A 100-Year Review: Cheese production and quality¹

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ABSTRACT

In the beginning, cheese making in the United States was all art, but embracing science and technology was necessary to make progress in producing a higher quality cheese. Traditional cheese making could not keep up with the demand for cheese, and the development of the factory system was necessary. Cheese quality suffered because of poor-quality milk, but 3 major innovations changed that: refrigeration, commercial starters, and the use of pasteurized milk for cheese making. Although by all accounts cold storage improved cheese quality, it was the improvement of milk quality, pasteurization of milk, and the use of reliable cultures for fermentation that had the biggest effect. Together with use of purified commercial cultures, pasteurization enabled cheese production to be conducted on a fixed time schedule. Fundamental research on the genetics of starter bacteria greatly increased the reliability of fermentation, which in turn made automation feasible. Demand for functionality, machinability, application in baking, and more emphasis on nutritional aspects (low fat and low sodium) of cheese took us back to the fundamental principles of cheese making and resulted in renewed vigor for scientific investigations into the chemical, microbiological, and enzymatic changes that occur during cheese making and ripening. As milk production increased, cheese factories needed to become more efficient. Membrane concentration and separation of milk offered a solution and greatly enhanced plant capacity. Full implementation of membrane processing and use of its full potential have yet to be achieved. Implementation of new technologies, the science of cheese making, and the development of further advances will require highly trained personnel at both the academic and industrial levels. This will be a great challenge to address and overcome.

Key words: cheese, cheese production, cheese history

INTRODUCTION: THE CHANGING SCENE OF CHEESE MAKING, EDUCATION, AND RESEARCH

The earliest records of cheese production in the United States, compiled by the United States Census (cited in Thom and Fisk, 1918), showed that more than 45 million kilograms of cheese was produced in the United States in 1849. Women made most of the cheese, and all of it was made from raw milk. The individual cheeses were generally small, quality was not uniform, and about 50% was produced in New York. The first cheese factory in the United States was built in New York in 1851, and it produced Cheddar. The cheeses were generally wrapped in cloth, greased or smeared with lard or paraffin to reduce moisture loss, and ripened on wooden shelves at ambient temperature. The factory system was the outgrowth of the increased demand from England, which required larger cheeses of more uniform quality than the cheeses produced on the farm. Higher prices would be secured if these conditions were met.

By 1914 there were 3,520 cheese factories in the United States, mostly in Wisconsin (1,720) followed by New York (995) and Michigan (196), but a considerable amount of cheese was still produced on the farm (more than 4 million kilograms on farms compared with more than 141 million kilograms in factories in 1909). Cheese production had shifted away from New York to Wisconsin in a very dramatic way; by 1914, more than 50% of the cheese produced in the United States was made in Wisconsin. New York and Wisconsin had a similar numbers of cows, and cheese production decreased in New York because of the huge demand for fluid milk in large cities. In 1916, cheese exports were 20 million kilograms and cheese imports were 14 million kilograms. Immigrants were requesting the cheeses of their native country, and production of the desired cheeses was becoming more common. Imported cheeses were mostly Parmesan and Gorgonzola from Italy, Emmental from Switzerland, Roquefort and Camembert from France, and Edam from Holland. Consequently, much of the research done in the United States on cheese was on the development of manufacturing schedules and improving quality of these specialty cheeses. In 1916, the average price of cheese in the United States was \$0.37/kg, but

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imported cheeses sold for \$0.55/kg. Because US cheese makers were successful at duplicating the imports, some of the cheeses were misbranded and sold as though they were imports.

Pasteurization of milk for cheese making was a new technology but was rarely used in 1914. There were no antibiotics and no standards for bacteria in milk or cheese or even for cheese composition. Milk was cooled in cans with water from natural springs. In 1914, the average dairy herd size was less than 10 cows; some large herds had 30 milking cows. Compared with 2016, in 1914 there were at least 200-fold more cheese factories, and in Wisconsin there were about 17 times as many dairy farms (Wisconsin Milk Marketing Board, 2017). In Wisconsin, the number of cheese factories reached a peak of 2,300 in the 1920s but decreased to 138 by 2014. Major reasons for the decline included (1) the presence of larger factories and increased Cheddar and mozzarella cheese production in California and other western states and (2) the demand for more consistency in the quality of cheese produced in larger factories.

Total cheese production in the United States was 5,370 million kilograms in 2015. In 2014, 368 million kilograms of cheese was exported and 142 million kilograms of cheese was imported, mostly from France and Italy. Mozzarella is currently the most-produced cheese in the United States. Correspondingly, per capita consumption of cheese has increased from about 2.3 kg in 1980 to 15.8 kg in 2015. There is also a very active and steadfast group of cheese makers devoted to the manufacture of cheese from raw milk and fancy styles of cheese that were once the mainstay of cheese production in the United States.

Technological advancements in cheese making equipment and curd handling allowed for mechanization and automation, which were necessary for this quantum increase in cheese production and resulted in uniform product, reduced bacteriological contamination, and reduced manufacturing costs. Implementation of advances in engineering of cheese making equipment began in the 1960s and has continued rapidly since. However, for automation to meet its potential, the rate and extent of acidification by the starter bacteria must be predictable and reliable. The main scientific advancement in cheese making in the last 40 yr was the development of such starter strains. Research to maintain the reliability of starter cultures and to improve them is a continuous effort and will require additional scientific advances.

Another technological advancement in cheese making, membrane processing of milk, also had its roots in the 1960s, but it was not implemented routinely until the last 20 yr. Membrane processing of milk refers to the separation and concentration of milk with membranes. It allows for the removal of a portion of the

water, lactose, minerals, and whey proteins depending on the pore size of the membranes. Consequently, CN and fat are concentrated. The use of membrane-filtered milk allows the cheese maker to obtain higher cheese yields. Membrane processing has also been applied to whey and is used to concentrate whey proteins. Major advances in membrane technology have demonstrated that it has still not reached its potential, but implementation of these advances in the United States is slow due to regulatory constraints. Mechanization and automation reduced labor costs, and the cost of milk is now the largest expense in cheese making. The yield of cheese per volume or weight of milk is based on fat and CN contents of milk, the recovery of each as cheese, the moisture content of the cheese, and the contribution of added salt. Concentrating milk components using membrane processes, using equipment and technologies that maximize recovery of fat and CN, and implementing standardized, fixed, timed manufacturing schedules have greatly improved cheese yield and cheese making efficiency but have also introduced many challenges. Two of the challenges are procuring trained personnel to operate the equipment properly and adapting a manufacturing schedule to produce cheeses that meet the changing demands of the customer. Research and the education of employees that results from its implementation are still at the heart of proper cheese making.

In 1890, the University of Wisconsin's Agricultural Experiment Station started its Wisconsin Dairy School, the first of its kind in the United States. Technical training for cheese makers was at least a semester-long endeavor and was not necessarily tied to a graduate degree (i.e., 4-yr college degree). Out of desperation and a lack of what he noted as a suitable book on cheese making, John Decker, an instructor at the school, published his own book on cheese making in 1893. He noted that his book was necessary because the advances in science (microbiology) and technology (refrigeration) changed our views on health and offered the potential to improve cheese quality.

THE JOURNAL OF DAIRY SCIENCE: CHEESE FROM THE BEGINNING

Almost all the research on cheese making published in the United States before 1917 was in the form of technical bulletins by agricultural research stations (located especially in New York, Vermont, Ohio, Connecticut, Wisconsin, and Iowa) and the USDA (Appendix Table A1). This trend would continue for several decades. Many of the technical bulletins were on the general method of manufacture of a specific type of cheese, mostly cheeses that were imported due to their high demand. Studies on the microbiology and chemistry

involved in the cheese making practice were included in these bulletins.

Consequently, in the first year of the *Journal of Dairy Science* very few papers were on cheese making or the chemistry of the cheese making process; that would continue for almost 10 yr. Most papers on dairy manufacturing were on butter. The first paper on cheese published in the journal was on eyes of Swiss cheese (Clark, 1917), followed 2 yr later by a paper on the use of buttermilk (by-product of butter making) in making a skim milk cheese for sale to recent immigrants (Rudnick, 1919), who needed an inexpensive source of protein and were willing to sacrifice quality for nutrition. Subsequent papers on cheese focused on fancy cheeses such as brick, Limburger, blue-veined, Swiss, and cottage cheeses but not Cheddar, the most common cheese produced.

Most initial papers on cheese making in the journal in the 1920s focused on improving cheese quality. Pasteurized milk for cheese making was being promoted as a sort of panacea to cure the major defect of the day: gassy cheese caused by coliforms. Pasteurization, a relatively new process, was met with resistance because of the cost of implementation and the availability of equipment. By the 1960s, there was a trend in cheese-related research published in the journal to detail the chemistry involved in cheese functionality and starter culture technology. This trend continues because of the pressure on cheese makers to supply cheese that requires machinability and specific bake performance (melt, stretch, color). Milk processing before cheese making, especially that involving membrane technology and issues associated with it, has played a major role in the numbers of papers published in the journal in the past 2 decades (Appendix Table A1). These research papers may eventually pave the way for necessary changes in the Code of Federal Regulations regarding the acceptance of membrane-filtered milks for making cheese and other dairy products.

CHANGES IN MILK PROCUREMENT AND MILK QUALITY FOR CHEESE MAKING

What was it like to produce cheese in 1917? Probably not unlike when the first cheese factories were built. Milk was delivered daily in metal cans. Milk was cooled by placing the cans in cold spring water—approximately 12°C was the norm. This was generally a poor means for cooling milk rapidly and resulted in very high bacteria numbers in the raw milk. Bacteria counts exceeding 1 million/mL of milk were common. Cooling was sometimes supplemented by the addition of ice to the water, which facilitated more rapid cooling. Hlynka et al. (1943) demonstrated that a rapid increase in ran-

idity and unclean flavors in cheese often occurred with more vigorous stirring and when the milk was warmer. They recommended cooling milk with no or very little agitation. New ways to cool milk were eventually developed, which facilitated the production of more milk at the farm, enabled pick up every other day, and led to changes in the regulations on milk handling. Rancidity in cheese is now very rare and, when it does occur, it is almost always attributable to excessive agitation of milk collected from animals with mastitis.

Can milk was common into the 1960s and was still used until the early 1970s. With the advent of electrification on the farm, it became possible to use mechanical cooling to cool milk faster and to a much colder temperature. It also resulted in expansion of dairy herds and facilitated the hauling of milk from the farm in specialized refrigerated milk trucks operated or contracted by the cheese plant. These trucks could transport up to 23,000 kg of milk. Milk was now collected from several farms by a single truck driver, which freed the farmer from making their own deliveries and the backbreaking lifting of 45-kg cans full of milk.

Two major changes in regulations resulted in the switch from can milk to bulk milk. Because it was now possible to rapidly cool milk to below 7°C, by the 1940s regulations were put in place requiring that milk be cooled within 2 h of milking to below 7°C and that mixed milk (milk already in the bulk tank mixed with newly obtained milk) not exceed 10°C. The second regulation helped set limits on the maximum bacteria numbers in raw milk for cheese making, which decreased from 1 million cfu of bacteria/mL of milk to 300,000 cfu of bacteria/mL of milk. With the development of better cleaning, sanitation, and cooling practices from the cow through delivery of the milk to the cheese factory, the numbers reached today by many producers are below 20,000 cfu of bacteria/mL of raw milk. Currently, most milk for cheese making contains less than 20,000 cfu of bacteria/mL of milk, and with numbers of bacteria between 5,000 and 10,000 cfu/mL of milk being very common, it could eventually become the standard.

Because of the high bacterial numbers in raw milk used in cheese making 100 yr ago and the negative effect it could have on cheese quality, technologists looked for ways to deal with poor-quality milk. Cheese makers had little control over milking practices and handling at the farm, and there were no real monetary incentives for the producer to improve milk quality, nor was it easy for the cheese maker to test raw milk quality. This situation would change in the 1960s with the direct microscopic counting of bacteria in milk. This method, initially promoted by Knaysi and Ford (1938), made it routine to rapidly determine the bacterial quality of milk from individual producers, and factories instituted

premium payments for low bacteria numbers in milk. The previous method for the bacteriological quality of raw milk was an indirect measurement that relied on the concept that poor-quality milk would contain a sufficient quantity of acid producers to reduce methylene blue to a yellow color in a short period (a few hours for good milk and less time for poor-quality milk).

Due to illness associated with drinking raw milk contaminated with pathogens, by 1917 many municipalities required the pasteurization of milk—but not milk for cheese making. The belief was that the acidic conditions in cheese would most likely kill or greatly diminish the growth of pathogens in cheese. There was also no real panic that eating cheese would cause illness. This mindset culminated in the 1940s with the requirement of using pasteurization for cheeses that were consumed young (less than 60 d) because of the perception that it would take that long under acidic conditions to kill pathogens present in cheese made from raw milk. Pasteurization of milk for cheese making, initiated to improve cheese quality, did not necessarily produce a cheese free of pathogens. Regardless of the heat treatment given the milk for cheese making, if the cheeses were contaminated with pathogens and the cheeses were of low acidity and high water activity, pathogens could grow or at least not die. Reports of pathogens that could affect the safety of cheese have been published (Pearson and Marth, 1990; el-Gazzar and Marth, 1992; Bachmann and Spahr, 1995; Ramsaran et al., 1998; Lundén et al., 2004; Stephan et al., 2008).

Pasteurization of milk for cheese making was common in New Zealand by 1923 but was rarely practiced in the United States at that time. Sammis and Bruhn (1912) summarized the advantages of using pasteurized milk for cheese making. These advantages included improvement in cheese quality, more uniform quality, and higher cheese yield, and the cheese making process could be systematized to such an extent that cheese production could be on a fixed time schedule. Price (1927), Phillips (1928), and Wilson et al. (1945) verified their conclusions. As a result, the industry increasingly used pasteurized milk for cheese making, even though it took more than 50 yr since it was first introduced to become commonplace. Milk quality at the time was poor by today's standard. Bacteria numbers as measured in research laboratories were generally greater than 500,000 cfu/mL of milk and as high as several million. An example of the times and milk quality, Kelly (1939) reported numbers of bacteria in raw milk for the manufacture of cheese ranging from 1.8 million to 5 billion cfu/mL of milk. To control gas formation caused by coliforms in Limburger cheese, which was a common defect in raw milk cheese

regardless of variety, Kelly (1939) advocated the use of pasteurized milk rather than the common practice of using raw milk for cheese making. However, there was great reluctance to use pasteurization because of a perceived decrease in the development of cheese flavor and the cost and availability of equipment. Pasteurization was generally done with the holder method—what we now call low temperature, long time pasteurization. Today only small-volume cheese makers use it, and all others use an HTST method (flash method, as it was called). The HTST pasteurization method facilitates high-volume milk throughput, which is essential in rapidly processing huge amounts of milk. Milk high in bacterial numbers would contain strains capable of fermenting lactose and could interfere with the desired rate of acidification during cheese making. The cheese maker would not have strict control over the rate and extent of acidification during cheese making, which is one of the key components of successful cheese making. Pasteurization kills most bacteria capable of fermenting lactose and thus necessitates the use of added starter culture for proper fermentation. Pasteurization resulted in much tighter control of acidification during cheese making, and this in turn helped facilitate better process control over cheese quality. In 1917, numbers of bacteria remaining in milk after pasteurization were in the thousands per milliliter of milk. Today, bacteria numbers in pasteurized milk are generally less than 100 bacteria/mL of milk. These lower numbers are attributable to the initial low numbers in raw milk, which is facilitated by more effective overall cleaning and sanitation practices and cooling of milk on the farm and in bulk-milk hauling trucks used today. By 1943, several states adopted the pasteurization requirement for milk for cheese making. Universal adoption of pasteurization of milk for cheese making has met resistance from many artisanal and farmstead cheese makers, whose customers demand cheeses made from raw milk. Regulatory agencies today are demanding a higher level of scrutiny of the cleanliness and sanitation of milk production on the farm and in the cheese making facility than in the past. The US government has adopted a zero tolerance policy for the occurrence of pathogens in cheese. Pasteurization of milk is only one hurdle in the effort to keep pathogens out of cheese. Cheese is not made in a sterile environment, and proper cleaning and sanitation of the cheese making facility to prevent contamination is required. The Food and Drug Administration is mandating efforts to enforce guidelines to prevent contamination (i.e., *Food Safety and Modernization Act*). The growth and survival of pathogens in cheese as the result of contamination during manufacture, ripening, or packaging depends on water activity, competitiveness with other bacteria, and pH history of the cheese.

Mold-ripened cheeses (e.g., Camembert or Brie) and soft, surface-ripened cheeses (e.g., Limburger) do not offer sufficient protection against the growth of pathogens because they do not meet the criteria required to keep pathogens from growing. These cheeses have high water activity, and during ripening they lose acidity and thus become conducive to the growth of contaminants. Illness due to the consumption of cheese is very rare, but when it does occur it adds to the argument for adoption of preventative measures, such as those described by the *Food Safety and Modernization Act*.

A benefit of using pasteurized milk was that essentially all of the acid development was from the added starter culture. Thus, the rate and extent of acidification could be controlled and resulted in a more consistent cheese quality. Cheese making could now be conducted on a fixed time schedule, a major event that makes large-scale cheese making feasible today. However, recognized in the 1920s, prolonged use of pasteurizers and failure to clean and sanitize the equipment properly led to the development of biofilms on the walls of the regenerative heaters. Biofilms are produced when bacteria attach to equipment surfaces, produce an exopolysaccharide, and grow into masses of bacteria. Biofilms are of concern in cheese plants and other dairy processing facilities because they are the major source of postpasteurization contamination of milk by bacteria (Wong, 1998; Somers et al., 2001). Bacteria that can survive pasteurization include gas formers, spore formers, and acid producers, particularly *Streptococcus thermophilus*, which, although greatly reduced in number by pasteurization, survive in sufficient numbers to eventually develop a biofilm in the regenerative section of the pasteurizer. The bacteria in the biofilm slough off and contaminate the milk. At times, *Streptococcus thermophilus* are so numerous in pasteurized milk that their acidification of milk overshadows the acid produced by the added starters; this prevents strict control over the rate and extent of acidification necessary for proper cheese making. Biofilms also develop on farm equipment and are a source of bacterial contamination of raw milk, including pathogenic bacteria (Latorre et al., 2010; Lee et al., 2014). Recent research involves the coating of equipment with material that prevents attachment of the bacteria and thus prevents biofilm formation (Jindal et al., 2016). Generally, enzymes are used as part of the cleaning regimen to remove biofilms because the biofilms are not always removed by normal chemical treatments.

Antibiotics in milk became a major issue in the late 1940s (Katznelson and Hood, 1949; Johns, 1953) through the 1960s (Albright et al., 1961; Kosikowski, 1961), and how to prevent antibiotics from getting into

the milk supply remained a topic for producers (McEwen et al., 1991). There was considerable debate on the overuse of antibiotics for treatment of mastitis. The arguments against the overuse of antibiotics included the potential that pathogens could become resistant to the antibiotic and the fact that if the antibiotic got into the milk it could inhibit lactose fermentation by the starter bacteria or cause an allergenic response in sensitive people who consumed the cheese. Although under federal law it was illegal to sell milk that contained antibiotics, it was not until the 1960s that routine testing of raw milk became mandatory.

Extraneous matter in milk was common, and it was correlated with cheese quality. Clarification of milk for cheese making was promoted by Combs et al. (1924) to remove extraneous matter (sediment, including dirt and hair), and the result was an improvement in cheese quality. With the advent of electric motors in the 1930s, mechanical separation became common. The sediment test for raw milk, which measured the amount of extraneous matter in milk, was established as an index of the quality of milking practices. A high sediment test meant that the teats were not cleaned properly before milking. The sediment test results were also used as an indicator of bacteriological quality because a high sediment test and a high number of bacteria in milk usually went hand in hand. Direct microbiological tests on raw milk were not yet done at the cheese factories. Sediment testing was required by many state regulations but has since been dropped by most states because direct bacteriological testing is now done. Mechanical clarification of milk was discontinued by many cheese factories in the late 1970s to early 1980s due to the cost of operation and the loss of milk solids, which decreased cheese yields and added to the expense of waste treatment of the resultant sludge. Wedge wire and cloth filters replaced mechanical clarifiers. Clarification was reintroduced by some Cheddar cheese makers in the mid-2000s because an oily residue from a very effective dry cow treatment (Huxley et al., 2002) sometimes got into milk. The oily residue could not be captured by the wire or cloth filters and had to be mechanically removed. The oily residue contained bismuth subnitrate, which produced a black spot discoloration when combined with sulfur compounds (Lay et al., 2007). The sulfur compounds are produced during extended ripening of Cheddar cheese as the result of microbial metabolism of sulfur containing AA.

Somewhat analogous to mechanical clarification, Swiss cheese manufacturers have implemented bacterial removal systems. First used in Europe decades ago, these systems were rarely used in the United States until about the last 5 yr. These systems remove bacte-

rial spores, including spores of *Clostridia* and *Bacillus* that cause gassy, slitty cheese and produce off-flavors. The systems include centrifugation or microfiltration.

DEVELOPMENTS IN STARTERS AND RENNETS

Major advances in cheese making technology have taken place over the last 45 yr. These include mechanization, automation, and development of cultures and rennets. The advances in cheese making technology, especially cheese making on a fixed time schedule, would not be possible without reliable starter activity. Standardization of the rate and extent of acidification by the starter bacteria is essential to producing consistent cheese quality. Prior to the 1890s, cheese starters were made at each cheese factory or farmstead through the natural fermentation of good-quality milk. In 1890, Chr. Hansen Inc. made pure cultures available to cheese makers. Cheese makers could purchase vials of cheese starter and grow them up to the volumes they needed. Unfortunately, not all went well. Cultures often did not perform well, meaning that they often lost their ability to produce sufficient acid. This was caused by a bacteriophage infection.

A major breakthrough in developing consistent acid production by the starter was the discovery that lactose fermentation and proteolytic activity (needed for rapid growth that was required for reliable lactose fermentation) were encoded by plasmid DNA (McKay et al., 1976; Romero and Klaenhammer, 1993). This discovery was instrumental in the eventual development of starter strains resistant to bacteriophage also encoded by plasmid DNA (Sanders et al., 1986). Strains of starters that resist infection by bacteriophage and that have consistent acidification were an essential component of the technology of cheese manufacture on a predictable and consistent basis and are vital to the automation used today (Cogan et al., 2007). Additionally, the medium used for the growth of starters received much attention because the activity of the starter depended on the conditions under which it was grown (Richardson et al., 1977; Whitehead et al., 1993). Although bulk cultures (starter grown in media at the cheese factory) are still used today, especially for cheeses that will be aged for extended periods, the technology of using starters has changed considerably. The cost of growing bulk cultures and the potential loss of cheese yield due to the replacement of milk by starter medium have led to the use of highly concentrated starters sold in frozen pellets. The pellets are added directly to the cheese milk without having to grow the cultures at the factory. Elimination of bulk culture preparation greatly reduced phage infection.

To facilitate large increases in cheese production, the development of a more stable and increased supply of rennet was required. Before the 1980s, almost all rennet was extracted from calf stomachs or specific molds. In the 1980s, development of fermentation-produced chymosin met the challenge. Insertion of the calf genes responsible for chymosin (i.e., the active enzyme in rennet) production into molds resulted in the molds producing chymosin in a fermentation process. More than 90% of the rennet used today is fermentation-produced chymosin, and it has the advantage of being both kosher and halal approved. This is especially important for the sale of products derived from whey.

TECHNOLOGIES FOR IMPROVING CHEESE MAKING EFFICIENCY

Cheese yield and milk composition have been an important part of cheese making. They are the basis for milk payment, profitability, and cheese making efficiency. Cheese yield depends almost entirely on the moisture content of the cheese, fat and CN contents of milk, and the retention of each during cheese making (Lopez-Fandiño et al., 1996; Klei et al., 1998; Fenelon and Guinee, 1999; Jaeggi et al., 2003; Guinee et al., 2006; Lilbaek et al., 2006; Wedholm et al., 2006; Guinee et al., 2007; DeMarchi et al., 2008). Prior to the 1960s, cheese making was done in vats that required cutting the clotted milk by hand using wire knives. Determination of the proper firmness of the coagulum at cutting was somewhat arbitrary but vital to the recovery of as much fat as possible. Proper cutting and stirring practices after cutting were also key to fat recovery as well as the retention of CN. Both fat and CN could be lost due to the breakage of the curd particles during cutting and stirring. Breakage of curd particles and subsequent formation of small cheese particles, known as fines, result in fat and CN losses. Fat losses can be as high as 10 to 12%. In actual practice, CN losses (including fines) are generally around 5%, although standardized yield formulas use a value of 4% or less (Emmons and Modler, 2010). In the 1960s, and again in the 1990s with new designs, mechanical cutting in large vats would shape the way cheese is made. Initially, the cutting mechanism in the mechanized vats was vertical stirring, but later the cutting mechanism changed to horizontal stirring; both increased fat recovery over hand cutting. Mechanical cutting facilitated the use of large volumes of milk, with some vats holding up to the equivalent of 45,360 kg of milk, and was vital in the development of automated systems for cheese making. Along with the larger vats, equipment that could handle huge masses of curd efficiently was also

developed. This included drain tables or curd matting machines for separation of whey from curd as well as towers (to form 18-kg blocks) or large containers (to form 290-kg blocks) for production of cheeses such as Cheddar, Colby, Muenster, and Monterey Jack.

The use of milks high in CN and fat has become commonplace but requires judicious adherence to the best practices to enable the manufacture of cheese with the desired melt, stretch, and machinability. One of these best practices is preacidification (addition of acid before addition of rennet). Much research has been done exploring the best means to accomplish this (Metzger et al., 2000, 2001a,b; Nelson et al., 2004). Direct acid addition was initially used in the 1920s to correct for poor-clotting milk but was popularized in the 1990s with the increase in use of concentrated milks for cheese manufacture. Breene et al. (1964) demonstrated that no starter was needed for mozzarella (pizza cheese) because acid could be added directly to the milk, and with the addition of rennet the desired cheese would eventually be obtained. Direct acidification, as it is called, is now used for the manufacture of string cheese and fresh mozzarella and is the basis for preacidification. Preacidification is widely used in the manufacture of low-fat cheese and cheese made from milk with higher solids to aid curd fusion and lessen water migration that occurs when large blocks of cheese are cooled.

Increasing the fat or CN contents of milk will enhance the yield of cheese. Cheeses that have a standard of identity with fat of less than 50% on a dry basis require the removal of cream from the milk or the addition of skim milk. Cream removal removes fat and some CN, and the decrease in both results in a major decrease in cheese yield. In the 1950s, instead of removing cream, some cheese makers began to add CN to the milk in the form of nonfat dry milk (generally rehydrated) or condensed skim milk. However, use of condensed milk or nonfat dry milk is not without potential problems. Half of the solids in these ingredients is lactose. Excessive acid development in cheese could occur with high-lactose milks, wreaking havoc on cheese quality.

The feasibility of using membrane filtration of milk to concentrate the fat and CN contents of milk and remove water and lactose from milk was strongly advocated in the 1970s (Kosikowski, 1974; Maubois and Mocquot, 1975). Adoption of UF of milk for cheese making prevented excessive acid development as lactose was removed and increased the fat and CN contents of milk, thus tremendously increasing cheese yield (Bush et al., 1983; Mistry et al., 1996; Brandsma and Rizvi, 1999; Papadatos et al., 2003; Govindasamy-Lucey et al., 2004; Nelson and Barbano, 2005; Moynihan et al., 2016). Microfiltration is used to remove a portion of the whey proteins in addition to the water, soluble minerals,

and lactose. As such, the Food and Drug Administration currently rules that after partial removal of whey proteins, milk is no longer milk and cannot be used to make cheeses that have a standard of identity. There is no such restriction on the use of membrane-filtered milk in other countries. Cheeses that do not have a standard of identity can be made from microfiltered milk.

DAIRY CHEMISTRY PUT INTO PRACTICE

Cheese makers of old relied on their senses to make cheese. There were no means to detect the changes in acidity caused by the fermentation of lactose by the added starter bacteria (or natural fermentations before starters) other than by the feel of the curd. Yet the rate and extent of acid development are key parameters in developing the desired characteristics of cheese. The first use of water to prevent excessive acidity is lost to antiquity, but once used it opened up new frontiers of cheese making and cheese types. Recognizing that acid development influenced characteristics of curds, technologists developed a means to detect changes to curd. The first test was a hot iron test. Curd was squeezed into a mass, and the mass was then pushed onto a hot iron or pipe until it bonded with the iron. The mass was pulled, and the length of stretch was measured. The more acid produced in the curd, the longer the stretch. The relationship of the stretch to the attributes of the cheese was noted. Skilled practitioners substantiated that the hot iron test could very accurately predict pH. Chemists have long used titration to measure acidity, and by the 1920s this method began to replace the hot iron test to determine the progress of fermentation. Widely used until recently, titratable acidity became the measure of quality assurance during manufacture of cheese because it was easy to use and cost very little. Brown and Price (1934) advocated the use of pH measurements instead of titratable acidity, but pH measurement during cheese making did not become common until the 1980s.

How cheese is packaged and consumed has put a lot of pressure on cheese makers to produce cheese with attributes that were not required in earlier times. Requirements by converters include the ability to successfully shred, slice, and cube cheese without a lot of trim loss. Application of cheese in food service, especially in cooking or baking, requires specific melt and chew characteristics. The amount of calcium bound to CN, pH, and composition of cheese control the physical and functional properties of cheese when it is heated. The rate and extent of acidification during cheese making control the calcium content and pH of cheese (Lawrence et al., 1984) and are the chief principles governing the manufacture of cheese. However, the desired physical

and functional properties of cheese can be destroyed by proteolysis (the breakdown or hydrolysis of protein). Rennet used to clot the milk is a proteolytic enzyme and is the main culprit regarding excessive proteolysis in cheese. Excessive proteolysis causes cheese to melt excessively with excessive free oil formation and will result in a cheese that cannot be machined (sliced, cubed, or shredded). The shelf life of cheese, or the time that a cheese maintains its desired characteristics (flavor, body, and functionality), is shortened by excessive proteolysis, which can destroy the best cheese. Because of the importance of the chemical changes that occur during manufacture and storage, there was renewed interest in exploring these changes in more detail. Consequently, a lot of research was performed on the chemistry of melt, stretch, color, and texture of cheese (Keller et al., 1974; Yun et al., 1995; Guo et al., 1997; Rudan and Barbano, 1998; McMahon et al., 1999; Rudan et al., 1999; Petersen et al., 2000; Metzger et al., 2001a,b; Feeney et al., 2002; Pastorino et al., 2002; Broadbent et al., 2003; Lucey et al., 2003; Pastorino et al., 2003a,b,c; Hassan et al., 2004; Lee et al., 2005; McMahon et al., 2005; O'Mahony et al., 2005; Upreti et al., 2006; Foegeding and Drake, 2007; Banville et al., 2013). Nutritional demands such as fat and sodium reductions were also major influences on research, particularly in the 1990s (Johnson et al., 1995; Fife et al., 1996; McMahon et al., 1996; Perry et al., 1997; Chen et al., 1998; Mistry and Kasperson, 1998; Paulson et al., 1998; Rudan et al., 1998; Fenelon et al., 2000; Johnson et al., 2001; Awad et al., 2005; Madadlou et al., 2005; McMahon et al., 2005; Dabour et al., 2006; Rogers et al., 2009; Costa et al., 2010; Drake et al., 2010; Grummer et al., 2013; Ozturk et al., 2013, 2015).

RIPENING PRACTICES FOR CHEESE

Ripening of cheese refers to the development of flavor, texture, and body characteristics of cheese. Ripening is the result of decomposition or breakdown of acids, fats, and protein due to metabolism of microorganisms and activity of enzymes. The development of flavor in dairy products has received considerable attention, especially for the contribution of enzymes and microbiota, both of which may be naturally present or added intentionally to the milk or cheese (Molimard and Spinnler, 1996; Lynch et al., 1999; El Soda et al., 2000; Madkor et al., 2000). Blue cheese would be feta cheese and Camembert would be similar to chevre without the addition of specific species of *Penicillium* mold. Provolone and Romano cheese flavor would be similar to mozzarella or Parmesan, respectively, without the addition of lipase enzymes. Gouda and Havarti would be similar in flavor to Colby or high-fat brick cheese without the

addition of specific species of lactococci and *Leuconostoc* bacteria. Swiss cheese would be similar in flavor to a high-moisture Parmesan without the addition of propionibacteria. It is recognized that microorganisms and enzymes can alter the flavor, body, and texture of cheese. Therefore, it has become a major research effort by companies that supply these ripening agents to find microorganisms that will positively affect desirable characteristics of cheese. The use of bacteria to develop unique flavors has skyrocketed over the past 20 yr and will continue. Within the past 10 yr, the development of genomics to quickly identify the microorganisms found in cheese, especially in mold and surface-ripened cheeses, has become a major effort in the search to understand the effect of various microorganisms on flavor development and identify their habitat in the cheese factory and at the farm. The study of microbiota ecology during ripening has led to a new scientific area of study on chemical ecology. Microorganisms change the chemical environment in cheese. This can alter the biochemistry of cheese flavor development. Scientists are able to examine the genomic sequences of microorganisms and can ascertain whether they have the potential to develop desired flavor characteristics in cheese without any detrimental effects. The use of genetics to select bacteria for desired flavor development and to discover bacteria with characteristics that inhibit the growth of undesirable bacteria in cheese is the next great adventure in cheese making technology.

However, from a manufacturing perspective, the enhancement of flavor quality and quantity has remained a rather simplified protocol. It is generally limited in practice to ripening cheese at elevated temperatures or to the addition of flavor-enhancing microorganisms and enzymes. The main defects in cheese 100 yr ago were gassiness and unclean flavors. They often go hand in hand. Cheese was generally stored at room temperature or, if the cheese maker was fortunate, in caves built into sides of hills; however, this greatly enhanced the growth of coliforms and other undesirables. Refrigeration of cheese greatly improved cheese quality (Wilson et al., 1941). The latter reference contains a great discussion on the early work of many researchers, including the initial work on refrigeration of cheese by Babcock and Russell (1902). All reports demonstrate that cooler temperatures resulted in better quality cheese. Bacteriological quality of milk was poor, and contamination of milk and cheese with coliforms was very common. Coliforms produced both gas and undesirable flavors. The use of pasteurized milk for cheese making was in large part to cure these issues. The destruction of coliforms as well as many other bacteria that may have contributed to the development of desirable flavor in cheese had consequences. In response to the lack of

flavor development in Cheddar cheese made from pasteurized milk, Harris and Hammer (1940) tested the addition of specific bacteria that were initially isolated from good-tasting cheese made from raw milk. It is now common practice in some cheese varieties, especially Cheddar, Parmesan, and aged Gouda, to add adjunct bacteria, mostly *Lactobacillus* species, to milk to develop unique flavors in cheese that are unlikely to develop without the addition of such bacteria. Almost all of the work done on isolation of these strains is performed in private commercial entities, but there are exceptions (Lynch et al., 1999; Swearingen et al., 2001). Addition of adjuncts may include species of bacteria that inhibit undesirable bacteria in cheese and may include species considered to be probiotics. Enzymatic activity and microbial growth are essential for developing cheese flavor, and their contribution to flavor is accelerated by ripening at warmer temperatures. Using elevated temperatures to reduce the time and cost of developing the desired flavor attributes of cheese has potential drawbacks. Defects associated with improperly made and ripened cheese include gas formation leading to splits in cheese (Ortakci et al., 2015) or sweating (liquid expulsion) leading to calcium lactate crystal formation on the surface of Cheddar cheese (Chou et al., 2003; Swearingen et al., 2004; Agarwal et al., 2006).

CHEESE PACKAGING

In 1917, cheese was not sold in the convenient forms we enjoy today (i.e., shreds, slices, small blocks of 227–454 g). Factory-made cheese, especially Cheddar, was ripened in large blocks that were coated with lard or cheese grease to protect them from drying out excessively. Rinds, or a hard outer layer of cheese, still developed and had to be cut from the cheese before sale. This trim resulted in a lot of waste. The traditional practice of ripening cheese has returned today as artisans have rediscovered the unique flavor of cloth-bound Cheddar. By 1917, cheese grease was largely replaced by paraffin, which prevented drying, created no rind, and was easily removed from the cheese. Wax coating was also a means to prevent drying but was done just before sale of the cheese to the market. Smaller blocks (2.3–4.5 kg) of Cheddar (called daisy, gems, favorites, young Americans, and midgets, to name a few) were becoming popular for sale out of convenience to the grocer, who then cut the cheese into smaller units as the customer asked for it. Labor costs were high, and the marketing of cheese was handicapped by the unsuitability of the packaging for modern methods of merchandizing (Rogers, 1932). Ripening or storage of cheese in cans was introduced in 1904. Gas-venting valves that facilitated air removal were introduced in the 1930s and helped

prevent growth of contaminating mold spores. Washington State University began experimenting with vacuum-sealed cans. This process is currently used in their popular Cougar Gold cheese. Today, vacuum sealing of packaged block-shaped cheeses and gas flushing of plastic bags of shredded cheese with mixtures of carbon dioxide and nitrogen are popular for mass distribution.

Undoubtedly, the increased consumption of cheese is attributable in large part to the convenient forms of presenting cheese to the consumer. The small blocks of cheese were not practical for the convertors. Cheese factories switched back to the larger forms, 9- and 18-kg blocks. However, Swiss cheese went from 90-kg wheels to 10-kg block form. Retailer demand for packages of exact weight resulted in a lot of trim loss from the larger blocks because they were not of perfect size and weight for this style. Eventually, much larger blocks of cheese called 640s, weighing roughly between 304 and 313 kg, substantially reduced trim loss, but they are not without issues. Moisture migration within the block produced higher moisture on the outer portions and reduced moisture in the inner portions (as much as 4–6 percentage points; Reinbold and Ernststrom, 1988; Reinbold et al., 1992). Convertors found at times that inner portions were not conducive to rapid slicing or shredding because the cheese was brittle or that the outer portions were too pasty to machine. The influence on flavor of added enzymes and adjunct cultures could be exacerbated based on location within the large block of cheese (Carunchia Whetstine et al., 2007), but this was generally not as much of a concern as the inability to machine the cheese.

Cheese marketing has in some respects reinvented itself over the last 15 yr. With the popularity of “fancy,” specialty, artisanal, or farmstead cheeses, cheeses directly cut from the block or individually cut, wrapped, and weighed at the retailer have reversed the trend of having convertors package cheese.

WHEY PROCESSING

Cheese production means whey production. In the early days of cheese making, whey was fed to livestock or otherwise discarded. The development of mechanical separation of the fat in whey allowed the manufacture of whey cream butter. Grade A butter can be made from sweet cream only. It was uneconomical for small factories to process whey because the volumes of whey were small (Webb and Whittier, 1948). Prior to the 1920s, lactose was derived from skim milk. Bell et al. (1928) developed a process of removing lactose and other solids from whey, but most of the work on whey processing was in the form of patents. Whey processing eventually transformed from whey cream production to

protein concentrates and lactose. The change in milk pricing to component pricing greatly accelerated the development of whey-based ingredients. The development of membrane filtration of whey enabled a more economically viable process and resulted in the development of many types of whey-based ingredients. A major drawback to the sale of products derived from whey in which annatto color has been added (Cheddar and Colby) to the milk is that buyers do not want color in the product. To appease the buyers, McDonough et al. (1968) promoted the use of hydrogen peroxide to bleach the color. Unfortunately, this led to off-flavors in the whey products (Croissant et al., 2009; Kang et al., 2010; Jervis et al., 2012). Some buyers do not accept the bleaching of whey or the addition of color to milk. This is especially true for whey-derived ingredients for baby food formulas. Consequently, there is special impetus to legalize the microfiltration of milk before cheese is made to remove a portion of whey proteins and lactose from milk before cheese making and the addition of color.

CHEESE SAFETY: MANDATORY INSPECTION OF CHEESE PLANTS

Although illness due to consumption of cheese is rare, the US government has zero tolerance for pathogens in cheese. This has set in motion a major debate on the abolition of raw milk for cheese making. Pasteurization of milk for cheese making does not ensure that the cheese will be free from pathogens, but it would be if postpasteurization contamination of cheese can be avoided. This may not be the case for cheeses made from raw milk, especially those in which the acidity is low. Implementation of rules and procedures to ensure the safety of all cheeses will become mandatory. As part of the *Food Safety and Modernization Act*, signed on January 4, 2011, all cheese plants must maintain and implement a food safety plan. Its aims are to shift the focus from responding to contamination of food by pathogens to preventing it. The food safety plan must contain provisions such as hazard analysis, preventative controls, monitoring procedures, and a plan for corrective action. It also includes a program for training workers on good manufacturing practices. Mandatory implementation of the act is required in all cheese plants by 2018. Larger cheese plants had to comply by September 2016.

SUMMARY AND FUTURE DIRECTIONS

Cheese making in the United States has progressed from small quantities produced on the farm to mega quantities produced in factories. In his commentary on

the changes made from the early 1900s to the 1950s, Price (1956) wrote eloquently about changes in the art, which was in essence the history of cheese making. Olson (1970, 1981) wrote about the changes in the mechanization and automation, and Johnson and Lucey (2006) characterized additional changes. This review does not cover all the changes to equipment for all cheese types, but innovation has occurred in all types of cheese. In some regards, the manufacture of cheese in small factories is quite the same as it was 100 yr ago but with equipment made of stainless steel and electric motors and pumps. The cheese produced today is of much higher caliber and more consistent in quality than that produced in 1917. One hundred years ago, educators believed that cheese makers were inclined to follow the same routine they had always known and that they seldom possessed any scientific comprehension of the process they used. The cheese industry would not be as robust today if that were true.

To be efficient, factory cheese making requires fixed time processes, which in turn require milk of high quality. The use of pasteurized milk for cheese making, increased herd size, and the increased need to process milk into cheese require mechanization and automation and knowledge of how this technology works. Using mechanization and automation to their fullest potential requires the development of starter cultures with dependable performance and the knowledge of the cheese maker to use them appropriately. Efficient use of the equipment and the need to improve cheese yield are at the forefront with membrane processing of milk, but changes to the regulations will be required to allow for its full potential. Increased cheese production requires increased promotion of cheese utilization. Changes in handling, utilization, and presentation of cheese require knowledge of the chemistry and enzymology of cheese manufacture and ripening. Education of cheese makers and those who will conduct the next generation of research is also of utmost importance.

Although exceptional progress has been made in the mechanization and automation of cheese making, there is still a need to refine the cheese making process to consistently produce cheese with the desired characteristics. Membrane processing of milk and whey will offer excellent opportunities to manufacture cheese with consistent functionality and use for milk components in an economically sound manner, but only if all the fractions of milk are used. Membrane processing also offers a means to recover water, and there is great potential for this water to be recycled in the cheese plant.

Changes to Code of Federal Regulations Title 21 (CFR, 2017) will be necessary to allow the use of milk separated through membrane processing for cheese making, and it will be a priority for the cheese industry.

A point of concern is the necessity of using terms on the labels of cheese that was produced from milk using membrane processing (i.e., UF, diafiltration, and microfiltration). These terms are not well understood by consumers and may lead to apprehension about cheeses made using milk concentrated or separated by these processes. Other countries do not have to indicate the use of membrane-filtered milks because they consider them all to be milks and simply put “milk” as the ingredient on the labels. The development of new products and utilization of milk components to their greatest advantage will also offer a new direction to improve cheese quality and sustainability of resources. Code of Federal Regulations Title 21 defines what ingredients can be used to make cheese, lists the compositional requirements for certain cheeses (standard of identity), and gives a rough outline of how these cheeses can be made. If a cheese does not have a standard of identity, no compositional requirements exist.

Major undesirable traits of cheese are the lack of flavor intensity and poor flavor quality. This has plagued cheese makers since the beginning. Perhaps it is just implementation of the technology already available, but perhaps it is that the technology is lacking. If the latter is the case, renewed emphasis on flavor development in cheese is warranted, especially in relation to reduced-sodium and reduced-fat cheeses. The linkage of genetic research and biochemistry of microorganisms is underway and has great potential to enhance flavor development and the safety of cheese.

The number of faculty devoted to full-time dairy research has declined, as has the number of universities with devoted dairy foods curricula and the financial resources to conduct research and training. These declines will have serious negative consequences for the cheese manufacturing industry and associated industries supplying starters and coagulants, equipment, converters of cheese (packaging), end users (pizzerias, chefs), and retail outlets. Demand for trained personnel by industry and academia is, and will be, high. Continued training of current and future employees will be necessary for a vital dairy industry and may require different approaches, perhaps as was done 100 yr ago with dedicated dairy manufacturing curricula.

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APPENDIX

Table A1. Selected milestones in cheese production and quality

Year	Milestone	Reference
1851	First cheese factory in United States.	Thom and Fisk, 1918
1890	Babcock fat test introduced.	Babcock, 1890
1890s	Commercial production of starter cultures begins.	Johnson, 2014
1902	Cold-curing of cheese introduced, with consolidated cold curing station to service several factories.	Babcock and Russell, 1902
1943	Pasteurization of milk for cheese making becomes mandatory in some states.	Price, 1956
1940s	Adjunct bacteria are added to enhance cheese flavor development.	Harris and Hammer, 1940
1943	Mechanized cooling of can milk.	Hlynka et al., 1943
1950	Establishment of definitions for several varieties of cheese by the Food and Drug Administration.	Price, 1956
1960s	Mechanized cutting vats are developed.	Olson, 1970
1964	Direct acidification of milk for cheese making of certain varieties.	Breene et al., 1964
1974	Membrane filtration of milk is used for cheese making.	Kosikowski, 1974
1976	Plasmid DNA is found to encode for lactose fermentation.	McKay et al., 1976
1980s	Fermentation produces chymosin.	Johnson and Lucey, 2006
1986	Resistance to bacteriophage found to be encoded by plasmid DNA.	Sanders et al., 1986