, butter milk or a combination thereof. A second definition was added for cheeses made from the liquid whey obtained during manufacturing of cheese. Whey cheese is the product obtained by concentration or coagulation of whey with or without the addition of milk or milk fat. Newer cheese manufacturing techniques deviate slightly from the details of these definitions but not from the general concepts.

The diversity of cheeses prompted the need for classification to more effectively describe and compare cheeses from different regions. Several approaches exist depending upon the need for the classification (Scott, 1986). Marketers of cheese often classify by country of origin, which is logical to create a merchandizing image but creates confusion and overlap of many cheese varieties. More systematic classifications use composition, firmness and maturation agents as criteria as shown in Tab. 1. Alternatively, cheeses are categorized in Tab. 2 as natural cheeses meaning that they are manufactured by acid or enzymatic clotting of milk or of milk fractions or as processed cheeses that are manufactured from natural cheeses.

Categorization by composition obviously groups cheeses of greatly different flavor characteristics into a single class. This approach is useful for regulatory purposes and for comparing physical properties of cheese types. The term, water in fat free substance, is relevant since it is effectively a ratio of water content to the protein (caseins) content; the latter being the structural matrix of cheeses. Firmness of cheeses is closely related to that ratio but is also influenced by the percentage

<table>
<thead>
<tr>
<th>Tab. 1. Classification of Cheeses According to Composition, Firmness and Maturation Agents (Vedamutha and Washam, 1983)</th>
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</thead>
<tbody>
<tr>
<td><strong>I. Soft Cheese</strong> (50% to 80% moisture)</td>
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<tr>
<td>Unripened – low fat</td>
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<tr>
<td>Cottage</td>
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<tr>
<td>Quark</td>
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<tr>
<td>Baker’s</td>
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<tr>
<td>Unripened – high fat</td>
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<tr>
<td>Cream</td>
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<tr>
<td>Neufchatel</td>
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<tr>
<td>Unripened stretched curd or pasta filata cheese</td>
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<tr>
<td>Mozzarella</td>
</tr>
<tr>
<td>Scamorze</td>
</tr>
<tr>
<td>Ripened by external mold growth</td>
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<tr>
<td>Camembert</td>
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<tr>
<td>Brie</td>
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<tr>
<td>Ripened by bacterial fermentation</td>
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<tr>
<td>Kochkaese</td>
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<tr>
<td>Handkaese</td>
</tr>
<tr>
<td>Caciotta (ewe or goat)</td>
</tr>
<tr>
<td>Salt-cured or pickled</td>
</tr>
<tr>
<td>Feta – Greek</td>
</tr>
<tr>
<td>Domiati – Egyptian</td>
</tr>
<tr>
<td>Surface-ripened</td>
</tr>
<tr>
<td>Liederkranz</td>
</tr>
</tbody>
</table>
II. Semi-soft Cheese (39%–50% moisture)
   Ripened by internal mold growth
   Blue
   Gorgonzola
   Roquefort (sheep’s milk)
   Surface-ripened by bacteria and yeast
   (surface smear)
   Limburger
   Brick
   Trappist
   Port du Salut, St. Paulin
   Oka
   Ripened primarily by internal bacterial fermentation but may also have some surface growth
   Münster
   Bel Paese
   Tilsiter
   Ripened internally by bacterial fermentation
   Pasta Filata
   Provolone
   Low-moisture Mozzarella

III. Hard Cheese (maximum 39% moisture)
   Internally ripened by bacterial fermentation
   Cheddar
   Colby
   Caciocavallo
   Internally ripened by bacterial fermentation plus CO₂ production resulting in holes or “eyes”
   Swiss (Emmental)
   Gruyere
   Gouda
   Edam
   Samsoc
   Internally ripened by mold growth
   Stilton

IV. Very Hard Cheese (maximum 34% moisture)
   Asiago Old
   Parmesan, Parmigiano, Grana
   Romano
   Sardo

V. Whey Cheese
   Heat and acid denaturation of whey protein
   Ricotta (60% moisture)
   Condensing of whey by heat and water evaporation
   Gjetost (goat milk whey; 13% moisture)
   Myost, Primost (13–18% moisture)

VI. Spiced Cheese
   Caraway – caraway seeds
   Noekkelost – cumin, cloves
   Kuminost – cumin, caraway seeds
   Pepper – peppers
   Sapsago – hard grating, clover

Tab. 2. Classification of Cheese by Manufacturing and Maturation Processes (Olson, 1979)

I. Natural Cheeses
   A. Cheese varieties in which milk is clotted by acid:
      1. Cottage cheese
      2. Baker’s cheese
      3. Cream cheese
      4. Neufchâtel cheese
   B. Cheese varieties in which milk is clotted by proteases:
      1. Cheddar cheese
      2. Colby and stirred curd (granular) cheese
      3. Surface-ripened cheeses – Brick cheese, Limburger cheese, Port du Salut, Bel Paese, Tilsit cheeses
      4. Other semi-soft cheeses – Edam, Gouda, Monterey, Münster cheeses
      5. Cheeses with eyes – Swiss, Gruyère, Samsøe
   6. Italian type
      a) Very hard (grating) – Parmesan, Romano
      b) Other hard – Asiago, Fontina
      c) Pasta Filata – Provolone, Mozzarella
   7. Mold-ripened
      a) Blue, Roquefort
      b) Cheese with surface mold – Camembert, Brie, Coulommiers

II. Process Cheese
   1. Processed Swiss, processed Cheddar, etc.
   2. Cold-pack cheese

of fat in dry matter of cheese which is a ratio of the fat content to fat + protein + mineral contents. Classifying cheese by firmness and maturation processes, as in Tab. 2, characterizes types more definitively. However, varieties such as Cheddar and Provolone cheeses that differ greatly in characteristics are placed in the same group illustrating the difficulties in defining a complex food group such as cheese.
3 Cheese Manufacturing Overview

In spite of the heterogeneity of cheese varieties, there are common ingredients and processes that apply to all cheeses as illustrated in Fig. 1. The diagram indicates that cheese manufacturing is continuous through virtually all of the process since it is biologically driven. Cheese is a dynamic, viable organism from the point at which enzymes and/or microorganisms are added or activated until it is digested by consumers and/or converted into more stable process cheese by heat processing. Cheese is probably one of the more complex fermented foods to manufacture, since biological actions (fermentation of lactose to acids) affect chemical changes (expulsion of water and the sugar, lactose, and solubilization and expulsion of calcium phosphate). These, in turn, influence biological actions and their impacts by altering lactose availability and buffering capacity of cheese. Both of these influence physical properties of cheese (firmness and brittleness). The one overriding principle of cheese manufacturing is control of rate and timing of acid production. This coincides with control of expulsion of serum (whey) that contains the substrate and buffering constituents which regulate the amount and impact of acid production. Numerous profiles of acid production are possible during cheese manufacturing if whey expulsion is coordinated with acid production profiles. The ultimate requisites are a cheese with the correct moisture content and pH. The two factors form a substantial basis for differentiating cheese varieties shown in Tab. 1 and their physical properties as discussed later.

3.1 Milk Analysis and Quality Control

The first step in cheese manufacturing as shown in Fig. 1 is analysis and quality control of milk, since these factors greatly influence the economics of cheese manufacturing, composition of cheeses and their sensory qualities. The amount of milkfat has traditionally served as the basis of payment for milk but value is now determined by levels of fat, protein and quality factors. Since casein and fat constitute about 90% of the solids in most cheese varieties, it is essential to measure concentrations of these accurately in milk because they, along with water, dictate the yield of cheese from milk (EMMONS et al., 1990). Casein is now estimated from protein concentrations until a feasible measurement can be developed.

3.2 Milk Pretreatments

Treatments of milk before cheese manufacturing vary with types of cheese and are reviewed in detail by VEDAMUTHIU and WASHAM (1983), SCOTT (1986) and JOHNSON (1988). Some of the common treatments of milk are (1) heating, including pasteurization, to reduce bacterial populations and heat-labile enzymes, and (2) adjustment of milk composition by removing milk fat by centrifugal separation and by adding nonfat solids or cream. Conditions for heating vary with the type of cheese, the intended use for the cheese and legal requirements. In the United States, pasteurization at 71.7°C for 15 s is required for cheese varieties that are traditionally consumed fresh and for any cheese that is not stored for at least 60 days at 1.67°C or higher. The holding requirement recognizes the typical reduction in numbers of pathogens in the environment of a cheese with a pH of 5.4 or lower. Higher than normal heat treatments adversely affect the clotting properties of milk and the physical characteristics of the cheese.

Adjustment of milk composition is dictated by the traditional composition of a cheese variety. The choice of removing milk fat or adding nonfat solids usually is determined by economics. Concentrated skim milk or nonfat dry milk are commonly used sources of solids. These must be of high microbiological quality and should not have been heat-treated excessively. The amount of nonfat solids added is limited to a few percent of the milk weight; excess levels will unduly increase lactose levels in cheese and can also impair the physical characteristics of the cheese.
Fig. 1. Flow chart of the cheese manufacturing process showing treatments of milk, cheese curd and finished cheese and ingredients used in the process.
Other physical treatments of milk are applied in manufacturing certain cheeses or in specific processes. Concentration of milk by vacuum evaporation will increase the through-put of a plant and may be used to regulate milk-clotting rates. The degree of concentration is limited by the previously mentioned impacts of higher lactose levels. Ultrafiltration (UF) of milk is applied in manufacturing of some soft cheeses and to a limited extent for hard cheese varieties (Lawrence, 1989). Partial concentration by UF to increase milk protein concentrations to 4 to 5% is common in Europe for soft and semi-soft cheeses. This treatment regulates lactose content and increases buffering capacity to enhance control of pH during manufacturing and in the final cheese. Adjustment of casein content should also create greater uniformity of milk-clotting that would be desirable in continuous cheese manufacturing operations.

Clarification of milk by high-speed centrifugation to remove extraneous matter has limited usage except for pretreatment of milk for Swiss cheese manufacturing (Johnson, 1988). Reducing extraneous matter yields an optimum number of foci for eventual eyes that form in the cheese. Higher-speed centrifugation, bactofugation, is used to reduce the aerobic and anaerobic spore count in milk for cheeses in which these bacterial types may create defects (Van den Berg et al., 1989). Greatest use has been for Gouda and Swiss-type cheeses in Europe as an alternative to use of nitrate for controlling outgrowth of spore-formers. Microfiltration which captures microbial cells but allows constituents of skim milk to pass through the membrane is an alternative approach to removing bacterial cells and spores (Malmberg and Holm, 1988). It is technologically less appealing than bactofugation at present, but may offer interesting alternatives to heat treatment of milk for certain cheeses that are matured (Maubois, 1991).

Homogenization imposes high-pressure shear to disrupt milk fat globules to produce substantially smaller globules that are recoated with milk proteins (Vedamuthu and Washam, 1983). Principal uses are to enhance lipolysis of blue-veined cheeses and the physical properties of cream cheese. Desirable levels of free fatty acids are higher in blue-veined cheeses, and these acids are also converted to important flavor compounds, methyl ketones. Application to most cheeses is limited since low levels of free fatty acids are usually desired.

In addition to milk solids, calcium chloride may be added to milk during certain seasons to enhance enzymatic milk clotting (Lucy and Fox, 1993). Higher calcium ion concentration increases the rate of firming of milk gels as described in Sect. 4.3.1. Adding acids to milk will also increase Ca²⁺ levels, but this may not be permitted for all cheeses by regulatory agencies.

A variety of enzymes, in addition to milk-clotting enzymes, are permitted as food additives and are presently used or may by applied to enhance cheese flavor and/or rate of cheese maturation (Anonymous, 1990). The most commonly used are lipases from oral or forestomach tissues of calf, kid goats or lambs that enhance flavors of Italian-type, blue-veined, Feta cheeses, and of Cheddar cheese used to make process cheese. Lipases from Aspergillus niger, A. oryzae and Mucor miehei are also used to produce highly flavored cheese products for use as food ingredients. Addition of microorganisms to milk is limited to certain cheese varieties. The most common are Propionibacterium species for Emmental and Swiss-type cheeses, spores of Penicillium roqueforti for blue cheese, and P. camemberti for brie and camembert cheeses. The spores are commonly sprayed on the surfaces of the last two cheese varieties prior to maturation. Various microbial species are being evaluated as cultures to accelerate cheese maturation rates, but commercial use is apparently limited or not publicized (El Soda, 1993).

3.3 Milk Culturing with Lactic Acid Bacteria

Cheese manufacturing occurs in vessels (vats) that vary widely in capacity, in cheese manufacturing plants that differ greatly in size and with a substantial diversity in mechanization and automation of the processes (Scott, 1986). There appears to be a trend
towards a dichotomy in which commodity cheeses, i.e., Cheddar and Mozzarella cheeses, are manufactured in large, highly mechanized plants, and specialty cheeses, i.e., trappist and blue, in smaller, less mechanized plants. However, specialty cheeses are also made in highly mechanized plants. Modern facilities utilize covered vats in which initial stages of cheese manufacturing are automated (WALSTRA, 1987). Subsequent handling of curd after removal of whey usually is mechanized but procedures vary widely for different cheese varieties.

The first step in cheese manufacturing carried out in the above equipment is addition of lactic acid bacteria. Acid-producing activity and metabolism of lactic starter cultures are the most important factors to control in cheese manufacturing, since they greatly influence cheese manufacturing efficiency and the composition, quality and safety of the finished cheese. Characteristics, functions and propagation procedures for these bacteria are discussed in Sect. 4.2. Facilities and technologies for preparing cultures and inoculating milk for cheese manufacturing vary between manufacturers. Modern operations will grow cultures under conditions approaching asepsis and will have procedures for accurately measuring cultures added to cheese milk. Strains of lactic acid bacteria will differ in acid-producing activity which necessitates adding different quantities to attain the same rate of acid production during manufacture of all lots of cheese.

### 3.4 Milk Clotting

In virtually all cheeses that are matured to develop desired flavor, the milk is clotted with selected enzymes which are described in Sect. 4.3. Uniformity of clotting and strength of the milk gel is critical for maximum retention of milk proteins (caseins) and milk fat in cheese and to minimize variations in cheese moisture levels. Milk-clotting enzymes are handled to avoid exposure to high temperatures and pH environments and to oxidizing agents such as hypochlorites. The enzymes usually are diluted in cold water and added uniformly to milk in the vat; inadequate distribution in milk will create variability in gel strength throughout the vat with the previously mentioned consequences.

Each type of cheese will require an optimum gel firmness at the point at which the gel is cut into smaller pieces. The choice of firmness level was developed subjectively, but a firmer gel will generally expel whey slower than a softer gel after cutting. The mechanisms regulating these effects are described in Sect. 4.3.1. Other factors such as size of curd pieces, temperature, pH, stirring of curd in whey and fat content influence syneresis of the curd (WALSTRA et al., 1987a).

### 3.5 Whey Expulsion

Whey is expelled rapidly from curd after cutting. This process is aided by raising the temperature of the curd–whey slurry which is being stirred in the vat. Most of the lactic acid bacteria are trapped in the curd and ferment lactose to lactic acid which diffuses from the curd. This is a dynamic system, since the substrate lactose is also being removed from the curd with the expelled whey. The relationship between the rate of moisture (and lactose) removal versus rate of lactic acid production by the lactic acid bacteria, to lower the curd pH, has profound effects on the characteristics of the final cheese as shown in Fig. 2 (LAWRENCE et al., 1984; LUCEY and FOX, 1993). These impacts result from the rate and extent of solubilization of calcium phosphate from the protein (casein) matrix of the curd. Calcium phosphate has a substantial effect on the physical proteins of the casein aggregates as described in Sects. 4.1.1 and 4.1.4. Rapid and extensive acid production will remove more calcium and phosphate, albeit less phosphate relative to calcium, to produce a brittle cheese with a lower mineral content. Several varieties of cheese illustrate the range of these interrelationships. In manufacturing Emmental cheese, acid production is slow when most of the whey is expelled from the curd. This solubilizes less calcium phosphate and yields a cheese that is more pliable. Acid production is more rapid and extensive during whey expulsion in manufacturing Cheshire and blue cheeses which are more brittle.
and less firm. Other varieties can be positioned between these extremes.

3.6 Moisture and pH Control

Physical properties of cheese are also influenced by the pH of the cheese which dictates the state of the calcium-phosphate-casein structure. The minimum pH of cheeses is usually reached within the first few days of maturation. It is regulated by the amount of lactose fermented to lactic acid and the buffering capacity of the curd during manufacturing of the cheese. Buffering capacity is determined by concentrations of undissolved calcium phosphate, caseins and lactate remaining in the cheese (LUCEY and FOX, 1993). Acid produced during early stages of cheese manufacturing will not be buffered as extensively because of higher moisture content of the curd. Acid produced later during manufacturing will be buffered to a greater extent by the higher concentration of buffering constituents. The pH of curd during whey expulsion also affects the degree of retention of the milk-clotting enzyme, chymosin, as shown in Fig. 2; lower pH values cause greater retention. This will accentuate the impact of low pH on depletion of calcium phos-