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Cheddar and Related Hard Cheeses

Stephanie Clark and Shantanu Agarwal

Washington State University, Department of Food Science and Human Nutrition, 1 Dairy Road, Pullman, WA 99164-6376, USA

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Cheddar, oh Cheddar, what could be better?
Crackers are naked not topped with a slice.
Laid on fresh bread makes a sandwich that's nice.
Waxed or canned, sharp is the best.
Omelets are bland not filled with some shreds.
Cheddar, dear Cheddar, what could be better?
Without you to eat, my meals aren't complete.
—Anonymous

24.1 INTRODUCTION

No book about dairy products is complete without a chapter dedicated to Cheddar cheese. Cheddar cheese originated in the village of Cheddar, in Somerset, England, in the nineteenth century (Banks and Williams 1997a, 2004). The term, "Cheddaring" specifies the process of piling and re-piling of blocks of warm curd into cheese vats. During the Cheddaring period of about 2 h, lactic acid increases rapidly and the proteins stretch and align, which results in the body and texture characteristic of Cheddar cheese. The first Cheddar cheese factory in the United States, other than farmhouse cheesemaking, was established in New York in 1861 (Lawrence and Gilles 1987a). The procedures for Cheddar cheese manufacture were popularized in America in 1876 by Robert McCadam, leading to the evolution of the American Cheddar cheese industry (Kosikowski and Mistry 1997a).

The United States is the largest producer of Cheddar cheese in the world. In 2001, production of Cheddar cheese in the United States exceeded 1.2 billion kg and supermarket

sales surpassed 219 million kg (IDFA 2002). Today, consumers eat approximately 4.6 kg of Cheddar cheese per capita (IDFA 2005). The greatest centers of American cheese production (including Cheddar) in 2001 were Wisconsin (1 billion kg), followed by California (723 million kg), New York (318 million kg), Minnesota (269 million kg), and Idaho (257 million kg) (IDFA 2002). Today, Idaho leads New York and Minnesota (IDFA 2005) in overall natural cheese production because of its high Italian cheese production.

Extensive modifications in Cheddar cheese manufacture have taken place with the introduction of continuous Cheddar cheese manufacturing systems in large establishments. However, regardless of advances in automation, starter cultures are always used in the manufacturing of Cheddar cheese and considerable attention is given to culture selection. The primary function of starter cultures is to produce acid during the fermentation process, but starters also contribute to cheese ripening, as their enzymes contribute to proteolysis and the formation of flavor compounds (Wallace and Fox 1997).

This chapter will describe similarities and differences among Cheddar and related hard cheeses, outline manufacturing steps involved in production, and describe technological advances in the production of cheeses in the Cheddar and Cheddar-type cheese category.

Please pass the cheese, Louise
Louise, please pass the cheese
The ham and spread
Are on the bread
I'm lacking Cheddar cheese
—Anonymous

24.2 DEFINITIONS

Cheddar cheese (FDA 2004c) is classified as a hard cheese, ranging in color from nearly white (particularly if made from goat or sheep milk) to yellow to orange (USDA 1978). Standards of identity for Cheddar include $\leq$39% moisture and $\geq$50% fat on a dry basis (FDA 2004e). Low-sodium Cheddar cheese contains not more than 96 mg of sodium per 454 g finished food.

Cheeses closely related to Cheddar include Longhorn, Colby (FDA 2004d), and Monterey Jack (FDA 2004h). Although a Cheddar is traditionally about 36.83 cm in diameter, 30.48 cm thick, and weighs between 31.75 and 35.38 kg, Longhorn is 15.24 cm in diameter (round), 33.02 cm long, and weighs 5.5 to 6 kg (USDA 1978). Longhorn is not separately defined in the Code of Federal Regulations, but it may be found commercially. Longhorn Cheddar is essentially a name that describes the round shape derived from Longhorn hoop usage during the pressing step.

Colby manufacture resembles Cheddar except that the curd is "washed" and stirred instead of matted and milled (Kosikowski and Mistry 1997a). Colby is moister, softer, and more open in texture than Cheddar. Moisture must not exceed 40% and fat in the solids must be at least 50% (FDA 2004d). Colby contains between 1.4 and 1.8% salt (USDA 1978).

Monterey, Jack or Monterey Jack cheese was first made in Monterey County, California, in 1892 (USDA 1978). Monterey is made in a similar fashion to Colby, but the procedure requires less time. Monterey contains more moisture and is softer than Cheddar and Colby (USDA 1978). Standards of identity state that Monterey must

contain not more than 44% moisture and at least 50% fat in the solids (FDA 2004h). High-moisture Jack cheese conforms to the definition and standard of identity and is subject to the requirement for label statement of ingredients prescribed for Monterey cheese, except that its moisture content is more than 44% but less than 50% (FDA 2004h). Monterey typically contains 1.5% salt (USDA 1978).

24.3 PRODUCTION OF CHEDDAR AND RELATED HARD CHEESES

Good cheese requires high-quality milk and carefully selected starter cultures. However, additional ingredients are often utilized to enhance visual appeal (annatto), coagulation properties (calcium chloride or enzymes), and flavor development (adjunct cultures or enzymes) to make great cheeses. How well the additional steps are employed determines whether or not one makes a great cheese. The following section will elaborate on individual ingredients and their function in cheesemaking.

24.3.1 Ingredients

24.3.1.1 Milk. To make high-quality cheese, producers must start with high-quality milk. Cheese quality will never be better than the starting materials. Cheddar and most Cheddar-like cheeses can be made from raw, heat-treated, heat-shocked, or pasteurized milk, nonfat milk or cream, alone or in combination (FDA 2004c). Legally, there is no distinction between raw and heat-treated/shocked milk. Because of the potential for pathogens to survive in cheese for up to 60 days, cheeses made from raw or heat-treated/shocked milk must be aged for at least 60 days at greater than 1.66°C prior to sale (FDA 2004e). Cheeses must be aged at greater than 1.66°C to ensure microbial metabolic activity and progression through the life and death cycle. Cheeses made from pasteurized milk need not be aged prior to sale. Monterey Jack cheese milk must be pasteurized because of its limited aging (FDA 2004h).

Regardless of use of heat treatment, low bacteria counts are essential for high-quality cheese, as high bacterial counts can lead to flavor and body defects. Psychrotrophic bacteria, including *Pseudomonas*, *Aeromonas*, *Flavobacterium*, *Acinetobacter*, *Bacillus*, *Micrococcus*, and other genera, can grow relatively rapidly in milk maintained at 7°C or lower (Frank and Marth 1988; Richard and Desmazeaud 2000; Banks and Williams 2004), so extended storage of milk (beyond 48 h) prior to pasteurization or cheesemaking is highly discouraged. Enzymes produced by psychrotrophs, including heat-stable lipases and proteinases, can act directly on milk proteins and lipids, reducing yield and contributing to quality defect development in the resultant cheese (Johnson 1988; Richard and Desmazeaud 2000).

Extended storage of milk prior to pasteurization and cheesemaking not only enables growth of psychrotrophic bacteria, but also encourages solubilization of colloidal calcium phosphate and a shift in caseins from the micellar to soluble state (Johnson 1988). Although soluble caseins constitute less than 15% of the total casein in normal milk directly from the udder, the proportion increases to up to 42% of total casein during storage at 4°C (Johnson 1988). Soluble calcium phosphate and casein are lost during whey drainage, which reduces cheese yield (Johnson 1988).

TABLE 24.1 Recovery of Milk Components in Cheddar Cheese.

Constituent	Percent in Cheese-Milk	Percent Recovered in Cheese
Water	87.0–88.0	4.5
Fat	3.0–4.5	92.5
Casein	3.0–4.0	96.0
Lactose	4.5–5.0	4.0
Whey protein/salts	1.2–1.8	29.0

Because approximately 90% of both fat and protein from cheese milk are captured in the cheese (Table 24.1), and these components make up 91% of the solids in cheese (Johnson 1988), detrimental effects on either component will be realized in the cheese yield and quality. Variability in milk composition is discussed in another chapter of this book. For consistency in yield and product composition, milk for Cheddar cheese is commonly standardized to a casein-to-fat ratio between 0.67 and 0.72 (Lawrence and Gilles 1987a; Banks and Williams 2004).

Somatic cells also have an impact on cheese yield. Barbano and others (1991) demonstrated that milk casein as a percentage of true protein (C%TP) and cheese yield efficiency were lower when milk somatic cell count (SCC) was high. Cheese moisture, as well as fat and protein losses in whey, increased with increased SCC (Barbano and others 1991). It was concluded that any increase in milk SCC above 100,000 cells/mL negatively affects cheese yield for milk from groups of cows with similar milk SCC (Barbano and others 1991).

Raw milk naturally contains low levels of endogenous enzymes, including alkaline phosphatase, plasmin, and lipoprotein lipase (Whitney 1988). Alkaline phosphatase (ALP) is slightly more heat stable than the most heat-resistant pathogenic microorganisms in milk. Thus, ALP is a convenient indicator of pasteurization. Indeed, the Pasteurized Milk Ordinance defines legal limits for ALP for Grade "A" pasteurized milk and bulk shipped heat-treated milk products (U.S. Department of Health and Human Services 1999 revision). ALP assays should also measure negative in cheeses made from pasteurized milk. Plasmin, which is stable at pasteurization temperature, hydrolyzes both β- and α_{s1}-casein in milk and in cheese during maturation, thus contributing to cheese maturation (Johnson 1988; Banks and Williams 2004).

The lipoprotein lipase found in milk is identical to the lipoprotein lipase in blood and represents a spillover from the mammary tissues (Weihrauch 1988). Lipoprotein lipase, if activated by severe agitation, temperature fluctuations, or other means, leads to hydrolysis of fatty acids from triacylglycerides and rancid off-flavors in milk and the subsequent cheese. Rancidity in milk may be detectable at acid degree values exceeding 1.2 meq/L (Bodyfelt and others 1988; Weihrauch 1988). Raw milk is somewhat resistant to lipase because of the protective nature of the milkfat globule membrane (Weihrauch 1988). Unlike contaminating bacterial lipases, natural milk lipase is heat labile. Heating of milk to 80°C for 20 s destroys all lipases in milk (Weihrauch 1988).

24.3.1.2 Calcium Chloride. Calcium chloride may be added to the cheese milk as a coagulation aid, in an amount not more than 0.02% (calculated as anhydrous calcium chloride) of the weight of the dairy ingredients. Addition of calcium chloride reduces

the coagulation time and increases curd firmness (Lenoir and others 2000b). Calcium added to milk is solubilized during acidification and thus lost in whey, so it does not contribute to total calcium in the final cheese.

24.3.1.3 Starter Cultures. Starter bacteria can be defined as isolates that produce sufficient acid to reduce the pH of milk to <5.3 in 6 h at $30-37^{\circ}C$, and aid in curd digestion and flavor development (Lewis 1987). Cultures selected for Cheddar cheese made throughout the world are typically "O" cultures, which are designated as cultures that produce lactic acid from lactose. The "O" type cultures are composed of *Lactococcus lactis* subsp. *lactis* and *Lactococcus lactis* subsp. *cremoris* (Harrits 1997; Strauss 1997). *L. lactis* subsp. *lactis* and *L. lactis* subsp. *cremoris* can be differentiated by their ability to grow at $40^{\circ}C$ and in the presence of salt. Whereas *L. lactis* subsp. *lactis* will grow at $40^{\circ}C$ and in the presence of 4% salt, *L. lactis* subsp. *cremoris* will not grow at $40^{\circ}C$ and will grow in the presence of salt up to a 2% concentration (Harrits 1997). The "L" type cultures consist of "O" type cultures plus the citrate-fermenting culture *Leuconostoc mesenteroides* subsp. *cremoris*, which produces flavor compounds (e.g., diacetyl) plus small amounts of carbon dioxide (Harrits 1997). "L" type cultures may also be used in the production of Colby, because an open structure is allowed in Colby (Harrits 1997). Ideally, acid should be formed quickly and at a steady rate during curd formation. Bacteriophage (phage) resistance, salt sensitivity, and protease activity (desirable flavor development) are additional selection criteria (Strauss 1997). Homofermentative starter cultures are added deliberately to initiate Cheddar cheese manufacture. The starter bacteria produce L(+)-lactate from lactose and they grow, typically attaining cell densities of 10^8 cfu/g within hours of the beginning of manufacture. L(+) refers to an optically active substance that rotates the plane of polarized light counterclockwise (also called levorotatory). The optical isomer of L(+)-lactate is D(−)-lactate. The optical isomers are mirror images of each other and result from the tetrahedral geometry around the chiral carbon center.

Production of homogeneous, high-quality Cheddar cheese requires uniform lactose fermentation, lipolysis, and proteolysis, each of which varies among bacterial strains. A relationship the exists between the extent of starter cell autolysis and the level of lipolysis during Cheddar cheese ripening (Collins and others 2003). The rate and extent of both fermentation and proteolysis depend upon temperature and salt concentration (Thomas and Pearce 1981). One of the main roles of starter bacteria is to provide a suitable environment for enzyme activity from rennet/chymosin (an acid protease) and favorable growth of secondary microflora with respect to redox potential, pH, and moisture content in cheese. Redox potential is a measure of the tendency of a system to donate or accept electrons, and indicates aerobic or anaerobic conditions. Typically, the environment inside cheese is anaerobic and reducing. Depending upon the type of culture preparation, usage rates vary between 0.75 and 1.25% for traditional bulk starter and 0.5% and 0.6% for pH controlled starter or DVS starter, respectively (Strauss 1997).

24.3.1.4 Adjunct Cultures. An adjunct culture is a one that is added, along with starter culture, for the desirable characteristics it may impart upon the cheese other than acid. Adjunct cultures are select nonstarter lactic acid bacteria (NSLAB), because not all NSLAB are desirable. Although the specific ripening mechanisms of NSLAB that contribute positively to Cheddar flavor have not been fully determined, to be successful, NSLAB adjuncts require two important features (Crow and others 2001). First, strains

must provide a balance of beneficial ripening reactions in cheese (Crow and others 2001). Secondly, strains need to be competitive against adventitious (not intentionally added) NSLAB and remain the dominant NSLAB during the ripening period (Crow and others 2001).

Lactobacillus helveticus is one species that may be added to Cheddar cheese milk for desirable cheese flavor development. *L. helveticus* species tend to be thermophilic, proteolytic, and have the ability to utilize galactose after other sugars are fermented (Harrits 1997). Because of their proteolytic capabilities, *L. helveticus* adjunct cultures have shown themselves to effectively improve the sensory quality of reduced-fat Cheddar cheese (Drake and others 1997).

24.3.1.5 Color. The recognizable yellow to orange color of Cheddar and Colby cheeses is derived from annatto, an extract from seeds of the "Lipstick tree," *Bixa orellana* (Walstra and others 1999). Annatto was first used to make cheeses appear more fat-rich, when made during seasons of the year when the milk of cows produced less colorful cheese because the cows were fed diets lower in beta-carotene. Sheep and goat milk cheeses are naturally whiter than cow milk cheeses because the beta-carotene is efficiently hydrolyzed to vitamin A in the digestive tracts of these species.

24.3.1.6 Enzymes. The Code of Federal Regulations permits the use of rennet/chymosin and/or other clotting enzymes of animal, plant, or microbial origin, as well as enzymes of animal, plant, or microbial origin, used in curing or flavor development for Cheddar cheese (FDA 2004j). Enzymes of starter, adjunct NSLAB, and adventitious NSLAB naturally contribute to flavor and body/texture development in cheeses. Kheadr and others (2003) were able to accelerate Cheddar cheese proteolysis and lipolysis using various liposome-encapsulated enzymatic cocktails. A neutral bacterial protease, acid fungal protease, and lipase were individually entrapped or mixed as cocktails and entrapped in liposomes then added to cheese milk prior to renneting (Kheadr and others 2003). Certain enzyme treatments resulted in cheeses with more mature texture and higher flavor intensity or Cheddar flavor in a shorter time compared with control cheeses (Kheadr and others 2003).

24.3.1.7 Salt. Cheddar cheese typically contains 1.6–1.8% salt (Williams and others 2000), in the form of NaCl. Salt enhances flavor, encourages syneresis, and slows or stops growth of salt-sensitive bacteria. Food-grade salt is essential to the production of safe, high-quality Cheddar cheese, and consistent salt grain size contributes to uniformity of salt concentration throughout the cheese matrix.

Investigators (Reddy and Marth 1993, 1995a,b) have demonstrated that reduced-salt, or low-salt Cheddar cheese can be made by replacing sodium chloride (NaCl) with potassium chloride (KCl) or mixtures of the two salts. Use of KCl to replace some of the NaCl for salting cheese has no detectable effect on the kinds of lactic acid bacteria, aerobic microorganisms, aerobic spores, coliforms, and yeasts and molds in cheeses when compared with control cheeses (Reddy and Marth 1993). Authors concluded that low-sodium Cheddar cheese can readily be produced without affecting its composition when one-third or more of the NaCl added to cheese curds is replaced with KCl (Reddy and Marth 1993).

24.3.1.8 Other Optional Ingredients. The Code of Federal Regulations allows the use of antimycotic agents, applied to the surface of slices or cuts in consumer-sized packages (FDA 2004a). Some of the antimycotic substances allowed by the FDA are calcium propionate (FDA 2004b), methylparaben (methyl *p*-hydroxybenzoate) (FDA

2004g), propylparaben (propyl *p*-hydroxybenzoate) (FDA 2004i), sodium benzoate (FDA 2004k), sodium propionate (FDA 2004l), and sorbic acid (FDA 2004m).

Hydrogen peroxide is allowed, if followed by a quantity of catalase preparation sufficient to eliminate the hydrogen peroxide. The weight of the hydrogen peroxide shall not exceed 0.05% of the weight of the milk (FDA 2004f) and the weight of the catalase shall not exceed 20 ppm of the weight of the treated milk (FDA 2004c).

24.3.2 Preparations for Cheesemaking

24.3.2.1 Culture Selection and/or Propagation. Culture quality is of the utmost importance in the production of high-quality cheese. Culture manufacturers commonly work closely with processing facility operators to effectively meet specific needs. Culture manufacturers continuously develop unique culture combinations for a given product. Several types of culture forms are available, including

1. Liquid (for propagation of mother culture; rarely used today);
2. Deep-frozen concentrated cultures (for propagation of bulk starter);
3. Freeze-dried concentrated cultures in powder form (for propagation of bulk starter or DRI-VAC, for preparation of mother culture); and
4. Deep-frozen or freeze-dried, superconcentrated cultures in readily soluble form for direct inoculation of the product (direct vat set, DVS).

The availability of frozen or freeze-dried cultures eliminates the need for small dairy plants to make cultures or operate a culture room (Lewis 1987). The culture room is a separate room in the dairy plant reserved for preparation and propagation of starters and an important element in production of quality cheese because it limits opportunities for contamination by airborne yeast, mold, and bacteriophage (Lewis 1987). Bacteriophage (phage) are viruses that infect specific strains of bacteria, which stresses the importance of utilizing mixed-multiple strains and starter culture rotation in cheesemaking. Proliferation of phage will result in a failure of lactic acid production, termed "stuck vat," necessitating strict sanitation and whey-handling practices to keep phage numbers to a minimum. Larger plants are typically supplied with frozen or freeze-dried cultures for the manufacture of bulk starters in aseptic bulk culture rooms (Lewis 1987). Cooling and storage conditions and shelf-lives of cultures vary. Generally, deep-frozen and freeze-dried cultures can be stored for 9–12 months at $-18^{\circ}C$ and $-45^{\circ}C$, respectively (Lewis 1987). Maintenance of consistency across cheese lots requires constancy of culture handling.

24.3.2.2 Cheese Milk Pretreatments. Centrifugal clarifier-separators are used to separate the cream and skim fractions, as well as remove solid impurities from milk prior to standardization. Cheese milk fat and protein content are commonly standardized for consistency of yield and composition. Fat may be increased with the addition of cream, and protein, particularly casein, may be increased with nonfat dry milk, skim milk, or condensed skim milk (Johnson 1988). A typical casein-to-fat ratio of between 0.67 and 0.72 may be used (Lawrence and Gilles 1987b; Banks and Williams 2004). Although cheese moisture is influenced by numerous factors during cheesemaking, higher fat levels in cheese milk are typically associated with lower moisture cheeses (Lawrence and Gilles 1987b). As a general rule, an increase of 0.05 in the casein-to-fat ratio in milk generally

results in a decrease of about 1.4% in the fat on a dry basis and an increase of about 0.8% in moisture in Cheddar cheese (Lawrence and Gilles 1980).

Most commonly in the United States, whole milk is preheated to 55–65°C in the regeneration section of the high-temperature short time (HTST) pasteurizer prior to separation. Following separation, the cream is standardized to a preset fat level and the fraction intended for standardization of milk is routed and remixed with the proper amount of skim milk to attain the desired fat and protein content. The surplus cream is directed to a separate cream pasteurizer, and the standardized milk flows through the pasteurizer.

El-Gazzar and Marth (1991) recommended the use of ultrafiltered milk for conversion into such cheeses as Cheddar, cottage, havarti, feta, brick, Colby, and Domiati because of an increase in yield of product. Ultrafiltration results in the concentration of milk proteins, with reduction in lactose and mono- and divalent cations. Additional benefits claimed for use of ultrafiltered milk in cheesemaking include reduction in costs of energy, equipment, and labor, improved consistency of cheese flavor, and the potential production of new byproducts (El-Gazzar and Marth 1991).

24.3.2.3 Homogenization. Although homogenization of cheese milk is typically not employed in the production of Cheddar cheese, research has shown that homogenization of cream may have applications to Cheddar cheese. Homogenization is most efficient when fat globules are in the liquid state, so milk is preheated in the plate heat exchanger in the regeneration section of the HTST pasteurizer, where the temperature is raised to at least 60°C prior to homogenization (Morr and Richter 1988). In a two-stage homogenizer, pressures typically range from 10 to 25 MPa in the first stage and 5 MPa in the second stage.

In a study with Cheddar cheese standardized to a casein-to-fat ratio of 0.70, Nair and others (2000) demonstrated that cheese hardness was not influenced by homogenization, and cheeses with homogenized cream had improved body and texture and flavor over controls. Cream homogenized at 6.9 MPa (first stage) and 3.5 MPa (second stage) was optimal for enhancing Cheddar cheese yield and functionality (Nair and others 2000). Metzger and Mistry (1994) demonstrated that cheese moisture and yield were higher in reduced-fat Cheddar cheeses made with homogenized cream than controls. The body and texture of reduced-fat Cheddar cheeses made from homogenized cream were improved over those for the control cheeses, which were hard, rubbery, and curdy (Metzger and Mistry 1994).

24.3.2.4 Pasteurization. The only step in the dairy processing system that guarantees the killing of pathogenic microorganisms is pasteurization. Thus, pasteurization may be considered the most critical segment of the cheese processing line. An added side-benefit of pasteurization is that it also kills many spoilage microorganisms and inactivates enzymes that may contribute to quality defects in cheese. Pasteurization contributes to consistency in product quality. Of course, strict sanitation is critical up to and beyond pasteurization to assure the safety and quality of dairy products. In HTST pasteurization, milk must be held at a temperature of at least 72°C for a minimum of 15 s to be legally pasteurized (U.S. Department of Health and Human Services 1999 Revision). In batch or low-temperature long time (LTLT) systems (uncommon in large-scale operations), milk is continuously agitated in a single tank, at a set temperature (legally at least 62.8°C) for a given time (legally at least 30 min if at 62.8°C) to guarantee inactivation of pathogens (U.S. Department of Health and Human Services 1999 Revision). Any lower temperature or shorter time than legal pasteurization means the cheese must be treated as if made from raw milk, which means products must be aged for at least 60 days at 1.66°C or higher.

Regardless of pasteurization method, cheese milk is then cooled, either to incubation temperature for selected starter cultures, or to refrigeration temperature for future applications.

Although all pathogens and most spoilage microorganisms are killed by pasteurization, potentially beneficial or flavor-producing microorganisms are also killed. And so, although cheeses made from pasteurized milk are safe, they also have less flavor than raw milk cheeses. Buchin and others (1998) studied the effects of pasteurization and fat makeup of experimental semihard cheeses with two different fat compositions. The raw-milk cheeses had more intense flavor and volatile compounds than the pasteurized milk cheeses. Raw-milk cheeses were characterized by higher amounts of numerous alcohols, fatty acids, and sulfur compounds, and pasteurized-milk cheeses were characterized by higher amounts of ketones (Buchin and others 1998). The differences were attributed to the high level of indigenous microflora in raw milk cheeses (Buchin and others 1998).

In addition to modifying milk microflora, pasteurization acts upon milk protein chemistry to influence cheese quality. Specifically, pasteurizing cheese milk influences the extent and characteristics of proteolysis during Cheddar cheese aging (Lau and others 1991). Pasteurization causes heat-induced precipitation of whey proteins upon casein micelles that results in retention of additional whey protein in the cheese beyond that which is soluble in the aqueous phase of raw-milk cheese. The presence of heat-denatured whey protein in cheese may influence the accessibility of caseins to proteases during cheese aging, a consequence of which would be differences in proteolysis during aging. These differences may be another factor that contributes to differences in flavor development in Cheddar cheese made from pasteurized and raw milk (Lau and others 1991). Temperatures higher than legal pasteurization (80°C) may be used to increase yield; however, gelling takes longer, the firming rate of the gel as well as its maximum firmness are reduced, and gel draining is more difficult and is incomplete (Lenoir and others 2000b). These factors are a consequence of denatured whey proteins, particularly β-lactoglobulin, which bind with caseins, particularly κ-casein. Indeed, a complex between β-lactoglobulin and κ-casein leads to modification in the conformation of the κ-casein chain at the chymosin cleavage site, detrimentally affecting coagulation properties (Lenoir and others 2000b). Denaturation of whey proteins is negligible at pasteurization temperatures, but reaches 10% after a treatment of 75°C for 15 s and 20% after 85°C for 30 s (Lenoir and others 2000b). Heat also decreases soluble calcium, ionized calcium, and soluble inorganic phosphorus (Lenoir and others 2000b).

24.3.3 Cheesemaking

A schematic diagram outlining the steps of cheesemaking, from fresh milk through aging cheese is shown in Figure 24.1. In large automated plants, cheesemaking is typically held to a well-timed schedule. Culture, $CaCl_2$, and color are typically added as cheese milk enters the cheese vat, after pasteurization and cooling. Chymosin is commonly added after the vat is completely filled with pasteurized milk. In pilot or small-scale operations, culture, $CaCl_2$, and color are commonly added when an entire vat of cheese milk reaches target temperature. Chymosin is added after a ripening period of 15–30 min.

24.3.3.1 Calcium Chloride Addition. If $CaCl_2$ is to be added to the cheese milk, typically 0.2% of cheese milk weight is adequate to improve coagulation properties (Kosikowski and Mistry 1997a; Lenoir and others 2000a).

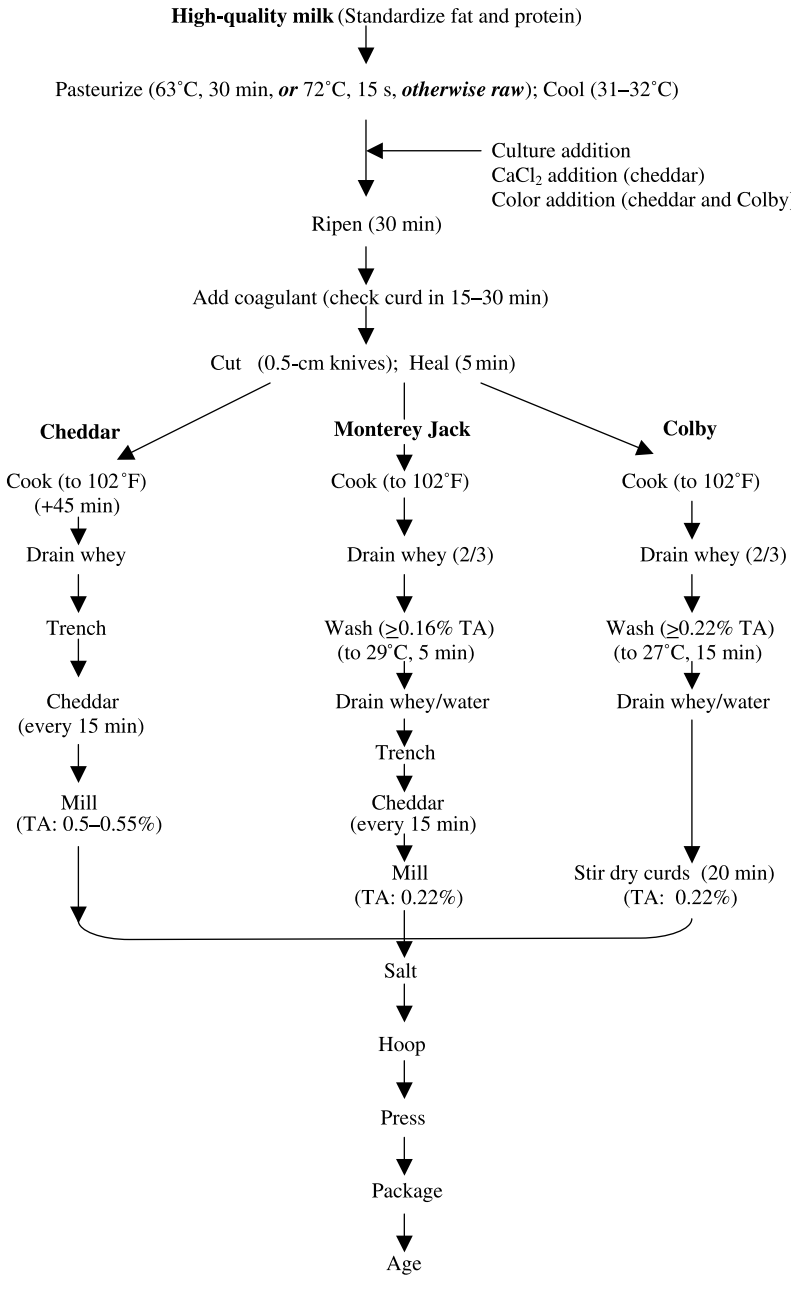


Figure 24.1 *Schematic of the steps in cheesemaking.*

24.3.3.2 Color Addition. Annatto may be added to cheese milk at a rate of approximately 66 mL per 1000 kg of milk, adjusted to desired product color (Kosikowski and Mistry 1997b). Annatto binds with protein to form a straw to orange color in the final cheese, upon a concentration that occurs with whey expulsion (syneresis).

24.3.3.3 Culture Addition. Prior to culture addition, raw or pasteurized milk must be tempered to the appropriate temperature for starter culture multiplication, approximately 26–30°C for Cheddar and related cheeses (Banks and Williams 2004). Inoculum level is defined by culture manufacturers, based upon whether the culture is DVS or bulk culture, typically from 0.5 to 5%. Cheese manufacturers may increase or decrease the amount of culture based on seasonal variation in milk composition (Lawrence and others 1999). Optional addition of adjunct culture typically varies from 0.1 to 1%.

24.3.3.4 Ripening. The titratable acidity (TA) of fresh milk is approximately 0.14–0.18, depending on composition, and pH is about 6.6–6.8. When starter culture is added, cultures need time to equilibrate to their environment (lag phase), so only a small rise in TA is noted during the 30-min ripening period. Little lactose is converted to lactic acid during the lag phase of the cultures, but TA rises steadily during the log phase of growth, during which time culture numbers increase exponentially. Even after lactic acid formation begins, little change in pH is noted because of milk's high buffering capacity, owing to the presence of proteins, citrate, and phosphate in milk.

24.3.3.5 Enzyme Addition. In fresh fluid milk, charges on the κ-casein "hairs" are negative (−), so casein micelles repel each other. With the production of acid, the charges on some κ-casein hairs begin to change to positive (+). When pH declines to near 5.2, calcium and phosphorus are solubilized and the micelle structure changes (Brulé and others 2000). At pH close to 4.6, coagulation occurs, as repulsive charges are neutralized and micelles come into contact with one another and coalesce (Brulé and others 2000). Some cheeses are made exclusively with acid coagulation (e.g., cottage cheese). Because acid development is slow, cheese make procedures that rely entirely on acid coagulation are in the order of 10–18 h in length. The cheesemaking process is accelerated by the use of coagulating enzymes.

Chymosin, originally derived from the abomasum of milk-fed calves, but now microbially or fungally derived, is the most common coagulating enzyme used in the manufacture of Cheddar and related varieties (Ramet 2000b). Chymosin is an acid protease, which means that it is more active at an acid pH than neutral or basic pH. Highest activity is observed at pH 5.5 and 42°C (Ramet 2000b). Specifically, chymosin cleaves the peptide bond Phe105–Met106, which leads to the formation of κ-para-casein (l-105) and glycomacropeptide or caseinomacropeptide (CMP, 106–169) (Brulé and others 2000). CMP is soluble in whey. When chymosin is added to milk, coagulation occurs in three steps:

1. κ-Casein hydrolysis,
2. Aggregation of destabilized micelles, and
3. Reorganization of calcium phosphate, or reticulation (Brulé and others 2000).

The coagulation process is shortened because rennet/chymosin cleaves the negatively-charged κ-casein hairs off the micelles, enabling approach and coagulation of micelles. During the coagulation process, calcium phosphate bridges form between micelles, and tighten as whey is expelled, forming a tight network of casein, which entraps some fat, water, and water-soluble components. As fermentation proceeds, Ca^{2+} are replaced by H^{+} and the casein network continues to tighten.

Approximately 5–50 mL of single-strength liquid chymosin should be used to coagulate 100 L milk (Brulé and others 2000). Chymosin should always be diluted (approximately 1 part to 40 parts water) prior to addition to the cheese vat to prevent localized coagulation. Dilution should always be done with cool (or room temperature) water immediately before adding to milk. Chymosin begins to lose its strength and activity immediately upon dilution, which is why dilution should not be done in advance. Also, chymosin is degraded by high temperatures and chlorine. Chymosin must not be overmixed into the milk because cleavage of κ-casein from casein micelle proteins begins immediately. In small operations, chymosin should only be mixed into milk for about 1 min to maximize yield. During the incubation period, the cheese vat must not be agitated or disturbed in any way, or a soft or weak curd will result and yield will be affected.

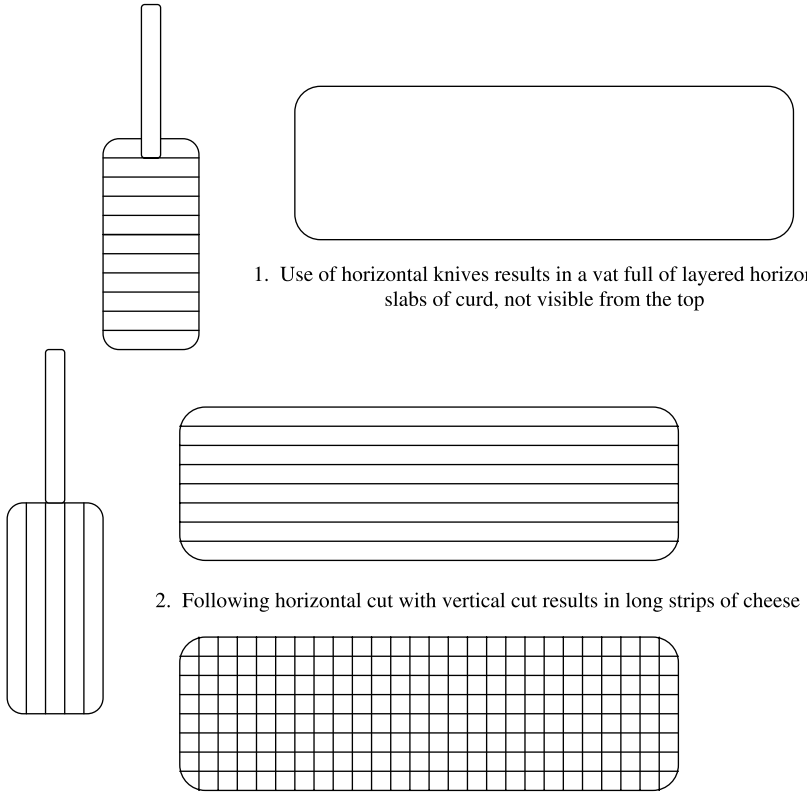
Chymosin is allowed to set the cheese for 20–30 min prior to curd testing. In large automated plants, the curd is typically not checked, and cutting begins at a set time. To check the curd, a spatula or knife may be used. A spatula works best for checking curd set because of its rounded shape. The blade is cut through the curd in a 5-cm vertical orientation and removed. The blade is then inserted at the bottom of the vertical cut, in a horizontal orientation, to form a T. The blade is pushed forward and lifted, to encourage the curd to split open. The curd is ready for cutting when the curd is firm, it breaks cleanly, and fills with clear yellow (not cloudy) whey.

24.3.3.6 Cutting. Cutting of the curd is an extremely important step in the cheesemaking process because it influences whey drainage and cheese yield (Ramet 2000a). Cutting to a consistent size, with sharp knives, is critical to minimize small curd particles (fines) that may get lost during whey drainage (Ramet 2000a). Manually, the coagulated mass of cheese is cut with harps: knives constructed of stainless steel hardware and wire spaced at regular intervals. The wires on one harp are horizontally oriented, and the other harp wires are vertically oriented. The cutting progresses in such a way that first horizontal and vertical sheets of curd are cut with the harp knives. The sheets are then cut into cubes by perpendicular cuts with the vertical harp knives (Fig. 24.2).

Large dairy plants have automated cheese vats that vary in size from 2000 to 25,000 L capacities. These cheese vats are equipped with a shaft to which agitators are attached. These agitators are designed in such a way that they cut the cheese when the shaft rotates in one direction and agitate the cubes gently when the shaft rotates in the other direction. Cheese vats are automated and allow the cheese curds to heal and cook before pumping the curds and whey onto a perforated conveyer belt where cheese curd is separated from the whey.

A schematic diagram of cheesemaking from cutting through cooking steps is shown in Figure 24.3. Cutting the coagulum increases the surface area of the curd and enhances syneresis. Upon cutting, curd particles immediately begin to expel whey and shrink, and the TA that had been rising in the cheese milk immediately drops in the whey, because the whey has lower apparent acidity, due to lower protein, citrate, and phosphate. The TA of whey will gradually increase as lactic acid is formed in the curds and released with whey during syneresis.

24.3.3.7 Healing. Freshly cut curd is fragile and shatters easily, so curds are allowed to "heal" for 5–10 min prior to agitating and cooking. A healing period is particularly important when goat Cheddar cheeses are made, because the curds are naturally more fragile than curd obtained from cow milk. During healing, a tender skin is formed



1. Use of horizontal knives results in a vat full of layered horizontal slabs of curd, not visible from the top

2. Following horizontal cut with vertical cut results in long strips of cheese

3. Only after the vertical sharp knife is used perpendicularly across the previous cuts will cubes be made out of the curds, enabling optimal syneresis

Figure 24.2 *Cutting of the curd.*

around each freshly cut curd. As the skin firms, the curd becomes more resistant to shattering and yield losses.

24.3.3.8 Cooking. The cooking process is essentially a controlled increase in curd–whey temperature. Heating allows individual curd cubes to shrink, release whey, and firm. Cooking also increases reaction rates, specifically bacteria growth and metabolism, and enzyme activity. Temperature-sensitive bacteria strains are slowed down as temperature is raised. Prior to raising the temperature of the curd–whey mixture, curds should be gently eased from the edges of the cheese vat, where they have matted. Curd cooking should begin slowly, with continual stirring of the curds. Hot water or steam may be used to increase the jacket temperature. The curd–whey mixture temperature should be raised slowly, about 2°C every 5 min until 38°C is reached (~35–45 min). Stirring speed may be increased as the curds firm, but stirring too fast will shatter curds and reduce yield. For a drier cheese, temperature should be held at 38°C for an additional 45 min, with stirring. In small or start-up facilities, whey TA should be recorded every 15 min. Regardless of plant size, good records should be kept of the entire cheesemaking procedure and final cheese quality. Failure to keep such records will reduce consistency.

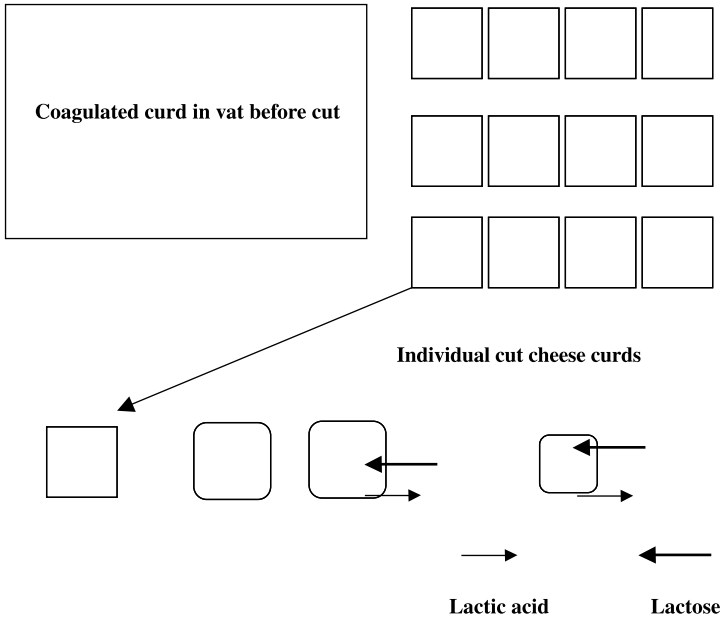


Figure 24.3 *Schematic of cheesemaking steps from cutting through cooking.*

For a short period after the curd is cut, lactose and lactic acid concentrations are at equilibrium in curd and whey. With time, the concentration of lactose drops faster in the curd than in the whey because starter bacteria concentrated in the curd deplete lactose in the curd (Fig. 24.3). As the lactose is fermented within the curd, replacement lactose diffuses into the curd from the whey (Fig. 24.3, broad arrows) (Lawrence and Gilles 1987a). As a neutral molecule, lactose diffuses easily through the matrix. Positively charged hydrogen ions exit the negatively charged curd much more slowly than lactose (Fig. 24.3, narrow arrows). As fermentation progresses, hydrogen ions are neutralized by the negatively charged proteins and phosphates. As the buffering capacity of the caseins and colloidal calcium phosphate (CCP) becomes saturated, the pH of the curd steadily drops. As pH drops, CCP is solubilized and lost into the whey.

Once cheesemaking starts, managing acid development during the cooking stage of cheese manufacture is the most important factor in the control of cheese quality (Lawrence and Gilles 1987a). Acid development determines the basic structure, moisture, final pH, and flavor of cheese (Lawrence and Gilles 1987a). As the pH drops, the body of the cheese changes from rubbery (pH 5.4) to plastic (pH 5.3–5.2) to Cheddar (pH 5.1–5.0) body and texture. When the vat TA rises too quickly, the curd will suffer an excessive loss of calcium but will not retain phosphate. The result is an increase in curd buffering capacity (Lawrence and Gilles 1987a). However, should a high TA result from an extended time between cutting and cheddaring, both calcium and phosphorus are lost in the whey (Lawrence and Gilles 1987a). The resultant cheese will have a low pH, an acid flavor, and a weak, pasty texture (Lawrence and Gilles 1987a). An objective for cheesemakers it to develop acid slowly during ripening and cooking, and more quickly during cheddaring, so that calcium phosphate is retained in the curd, as the loss of CCP alters the body and texture of the cheese (Lawrence and Gilles 1987a). Curds shrink and tighten as syneresis proceeds during the cooking process, prior to whey drainage. Approximately

75% of the whey in the curd is expelled in the time from cutting to the end of stir out. Longer stir-out times can significantly reduce moisture in cheese.

24.3.3.9 Draining. Whey may be drained entirely, in the case of Cheddar, or partially, with washing, as in the case of Colby or Monterey. In large plants, a cleaned and sanitized finishing table/vat may be aligned with the exit port of the cheese vat. The drain of the vat is opened and curds and whey are allowed to flow onto the finishing table. Alternatively, in small plants, the cheese vat may double as a finishing table. A screen is installed ahead of the finishing table drain port to prevent curd loss as the whey is drained. Whey is commonly collected in a separate reservoir.

Cheese curds should be allowed to settle into the vat or finishing table, at an even depth throughout the length, and permitted to mat for 15 min. Whey TA will rise more quickly during this interval and should be recorded every 15 min from this point forward, throughout the cheddaring process. In the largest plants, curds are delivered to a perforated conveyer belt for drainage and cheddaring, which allows formation of a sheet of curd and continuous whey drainage. The conveyer is enclosed in a tunnel. Upon drainage, in the absence of the whey bath, the curd pH will drop at a faster rate and the curds will continue to shrink and tighten. Much of the calcium is lost at drainage, particularly at low pH.

24.3.3.10 Washing. Washing is essential in Colby and Monterey production. Washing, or curd rinsing, removes lactic acid and residual lactose and lactic acid from the curd and the result is a higher pH in the final cheese. Washing is rarely included during Cheddar cheesemaking, but when it is, the duration of such rinsing is so limited that only the whey on the surface of the curds is removed (FDA 2004c).

In Colby and Monterey production, whey is drained off until the curd on the bottom of the vat is visible, then sufficient cold water is introduced to reduce the temperature of the curd–whey mixture to 27°C (Lawrence and Gilles 1987a). Rate of syneresis is slowed if cool water used, resulting in higher cheese moisture content. Long wash time removes more lactose, resulting in higher final pH of cheese. Temperature-sensitive strains may be revived if cool water used.

24.3.3.11 Cheddaring. The step known as "cheddaring" was standardized into commercial practice by Joseph Harding in 1857 (Kosikowski and Mistry 1997a). During manual cheddaring, curds are flipped and stacked at regular intervals, naturally pressed under their own weight, which enhances syneresis, yet still maintains a controllable level of moisture retention. The main purpose of cheddaring is to allow time for the acidity to increase and whey to be released (Lawrence and Gilles 1987a). Curd particles fuse into a solid mass, syneresis continues as acid builds, rennet/chymosin continues to act, and these forces cooperate to tighten the casein network. As lactic acid continues to build, curds begin to flow or stretch under the weight of piled slabs. Cheddar gains its characteristic body through the process of knitting, stretching, and orientation of the casein network during cheddaring, which requires a pH below 5.8 (Lawrence and Gilles 1987a).

In manual operations, after the cooking step is completed and curds are allowed to settle for 15 min, matted curd should be trenched, then cut into equal-sized slabs. A wide (20–30-cm) trench is made in the center of the vat to facilitate syneresis and curd stretching. Slabs should be separated as they are cut, to enable syneresis and stretching. Extra or broken curd should be placed on top of each slab, to minimize loss of fines. Slabs should be allowed to settle 15 min before the next step.

Cheddaring begins with flipping of slabs, one by one. The bottom becomes the top and the end toward the trench becomes the end toward the vat wall. Slabs should be allowed to settle 15 min before each subsequent step. The next step of cheddaring involves the flipping of one slab, followed by placing of an adjacent slab on top of the flipped slab (without flipping). This step is called "flip–stay." The process continues for every pair of slabs. After 15 min, the top slab is placed (not flipped) into an empty spot in the vat. The previous bottom slab is then flipped and placed atop the new bottom slab. This step is called "stay–flip." Cheddaring continues with flipping and stacking of slabs, alternating between "flip–stay" and "stay–flip" steps, until a whey TA of 0.35% as lactic acid is measured in a fresh sample of whey. In large plants, the process of cheddaring is automated. As the perforated conveyor mentioned previously transects a number of parallel planes during the approximately 90-min cheddaring process, the matted curds are flipped and stretched continuously in a tumbling motion.

24.3.3.12 Milling. Milling is the process of cutting the slabs into cubes about 5 cm in size, which enables more uniform salt distribution, encourages syneresis and makes hooping more convenient (Lawrence and Gilles 1987a). When curds are milled, more whey is expelled because milling greatly increases curd surface area and opens pores for syneresis. Salt distribution will be most uniform in cheese if curds are milled to a uniform size (Lawrence and Gilles 1987a). In large plants, as the mat of curd arrives at the discharge point of the perforated conveyer, it is cut to desired size in a reciprocal dice-type mill or rotary curd mill.

24.3.3.13 Salting. Milled curds of Cheddar and related hard cheeses are dry-salted rather than brine-salted. Cheese is salted because it:

1. Encourages further syneresis,
2. Inhibits further growth and metabolism of most microorganisms (thus arresting lactic acid production), and
3. Provides flavor.

Approximately 2.5 kg salt for every 100 kg of cheese curd is used. The salt is added in three equal applications and mixed for 5 min between applications. Adding salt too quickly will cause a "skin" to form on the curds, inhibiting salt absorption and syneresis. In large plants the milled cheese quantity is determined continuously by weight prior to entering the salting machine. The salter automatically calculates the salt and sifts it over the milled cheese. The pH and TA will only change slightly beyond the point of salt addition.

Salt, more specifically salt in moisture (S/M), directly influences the final pH of the cheese, growth of microganisms and overall flavor, body, and texture of cheese (Lawrence and Gilles 1987a). At S/M levels greater than 5.0, bitter flavors rarely occur (Lawrence and Gilles 1987a). Curd salted at low TA retains more salt (higher S/M) and is more plastic than curd salted at high TA (Lawrence and Gilles 1987a).

24.3.3.14 Pressing and Packaging. Pressing gives cheese its final shape, reduces openings between curd particles, promotes fusion, and releases more free whey. In small plants, Cheddar curds are pressed overnight using a batch method (Lawrence and Gilles 1987a). Pressure, approximately 1.4 atm, is applied to molds for 8–12 h at room

temperature. After one or two hours of pressing, cheeses may be flipped in the molds and lined with cheesecloth, which provides an attractive surface pattern. Large plants have a continuous "block-former" system (Lawrence and Gilles 1987a). Curds are fed into a tower under a partial vacuum, whey is siphoned off, and for a short period, mechanical pressure is applied at the base of the tower prior to packaging (Lawrence and Gilles 1987a; Banks and Williams 2004). A block former cuts 20-kg blocks from the stack at regular intervals and the blocks are transferred to a vacuum packaging system prior to aging (Banks and Williams 2004).

24.3.3.15 Aging. Aging enables flavor and texture development of hard cheeses. Nearly all residual lactose should be fermented within about 48 h. With cold storage, between 5 and 12°C, acid production slows down, but continues until limiting conditions occur (Banks and Williams 2004). Starter bacteria lyse (burst) and release proteolytic enzymes into the matrix. Residual plasmin and coagulant also contribute to proteolysis during aging. Caseins are broken down into peptides and amino acids, which yield flavor and modify cheese body/texture. Secondary fermentations can occur if NSLAB are still active, which results in further changes in flavor and body/texture. Cheeses with low S/M have a higher rate of proteolysis, resulting in a softer texture, than cheeses with high S/M (Lawrence and Gilles 1987a).

Cheddar cheese is typically aged for 3–18 months at 7–13°C, but it is not unheard of to age Cheddar for years in the case of specialty varieties (Banks and Williams 2004). Colby and Monterey are aged for shorter periods of time due to their higher moisture content and milder expected flavor.

24.4 QUALITY CONTROL

24.4.1 Shelf-life

The shelf-life of Cheddar and related cheeses is limited by quality, not safety. The quality of good Cheddar cheese improves with storage. Cheddar cheese may be removed from shelves due to flavor, body, or appearance defects. The most common flavor defects are high acid, bitter, unclean, and fermented/fruity. Common body defects are weak or crumbly body, gas holes, surface discoloration, and appearance of crystals on surfaces.

24.4.2 Evaluation

High-quality Cheddar cheese has a full, balanced nutty, sharp, but not bitter flavor. The ideal texture should be closed (no gas holes or mechanical openings), and the body should be firm, smooth and waxy (responds to moderate pressure). Colby and Monterey/Jack cheeses are similar to Cheddar, but are milder in flavor and possess a softer body. Colby and Monterey/Jack are prone to the same defects as Cheddar. However, due to higher moisture content, lower acid and salt, and higher microbial and enzymatic activity, some sensory defects may reach greater intensity and frequency in Colby and Monterey/Jack cheeses than Cheddar, particularly with extended aging.

Gas liquid chromatography (GLC) analysis of Cheddar cheese has shown that there are as many as 200 different compounds that may contribute to cheese flavor. However, flavor chemists believe that as few as 20 volatile compounds are pertinent to determination of the eventual flavor of Cheddar cheese. Cow diet, milk handling and sanitation

TABLE 24.2 Common Flavor Attributes in Hard Cheeses, Identification of Them and Their Probable Causes.

Flavor	Identification	Probable Cause
Bitter	Sometimes perceived as throbbing/piercing Sensation perceived at back of tongue Very common defect in aged Cheddar	Excessive moisture Low salt Excessive acidity Proteolytic starter culture strains Microbial contaminants Poor quality milk Plant sanitation issues
Feed	Grassy flavor	Feeding of strong flavored feeds Feeding of cattle too close to milking
Fruity/fermented	Sweet – like pineapple	Psychrotrophic *Pseudomonas fragi* may produce ethyl-butyrate and ethylhexanoate (esters) Low acidity Excessive moisture Low salt level Poor milk quality
Flat/lacks flavor	Lacks nutty flavor components Lacks typical Cheddar flavor	Lack of acid production Use of milk low in fat Excessively high cooking temperature Use of low curing temperature Too short a curing period
Heated	Sweet – like cooked flavor Reminiscent of Velveeta®	High pasteurization or cooking temperature
High acid	Excessive acid taste Unbalanced acid taste	Development of excessive lactic acid Excessive moisture Use of too much starter culture Use of high-acid milk Improper whey expulsion from curd Low salt level
Oxidized	Paperboard/cardboard Sometimes discoloration also Burnt hair aroma/flavor	Use of oxidized milk in cheesemaking Excessive exposure to UV light during aging
Rancid	Butyric, caproic, caprylic, capric acids Soapy Romano cheese aroma/flavor Baby vomit aroma	Milk lipase activity Microbial lipase activity (from contaminants) Accidental homogenization of raw milk Late lactation or mastitic milk
Sulfide	Eggy	Excessive breakdown of amino acids Only a defect when excessive for age of cheese
Unclean	Unpleasant off-flavor lingers	Microbial contamination Poor quality off-flavored or old milk Allowing off-flavored cheese to be aged Improper techniques of cheddaring
Whey taint	Combination of acid, bitter, fermented Aftertaste does not linger like unclean	Poor whey expulsion from curd Improper cheddaring techniques Failure to drain whey from piles of curd slabs
Yeasty	Ethanol aroma Yeast (bread, beer) aroma	Development of ethanol flavors by yeast contaminants Poor packaging procedures

TABLE 24.3 Common Appearance, Body and Texture Attributes in Hard Cheeses, Identification, and Their Probable Causes.

Body/Texture	Identification	Probable Cause
Corky	Dry, noncompressible Often crumbly as well	Lack of acid development Low fat
Crumbly	Falls apart while working	Excessive acid production Low moisture retention in cheese
Crystals	White crystals observed by visual examination	Tyrosine (only in aged cheese), calcium lactate, calcium citrate, calcium phosphate
Curdy	Resistant to compression	Inadequate aging conditions
Gassy	Smooth round gas holes	Contamination of cheese with CO_2-forming microorganisms
Mealy	Grainy (like corn meal)	Excessive acid production Formation of salt complexes
Open	Openings along curd lines	Improper mechanical pressing, lack of fusion between curds
Pasty	Sticky when working between fingers	High moisture retained by curd Excessive acid production
Short	Plug breaks quickly (snaps)	Excessive acid production
Weak	Plug is resistant to breaking (bends)	High moisture in cheese Excessive proteolysis

practices, milk composition, and cheese manufacturing conditions all affect cheese chemistry (Buchin and others 1998). What appears to be critical is the relative proportions of the key chemical flavor compounds in providing "balanced Cheddar flavor". Ammonia-like and sulfur-like odors and bitter taste typically occur in aged cheeses, a consequence of amino acid breakdown. Common flavor attributes encountered in Cheddar and related cheeses are included in Table 24.2. Although some attributes, such as sulfide, may be considered desirable in an aged cheese, mild cheeses are discredited for pronounced attributes.

In addition to flavor attributes, consumers look for certain functional properties in cheese (melting, grinding, slicing). Cheeses continually change during ripening, not only in flavor, but also in body/texture. Common body/texture attributes encountered in Cheddar and related cheeses are included in Table 24.3.

24.4.3 Safety

Cheddar cheese and other semihard cheeses are generally considered safe and have rarely been associated with foodborne illness outbreaks (Wood and others 1984; Johnson and others 1990; El-Gazzar and Marth 1992; Leyer and Johnson 1992). However, some pathogens can survive the cheesemaking process and during ripening. Hargrove and others (1969) demonstrated that cheese pH, rate and amount of acid produced during cheesemaking, and type and amount of starter inoculum all influence growth and survival of salmonellae in Colby and Cheddar cheeses. Raw-milk Cheddar cheese was linked to major salmonellosis outbreaks in Canada in 1982, 1984, and 1998 (Wood and others

1984; D'Aoust and others 1985; El-Gazzar and Marth 1992; Ratnam and others 1999). *Salmonella* can survive in ripening Cheddar cheese for 7–10 months (Wood and others 1984; El-Gazzar and Marth 1992). Additionally, Ryser and Marth (1969) showed that *L. monocytogenes* can survive as long as 434 days in Cheddar cheese ripened at temperatures above 1.66°C. These facts highlight the importance of using the highest quality milk and good manufacturing practices, including strict sanitation and handling procedures to prevent contamination and ensure cheese quality and safety.

24.5 TROUBLE-SHOOTING

Although poor-quality milk will always result in poor-quality cheese, even use of high-quality milk does not guarantee high-quality cheese. This section will summarize factors that influence cheese curd formation and crystal formation in Cheddar cheese.

24.5.1 No Curd or Weak Curd Formation

A weak curd can result from at least one of two main factors, namely low starter numbers or poor chymosin activity. The following factors influence the starter and chymosin activity: presence of natural inhibitors or antibiotics in the milk, residual cleaners/sanitizers on equipment, or the presence of bacteriophage in cultures or in the environment. Each factor will be discussed separately. Operator error is another reason for no curd formation. The bottom line is that personnel must be adequately trained to (1) measure appropriate levels of culture and coagulating enzyme to be added to cheese milk and (2) actually add the ingredients to the cheese milk.

24.5.2 Natural Inhibitors

Natural inhibitors in milk include lactenin L_1, L_2, and L_3, and the enzymes lysozyme and lactoperoxidase. Lactenin varies with individual animals and is inactivated by heat treatment (Desmazeaud 2000). Lysozyme attacks the glycosidic bonds found in Gram-positive bacterial cell walls, but it is unlikely to cause inhibition of lactic acid starter bacteria (Jensen 1995; Desmazeaud 2000). When supplied with hydrogen peroxide (from lactic acid bacteria in the presence of oxygen) and thiocyanate (arises from catalysis of thiosulfate or glucosides in liver), lactoperoxidase will catalyze the formation of lactococci bacteriocides (Ruden 1997), including bacteriocides that attack lactococci. Therefore, this method of preserving milk in areas with limited access to refrigeration is inappropriate for handling cheese milk. Mastitic milk naturally contains higher levels of leucocytes, which will also engulf and destroy lactic cultures (U.S. Department of Health and Human Services and others 1999 Revision).

24.5.3 Antibiotics

Every tanker load of milk must test negative for the presence of beta-lactam antibiotics (Desmazeaud 2000), however cultures can be inhibited by the presence of antibiotics at levels even lower than detectable by standard dairy lab testing methods. Lactic cultures can be inhibited by as much as 50% by 1.91 μg cloxacillin, 0.13 μg tetracycline,

0.59 μg streptomycin and as little as 0.12 μg of penicillin per mL milk (Desmazeaud 2000). Thermophilic bacteria are more resistant to streptomycin and more sensitive to penicillin than mesophilic starters (Ruden 1997).

24.5.4 Residual Cleansers/Sanitizers

Residual cleansers/sanitizers can slow a cheese vat precisely because they are intended to kill microorganisms. Quaternary ammonium compounds, or "Quats" are not appropriate for use in a cheese plant because they leave a residue on equipment that are effective against lactic acid bacteria. Quats will inhibit many starter culture strains at concentrations as low as 10 to 20 μg/mL (Ruden 1997). Other effective bactericides include organic and inorganic chlorine compounds, chlorine dioxide, iodine compounds, acid anionic sanitizers and peroxyacetic acid, but they are unstable in the presence of organic matter such as milk (Leach 1997). Regardless of sanitizer, pipelines, vats and other equipment must be allowed to drain after bactericidal treatment to prevent contamination of the cheese milk supply.

24.5.5 Bacteriophage

Bacteriophage literally means "eaters of bacteria." Bacteriophage/phage are obligate intracellular parasites that attack and replicate within specific strains of bacterial cells (Leach 1997). Bacteriophage are naturally present in the cheesemaking environment and can spread throughout a plant with poor sanitation practices. Bacteriophage are the largest single cause of slowed or failed vats of cheese (Tamime and Deeth 1980; Leach 1997). Each strain of culture has a different level of sensitivity to bacteriophage. Since it is impossible to entirely eliminate bacteriophage from a dairy plant operation, control measures must be employed. Careful selection of starter cultures, aseptic techniques for starter culture propagation, air filtration, equipment sterilization, plant sanitation, culture rotation of phage-unrelated strains, or use of phage-resistant strains are necessary techniques to control phage (Leach 1997). Starter culture rotation essentially ensures that the bacteriophage population is diluted (through the process of repeated sanitation efforts) to the point that their numbers are low enough to allow the starter culture to function normally (Desmazeaud 2000).

24.5.6 Milk Pretreatment

Excessive heating, agitation or aeration can reduce growth and acid development by lactic acid bacteria. Heating of milk to pasteurization only slightly modifies the characteristics of milk for cultures. However, temperatures above 80°C for 20 sec. induce chemical reactions that can either inhibit (by destruction of certain vitamins) or stimulate (destruction of lactoperoxidase, production of formic acid from lactose, release of non-protein-nitrogen) bacterial growth (Ruden 1997). Excessive heating of milk should be avoided, not simply because of subsequent effects on culture, but the detrimental effects on curd formation, curd moisture retention and cheese quality. Aeration or excessive agitation will slow the vat by introducing dissolved oxygen. Presence of oxygen inhibits starters since they prefer a micro-aerophilic environment (McDowall and McDowell 1939).

24.6 CRYSTAL FORMATION

The occurrence of undesirable crystals in Cheddar cheese has been documented since the 1930s (Tuckey and others 1938; McDowall and McDowell, 1939; Harper and others 1953; Conochie and others 1960; Pearce and others 1973; Washam and others 1985; Severn and others 1986), yet the problem still represents a challenge and expense to cheese manufacturers (Chou and others 2003). Cheese crystals have been identified as calcium lactate (Severn and others 1986), a racemic mixture of L(+)- and D(−)-calcium lactate (Conochie and Sutherland 1965), calcium phosphate (Dorn and Dahlberg 1942; Harper and others 1953; Conochie and others 1960), tyrosine (Harper and others 1953; Bianchi and others 1974), or mixtures of amino acids (Severn and others 1986; Dybing and others 1988; Johnson and others 1990a,b). However, most frequently the crystals in young cheese have been identified as calcium lactate (Pearce and others 1973; Blake and others 2005).

The development of CLC may result from a number of causes, including milk composition (Dybing and others 1988), cheesemaking procedure (Pearce and others 1973; Dybing and others 1988; Johnson and others 1990b; Chou and others 2003), aging temperature (Johnson and others 1990b; Somers and others 2001; Chou and others 2003), and the growth of nonstarter lactic acid bacteria (NSLAB) in cheese during aging (Dybing and others 1988).

Cheese milk lactose concentrations exceeding 4.8% lead to increased lactose in cheese, which can be used by starter or NSLAB to produce lactate in cheese and a resultant increase in calcium lactate concentrations. Dybing and colleagues (1988) concluded that casein-bound calcium is the major source of calcium in calcium lactate crystals (CLC). The investigators showed that fast acid production and high milling acidities are associated with reduced CLC formation owing to reduced concentrations of casein-bound calcium. Seasonal changes affecting milk casein and calcium affect CLC formation. A low casein to calcium ratio leads to increased amount of bound calcium in milk, contributing to increased calcium in cheese and greater predisposition to CLC formation (Khalid and Marth 1990; Williams and others 2000; Agarwal and others 2006a).

Although starter bacteria make up the majority of cheese microflora initially, NSLAB dominate the viable population in cheese for much of the ripening period (Somers and others 2001). Secondary NSLAB introduced at the cheese plant (Blake and others 2005) or during cut and wrap, may proliferate upon stimulation by warm tempering temperatures (Dybing and others 1988; Williams and others 2000). Heterofermentative NSLAB utilize a variety of substrates for growth and produce an assortment of metabolites, including both L(+)- and D(−)-lactate (Johnson and others 1990b). NSLAB that are capable of racemizing L(+)- to D(−)-lactate can contribute to CLC since D(−)-lactate is less soluble than L(+)-lactate, particularly at aging temperatures, in maturing cheese (1990b). In the early 1990s, Johnson and colleagues (Turner and Thomas, 1980; Shakeel Ur and others 2000) established correlations among CLC, D(−)-lactic acid enantiomer, and numbers of NSLAB. Cheeses with racemase-positive *Lactobacillus* developed crystals compared to cheeses without *Lactobacillus*, which did not. Cheeses aged at lower temperatures developed crystals faster when compared to cheeses aged at higher temperature. CLC were never observed on cheeses with less than 20% of the lactic acid in the D(−) form. It follows, then, that since high temperatures favor the growth of NSLAB (Johnson and others 1990b), aging cheese at high temperatures, as may be done to accelerate ripening, can result in elevated D(−)-lactate by NSLAB and induction of CLC (Linke 1958).

Additionally, aging of cheese at low temperatures may also increase CLC, due to decreased solubility of calcium lactate at a low temperature (Chou and others 2003). Chou and colleagues (2003) demonstrated that earliest and most extensive CLC occurred on cheeses aged first at higher temperatures and then stored at lower temperature. They also showed that specific NSLAB, production of D(−)-lactate, and aging temperature affect CLC in maturing Cheddar cheese (Chou and others 2003).

Elimination of racemizing NSLAB and control of storage temperature is critical to the prevention of CLC. Agarwal (2006a) and Sharma (2002) showed that, irrespective of lactose to protein ratio, contamination of cheese milk with racemizing NSLAB *L. curvatus*, may lead to CLC, particularly in combination with elevated storage temperatures. Finally, Agarwal and colleagues (2005) demonstrated that, regardless of the presence of racemizing NSLAB, CLC are more likely to form in cheeses flushed with gas than cheeses that are vacuum packaged.

More recent research (Agarwal and others 2006b) shows cheese milk composition and cheese making techniques have greater influence on the occurrence of CLC, particularly calcium L(+) lactate crystals. Increased casein concentration in cheese milk is linked to increased colloidal calcium, which solubilizes as the pH of the cheese decreases (Upreti and others 2006). If cheese is made such that it has increased residual lactose, microorganisms present in cheese will ferment residual lactose to produce excess lactic acid and decrease the pH of the cheese, encouraging solubilization of colloidal calcium previously bound to casein micelles. Increases in concentrations of soluble calcium and lactate above saturation in cheese serum during aging tends to favor development of CLC. Control of pH and whey removal prior to packaging influence the occurrence of CLC.

In summary, cleaning, sanitizing, prevention of contamination of cheese milk with lactate-racemizing NSLAB, acidification and whey removal, consistent storage temperature and vacuum packaging are encouraged to minimize CLC. Due to the prevalence and expense of the problem in the industry, additional research in the area of CLC formation is warranted.

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