Novel Products and New Technologies for Use of a Familiar Carbohydrate, Milk Lactose

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ABSTRACT

The cheese industry produces large amounts of lactose in the form of cheese whey and whey permeate, generating ~27 million tonnes/yr in the US alone. Many uses have been found for whey and lactose, including uses in infant formula; bakery, dairy, and confectionery products; animal feed; and feedstocks for lactose derivatives and several industrial fermentations. Lactose use in food products, however, is somewhat limited because of its low solubility and indigestibility in many individuals. For this reason, lactose is often hydrolyzed before use. Still, demand is insufficient to use all available whey lactose. The result is a low market value for lactose; almost half of the whey produced each year remains unused and is a significant waste disposal problem. Several approaches are possible for transforming lactose into value-added products. For example, galactooligosaccharides can be produced through enzymatic treatments of lactose and may be used as a probiotic food ingredient. Organic acids or xanthan gum may be produced via whey fermentation, and the fermented whey product can be used as a food ingredient with special functionality. This paper reviews the physical characteristics, production techniques, and current uses of lactose, whey, and lactose derivatives. Also examined are novel fermentation and separation technologies developed in our laboratory for the production of lactate, propionate, acetate, and xanthan gum from whey.

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(**Key words**: lactose, milk, whey, review)

Abbreviation key: **BOD** = biological oxygen demand, **CMA** = calcium magnesium acetate, **SCP** = single-cell protein, **TOS** = transgalactosylated oligosaccharides, **WPC** = whey protein concentrate.

INTRODUCTION

The yearly milk production in the US from 1992 to 1993 was ~69.1 million tonnes (152 billion lb), of which ~43% (65 billion lb) was used in cheese production (107). Thus, about 27 million tonnes of liquid whey (equivalent to ~1.7 million tonnes of whey solids or ~1.3 million tonnes of whey lactose) are produced each year in the US as a by-product of cheese making. The development of new uses for lactose, a major component of milk and whey, both as whey or whey permeates and as pure lactose, is, therefore, of great interest, as it has been for hundreds of years. During the Middle Ages, cheese whey was used as a component of hair tonics and burn salves, although certainly these uses would not have kept pace with supply (56). Undoubtedly, the bulk of the whey produced was simply dumped into rivers and streams, the same approach taken until recently by modern cheese makers (56). Justifiable environmental concerns over dumping this waste with high biological oxygen demand (**BOD**) have ended that practice, leaving dairies with enormous amounts of whey for disposal. The industry has developed many uses for lactose, as well as for whey itself, in order to consume some of this costly waste stream. However, because of continuing increases in the production of cheese (Figure 1) and whey protein concentrate, a huge lactose surplus in the form of whey and whey permeate still exists (46). Recent estimates place the surplus at ~13 to 17 million tonnes of whey/yr (3, 120).

Currently, the major uses of whey and whey permeate are the manufacture of dried whey powder and refined lactose. These uses, however, are often aimed at keeping the surplus whey out of the sewers, rather than at producing a highly desirable product. The ultimate goal for the dairy industry should be to turn whey lactose into a profit-generating feedstock for high value-added products. This paper reviews current and novel products from whey lactose and new technologies that can improve the economics of whey lactose. Properties of lactose and various whey products based on lactose and their market potential are also discussed, and several promising areas for future research are suggested. There are many excellent reviews (48, 54, 56, 73, 124, 128) of whey and lactose utilization to which the reader can turn for additional information.

LACTOSE

Chemical Structure

Lactose is present in the milk of most, but not all, mammals (49). At approximately 4.8% (wt/vol), lactose is the major carbohydrate in bovine milk. The chemical structure of the lactose molecule, along with those of several lactose derivatives, is shown in Figure 2. The α- and β-anomers arise from the asymmetric glucose carbon. Several excellent reviews of lactose and lactose chemistry exist (39, 103, 104). This paper does not attempt to cover lactose chemistry in detail, but rather describes existing and potential products based on the chemical and physical properties of lactose and lactose derivatives.

Manufacturing Processes

Western Europe typically uses whole whey to produce lactose, although, in the US, permeate is typically used. At one time, for whole whey processes, the whey protein was steam-denatured prior to crystallization; modern techniques have eliminated this step by carefully controlled processing conditions (108).

There are three general methods for producing lactose from whey permeate (39). The most common method, the traditional one, is crystallization from a supersaturated solution, but this

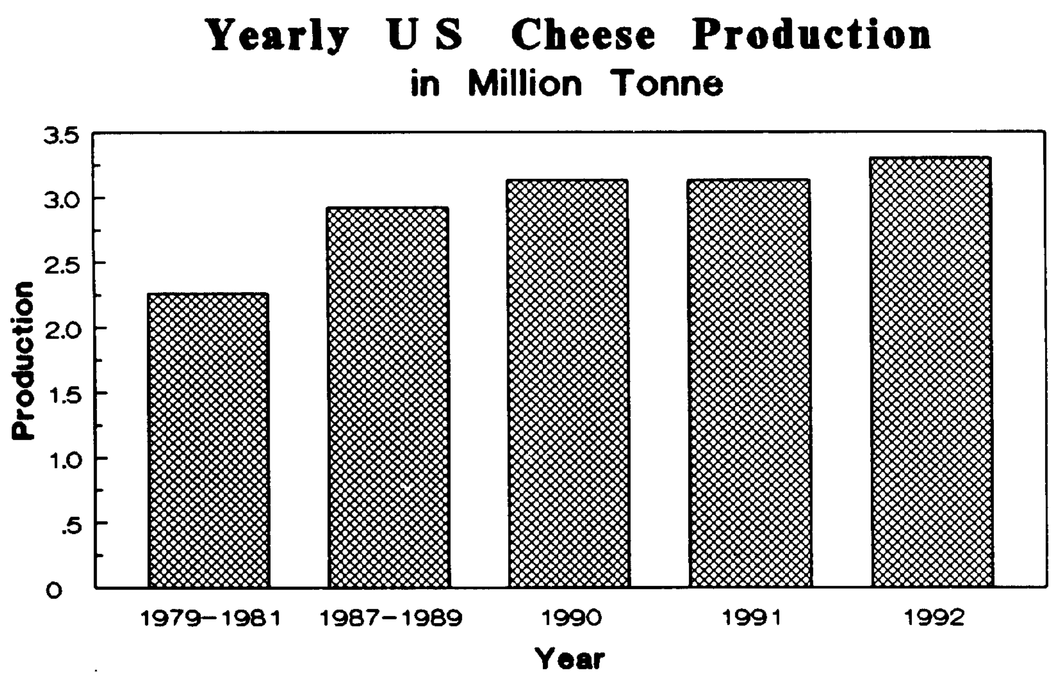

Figure 1. Yearly cheese production in the US.

method is economically favorable only on a large scale (124). Because amorphous lactose cakes upon drying, seeding is often used to initiate growth of α-lactose hydrate crystals, followed by spray-drying the semi-crystallized concentrate to produce a noncaking lactose powder (51). Precipitation of lactose by alkali earth metals that form complexes with the sugar, known as the Steffen process (78), is also possible. Alcohols or other solvents that decrease the solubility of lactose can also be used to crystallize lactose, but this method is not used commercially.

A conceptual flow sheet of the standard industrial method, crystallization from concentrated permeate, is given in Figure 3. Whey protein is first removed by UF. At some plants, reverse osmosis is then used to preconcentrate whey permeate to 12 to 15% solids. Seven-effect evaporators are used in modern plants to concentrate the whey permeate further. Vapor recompression, in which the vapors from the evaporator are compressed and fed back to the steam chest, is often used to increase steam economy in the evaporator. Thermal vapor recompression is preferred to mechanical vapor recompression in the US because mechanical compressors are expensive, have high power requirements, and result in higher maintenance costs than do the steam jets used in thermal vapor recompression.

Not all of the lactose present in whey permeate can be economically recovered by crystallization. About 20 to 40% of the original lactose content goes with salts in the mother liquor, which generally has no industrial use because of its high salt content. An alternative process is to separate minerals from lactose in whey permeate by nanofiltration. The lactose-containing stream is then further demineralized by electrodialysis and ion exchange before spray drying. Very little waste is generated from this process.

Properties

Several crystalline forms of lactose with differing physical properties exist (77, 124). The α-lactose monohydrate, the predominant

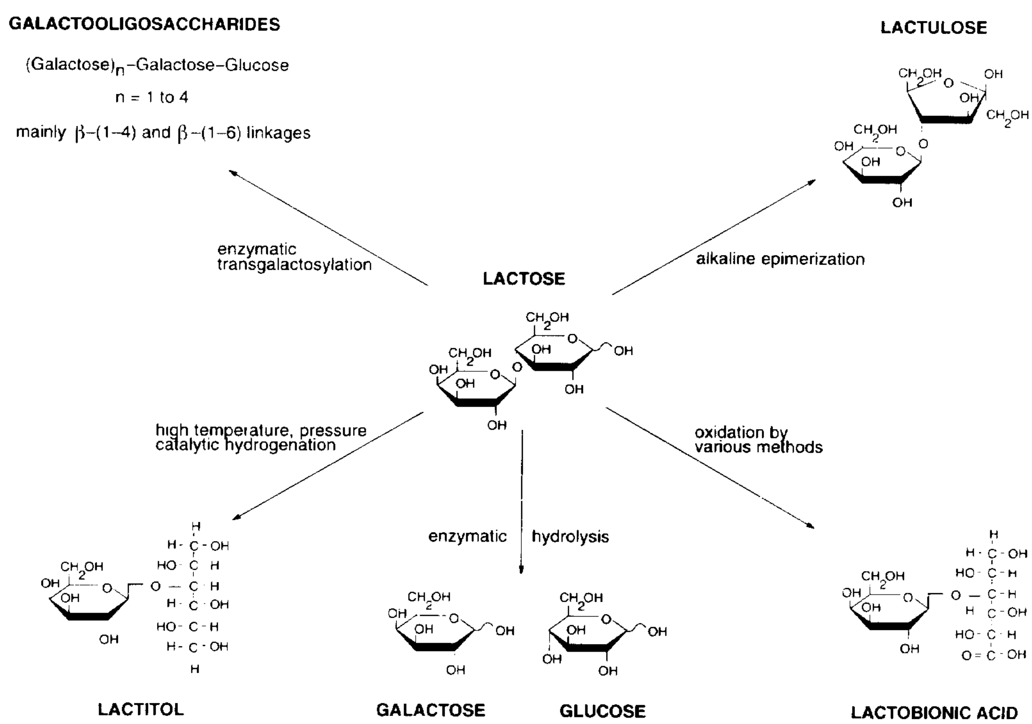

Figure 2. Chemical structure of lactose and lactose derivatives.

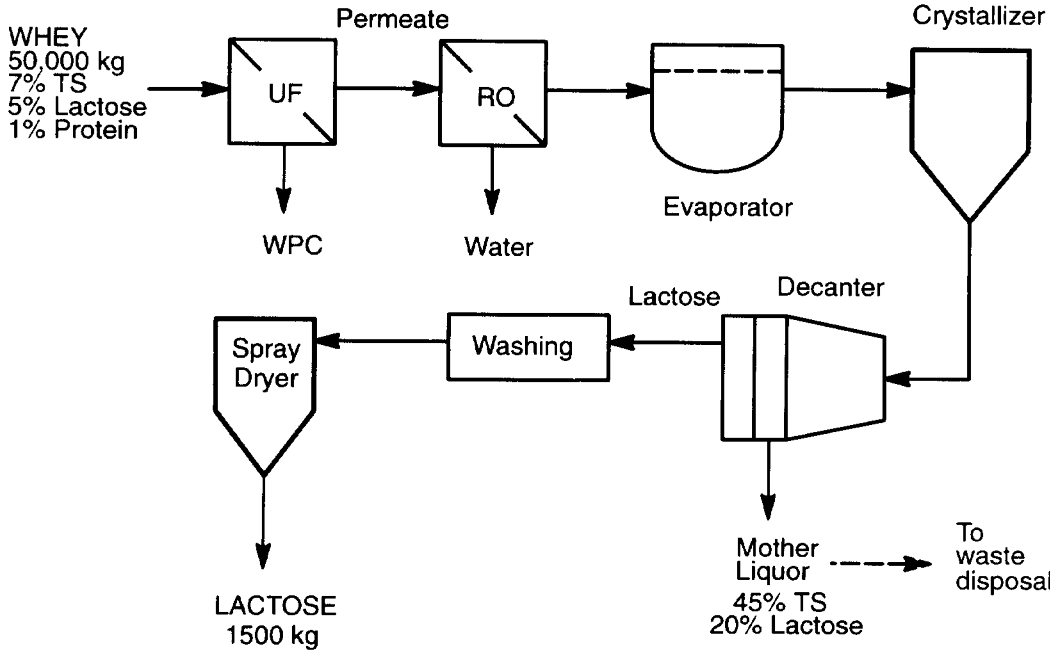

Figure 3. A conceptual flowsheet for lactose production from whey permeate. RO = Reverse osmosis.

commercial form, forms upon crystallization below 93.5°C and is nonhygroscopic. From α-lactose monohydrate, the α-anhydride can be formed by heating above 100°C under vacuum. The anhydride is very hygroscopic. Crystals of β-anhydride form when crystallization is carried out above 93.5°C. This form is more readily water soluble upon mixing and so has some specialized uses in products that require fast dissolution. The β-anhydride is also markedly sweeter than either α-form (124). Unlike the α-anhydride, the β-anhydride is not particularly hygroscopic. The β-anhydride is less soluble in water above 93.5°C than is either α-form. This difference in solubility is the basis of several conversion schemes to produce β-lactose anhydride. In solution, an equilibrium mix of about 63% β-form results (39, 124).

A glassy form of lactose also exists that is a noncrystalline mix of α- and β-lactose that occurs upon rapid drying. The glass is hygroscopic, and, if moisture exceeds 8%, α-monohydrate begins to crystallize, resulting ultimately in a hardened cake (124). This tendency must be considered when products based on lactose are manufactured.

Many of the physical properties of lactose affect its use in its major market, food applications. These properties are summarized in Table 1. The sweet, mild taste of lactose accentuates natural flavors without being cloying, which is an advantage in many food applications (77). The ability of lactose to adsorb volatiles and coloring agents allow its use to extend shelf-life of food powders and improve flavors of products such as instant coffee. Because lactose is nonhygroscopic, free-flowing formulations may be prepared based on lactose. The reducing glucose moiety of lactose participates in Maillard reactions, which contribute to brown colors and flavor development in foods (39). Lactose, similar to other carbohydrates, improves calcium absorption in the digestive system and increases the beneficial production of lactic acid in the intestine, thereby inhibiting undesirable organisms and increasing peristalsis (91).

Lactose does have some undesirable properties when used in foods. It is relatively less soluble than other sugars (39), leading to a tendency to crystallize at relatively low concentrations, producing a sandy mouthfeel. Lac-

TABLE 1. Physical and chemical properties of lactose important to food uses.

Desirable	Undesirable
Sweet, mild taste	60% less sweet than sucrose
Accentuates natural flavors without overwhelming sweetness	Low solubility
Adsorbs pigments and volatiles, especially in anhydrous forms	Sandy mouthfeel at high concentration
Nonhygroscopic and free flowing	Poor digestibility
Participates in Maillard reactions, giving appealing brown color in baked foods	Lactose intolerance for some individuals
Improves calcium absorption in human intestine	
Increases beneficial production of lactic acid in intestine	

tose is also relatively less sweet than sucrose, although the difference decreases as concentrations increase (39). Lactose is not digested as readily as other sugars, which results in limitations in the use of lactose in some foods. Because the lactose molecule must be hydrolyzed to galactose and glucose before it can be absorbed in the small intestine, individuals lacking the necessary enzyme activity suffer from lactose malabsorption or lactose intolerance when they ingest lactose. Lactose malabsorption is the inability to digest an oral dose of lactose of the order of 10 to 50 g of pure lactose, as shown by breath hydrogen testing. The higher dose is the lactose equivalent of a full liter of milk, an amount unlikely to be consumed in a normal serving of a product containing lactose. The incidence of lactose intolerance is of greater importance to the food industry. Lactose intolerance results in clinical symptoms (diarrhea, bloating, and flatulence) upon the consumption of relatively small quantities of lactose and must be considered in the formulation of a food or pharmaceutical product containing lactose (125).

Uses

The major uses of lactose include food ingredient, ingredient in infant formula, tablet compound for the pharmaceutical industry, and raw material for lactose derivatives (Table 2).

Food uses of lactose are listed in Table 3. The most natural use is infant formula; human milk is 7% lactose. Lactose has also been used to sweeten flavored milks, such as chocolate milk (77). Although lactose may sometimes crystallize in foods, causing a "sandy" mouthfeel, lactose can be used to delay the crystallization of other sugars, such as sucrose, and therefore is used widely in confectioneries. Because it is not fermented by baker's yeast, *Saccharomyces cerevisiae*, lactose is used for emulsification in baked goods (124). The anhydrous forms of lactose trap volatiles and act as a flavor and dye carrier, as it does in instant coffee (78).

Lactose use in pharmaceuticals is primarily as a filler and drug carrier (39). Tablets are also occasionally covered with lactose coatings (77).

Lactose has been used as a carbon and energy source in several fermentations, including penicillin production in the early days of the antibiotic industry. However, this use has diminished, partially because of the cheaper dextrose from the corn milling industry. One of the more novel uses recently suggested for lactose is as an inducer for overexpression of protein in genetically engineered organisms. Isopropylthio-β-D-galactoside, or IPTG as it is more commonly known, is the inducer used experimentally for the *tac* and *lac* promoters, but its cost is a problem in large-scale production. Neubauer et al. (75, 76) have shown that lactose can be used to induce the desired expression by timing its addition to the fermentation to coincide with the onset of glucose depletion.

Lactose also serves as the raw material to produce several useful derivatives for food and pharmaceutical applications. Large quantities of crude lactose are available in whey and whey permeate, and their uses are also dependent on the composition and properties of the whey. These uses are discussed in separate sections in this article.

Market

If the lactose supply increases, price decreases rather than demand increasing (124). Although recent trends for use of lactose in

TABLE 2. Uses of lactose.

Use	Examples
Food	Infant formula, baked goods, beverages, dairy products, candies, sauces, and frozen desserts
Raw material for lactose derivatives	Lactulose, lactitol, lactobionic acid, oligosaccharides, and lactosyl urea
Pharmaceutical formulations	Filler and drug carrier; tablet coating
Fermentation substrate	Penicillin production
	May be used as an inducer for gene expression in recombinant protein production using *lac* promoter

candy (replacing whole and skim milk powder) doubled lactose consumption from 1990 to 1991 (36,000 to 86,000 tonnes) and temporarily caused an increase in demand and price from 29¢/kg in 1988 to 76¢/kg in 1991 (46), recent increases in industry capacity have again reduced lactose prices. Fierce US competition from high fructose corn syrup makes it highly unlikely that the lactose market will improve dramatically enough to justify increased lactose manufacture from whey. For this reason, the thrust of the dairy industry should be to use whey lactose as a raw material for value-added products.

LACTOSE DERIVATIVES

Several important lactose derivatives and their applications are summarized in Table 4 and are discussed in this section.

Lactulose

Lactulose (4-O-β-D-galactopyranosyl-D-fructose) is an isomer of lactose in which the glucose aldehyde is converted to a ketone (fructose) by alkali hydroxide catalysis (124). Lactulose is not found in milk, but is found in various wheys and heated milk (104). Lactulose syrup is a widely used pharmaceutical in Japan, the US, and worldwide. Lactulose has a mildly purgative action and inhibits the growth of ammonia-producing organisms, thereby aiding in the treatment of chronic hepatoportal encephalopathy, a condition in which the brain is affected by nitrogenous substances from the colon (38, 103). In Japan alone, lactulose is used to treat 20,000 patients a day (101). Lactulose syrup is also widely used as a laxative in the treatment of chronic constipation.

In addition to medical uses, lactulose is becoming a health food ingredient in Japan.

TABLE 3. Food uses of lactose (39, 78, 103, 124).

Application	Function or motivation of use
Baked goods	Carrier of flavor and color, increased crust browning, and enhanced shortening emulsification
Sweetened condensed milk	Price advantage
Canned fruit	Improved texture
Dairy products	Price advantage
Dry soups and sauces	Flavor enhancer, reduced sweetness, extended shelf-life, anticaking agent, dispersibility, and price advantage
Fruit beverages	Health aspects
Instant drinks	Anticaking agent, aroma enhancement, and dispersibility
Salad dressings and mustard	Reduced sweetness, extended shelf-life, and price advantage
Confectionery products	Reduced sweetness, aroma enhancement, color binding, better mouthfeel, improved chewiness, and extended shelf-life
Cocoa	Reduced sweetness; aroma enhancement
Frozen desserts and ice cream	Price advantage
Infant formula	Mimic of human milk
Meats and sausages	Reduced sweetness, extended shelf-life, and price advantage
Spices and flavorings	Anticaking agent, aroma enhancement, and dispersibility

TABLE 4. Lactose derivatives.

Lactose derivative	Application
Lactulose	Health food, infant nutrition, and pharmaceutical use
Lactitol	Sweetener for diabetics, noncariogenic sweetener, and raw material
Fatty acid esters of lactitol	Emulsifiers and humectants
Lactosyl urea	Animal feed
Lactobionic acid	Lactose determination and firming agent in foods
Galactooligosaccharides	Probiotic food and infant formula

Lactulose is not digested in the small intestine. In the large intestine, it promotes the growth of *Bifidobacterium* species. This trait is especially of interest in nutrition of infants for whom lactulose is thought to stimulate growth of intestinal flora similar to those in breast-fed babies (70, 124). *Bifidobacterium* species are the predominant microorganisms in these babies. A bifidobacteria-rich intestinal flora ought to benefit humans by inhibiting undesirable organisms, stimulating peristalsis through the production of organic acids, inhibiting ammonia formation, improving protein metabolism, and producing vitamins.

The Japanese are marketing many products containing lactulose, including but not limited to infant formula (70, 101). Lactulose has been approved in Japan as a "special food material for health maintenance and protection against enteric infection" (102). The recent discovery of a new crystalline form, lactulose trihydrate, with a positive heat of solution and a cool, sweet taste may expand the product possibilities considerably (101). The major lactulose limitation is that consumption of large quantities can lead to diarrhea (104).

Lactulose is relatively expensive to produce because of the low product yield (~30%) from the reaction and high costs of purification (38). Current worldwide production (1992) is nearly 20,000 tonnes (50% lactulose syrup) annually with a new plant scheduled to open soon in Canada (72). Lactulose has been successfully tested as growth promoter for pigs and calves; this large potential market could stimulate further increases in capacity (38).

Lactitol

Lactitol (4-O-β-D-galactopyranosyl-D-glucitol) is produced by catalytic hydrogenation (reduction) of lactose, resulting in a polyol composed of galactose and sorbitol (9). The product yield is >90%. Like lactose, lactitol can be easily crystallized and dried to a powder. Lactitol is softer than lactose and does not have the gritty mouthfeel problem that is associated with lactose (9, 104). Lactitol is useful for diabetics and as a noncariogenic, low calorie, bulk sweetener, readily replacing or expanding lactose use in food products. Lactitol is stable to Maillard reactions and can be used as bulk sweetener in ice cream, candy, baked goods, and chewing gum. The low hygroscopicity of lactitol makes it useful in crisp products such as crackers (104). Lactitol also may have probiotic effects similar to those from lactulose. Lactitol has been suggested as a growth promoter for pigs and calves (38). Its use as a food ingredient has been approved by the European Community. However, the greatest immediate potential of lactitol may be as raw material for ester emulsifier manufacture.

Esters of lactitol and long-chain fatty acids are excellent surfactants and have applications as industrial detergents, surface coatings, antimicrobials, and food emulsifiers. Their detergent, emulsification, and wetting properties are determined by the substituent ester group (103, 104). They also have potential for use as humectants, plasticizers, lacquer additives, hot-melt adhesive additives, and bittering agents (103). The higher esters may be useful as low calorie fat substitutes (104).

Lactobionic Acid

Lactobionic acid (4-O-β-D-galactopyranosyl-D-gluconic acid) can be produced from lactose by catalytic oxidation of the free aldehyde group (38). Lactobionic acid is used for lactose analysis and can be used as a firming agent in gels or to improve dispersibility and reduce caking in pudding mixes (104). Lactobionic acid is also an essential part of the preservation solution for organs prior to transplantation (38).

Galactooligosaccharides

Galactooligosaccharides, also known as transgalactosylated oligosaccharides (**TOS**), are formed during the hydrolysis of lactose by a transgalactosylation reaction in which the enzyme transfers the galactose moiety of a β-galactoside, such as lactose, to a hydroxyl group on an acceptor molecule, which may be galactose, lactose, or a previously formed TOS (87, 89, 116). Under usual hydrolysis conditions, any TOS formed is eventually hydrolyzed, and the final product has little or no oligosaccharide content. Conditions may be manipulated, however, to yield high concentrations of oligosaccharides. High lactose concentration leads to more TOS formation. Trisaccharides (galactosyl lactoses) often form, then act as acceptors, leading to tetra-, penta-, and even hexasaccharides. Different enzymes lead to different product mixes, and an individual enzyme species is likely to lead to only a limited number of TOS from the wide variety possible (98).

Oligosaccharides are beneficial in several ways. Like lactulose, oligosaccharides are not digested in the small intestine, passing instead to the colon, where they promote the growth of *Bifidobacterium* species. Because they are indigestible, the TOS may be used as a low calorie sugar. The TOS are also noncariogenic. The TOS occur in human milk and so are presumed safe (98). The TOS apparently stimulate the predominance of bifidobacteria observed in the gastrointestinal tract of breast-fed infants; bifidobacteria are lacking in infants fed formula (40). They appear to block enterotoxin receptors and bind bacterial pathogens, although data are insufficient for us to be confident of these two roles (72, 98).

The TOS present a tremendous market opportunity for lactose. If health claims are true, TOS will likely have a large health food market. If disease prevention claims are true, large pharmaceutical markets may materialize. With the enzyme technology required already in existence, this product area can be commercialized quickly in response to developing demand. However, there will be market competition with other oligosaccharides, such as lactulose, raffinose, fructo-oligosaccharides, isomaltooligosaccharides, and soybean oligosaccharides, which may also have similar health benefits. Current production includes 6500 tonnes/yr by Yakult Honsha Co. (Tokyo, Japan), using enzymes of *Aspergillus oryzae* (72, 98) for infant formula and health food products. Snow Brand Company (Tokyo, Japan) has added galactosyl lactose to its infant formula for several years (98).

Other possibilities include development of heterologous oligosaccharides based on more than one substrate saccharide or production of oligosaccharides from lactose derivatives, such as lactitol, to form novel compounds for foods and pharmaceuticals (98).

The technology to produce galactooligosaccharides is basically that of lactose hydrolysis. Whey or whey permeate is usually used as the feedstock. The oligosaccharides, which are present in a mixture with lactose, glucose, and galactose, are separated by activated carbon adsorption, followed by alcohol elution. The oligosaccharides yield from the enzyme reaction is generally <40% of the initial lactose in the solution (53). This low yield and high enzyme costs contribute to the high product cost. However, the enzymatic synthesis of oligosaccharides can be improved using various novel process approaches, which have been reviewed recently (89). Also, Mozaffar et al. (74) have reported that one of the two forms of lactase produced by *Bacillus circulans* formed 41% of total sugars as TOS, and the other produced only 6%. This result suggests that modern enzyme engineering approaches may be useful in changing lactase from a hydrolase to a synthase, thus greatly improving the yield of oligosaccharides.

Other Lactose Derivatives

For ruminants that can use nonprotein nitrogen, lactosyl urea is a preferred feedstock over urea because of increased palatability, reduced toxicity, and controlled release of the nitrogen, but lactosyl urea has not been commercially developed (124).

Many other compounds can be produced from lactose via chemical, enzymatic, or fermentation processes, but an economic incen-

TABLE 5. Composition of whey and whey permeates (5, 36, 83).

Whey type	Composition					
	Lactose	Protein	Lactic acid	Ash	Salt	Fat
	(% dry basis)					
Sweet whey	74–81	12.8–15.2	1.8–2.2	8.0	2.5	1.0
Acid whey	65–80	9.9–15.5	7–10	7.0–19.4	2.5	1.0
Sweet whey permeate	86.0	.2	2.4	8.8	NA	<.1
Acid whey permeate	74	.3	7.5	9.7	NA	<.1
Delactose whey[1]	<60	16–24	NA	11–27	NA	.2–.4
Demineralized whey	<85	10–24	NA	<7	NA	.2–.4

[1]Industrial term for mother liquor resulting from lactose crystallization.

tive may not currently exist to use whey lactose as a raw material (39).

WHEY AND WHEY PERMEATE

As shown in Figure 1, US cheese production has risen over the last several years. Although new uses for whey and whey products have been developed, the market for such products has not been sufficient to keep up with the growing supply of whey (19). In both the US and Europe, only approximately 50% of the whey produced is used to formulate product. The remainder is treated as waste (73). Production of additional lactose from whey is not the answer. Lactose has been sold at only $.22 to $.88/kg (contract price) in recent years, and additional capacity will only drive the price down further. The development of new products and expanded markets for whey lactose, as well as new technologies to enable economical whey processing and product manufacture, will be critical to convert waste costs into product profits for the dairy industry.

Sources and Composition

The composition of various types of whey affects their use. Sweet whey, which results from the production of hard cheeses such as Cheddar, has relatively high pH and low ash content compared with that of acid whey, which is from fresh or soft cheeses such as cream and cottage cheese. Salt whey, the drippings from salted curds, may contain up to 10% salts. Whey permeates, which are produced as a by-product of whey protein production by UF, have little of the protein found in whole whey. The dry solids of deproteinized wheys and whey permeates are mostly lactose, making these forms potentially more manageable as a raw material for further processing (124). Table 5 shows the composition of the major categories of whey and whey permeate.

Demineralization of whey removes excess ash, expanding the application possibilities. Demineralization is accomplished either through ion exchange, which can produce up to 95 to 99% demineralization, or electrodialysis, by which 90% demineralization is possible (44, 52). A combination of the two methods may be desirable; electrodialysis can be used to bring about ~50% demineralization and then, as the energy requirements increase with decreasing electrolyte concentration, ion exchange can finish the process (7). Heat and pH treatments lead to precipitation of salts such as calcium phosphate, resulting in moderate demineralization. Nanofiltration and counter diffusion are newly developing techniques that may have future use (44).

The increasing use of UF milk retentate in cheese making yields yet another stream of permeate for which many applications could be similar to those for sweet whey permeates (42). Milk permeate, produced by concentrating milk by UF, is high in lactose with little or no protein. Uniformity of composition may make UF milk permeate an ideal feedstock for some applications, such as in beverage formulation or as a fermentation substrate (127). On-farm filtration may influence whey availability: cheese made from concentrated milk yields much less whey. Currently, the permeate is generally used on the farm, presumably for animal feed or fertilizer (73).

Whey Products

The major economic use for whey is to produce various whey products for food uses. As shown in Figure 4, dried whey powder accounts for >60% of all the whey processed in 1993 (3). Most of these whey products are from sweet whey. Only ~10% of the acid whey produced in the US is processed to a marketable product. Separation of whey into various fractions, such as whey protein concentrate (WPC), has increased the whey product values. Of course, when WPC is a desired product, the whey permeate and lactose remain as a low value by-product. Uses for whey proteins are beyond the scope of this paper; we discuss only lactose-containing wheys and whey fractions.

How an individual dairy chooses to use its whey stream depends on its size. Dairies that produce <50 kl/d of whey might be limited by economies of scale to use whey as animal feed or fertilizer; dairies producing 50 to 200 kl/d might profitably produce UF retentates, lactose lick blocks, fermented ammoniated condensed whey, whey cheese, whey powder, and Ricotta cheese; dairies producing over 200 kl/d could pursue markets in WPC, lactose crystallization, fermentations, hydrolyzed lactose whey syrup, and whey protein blends (71). Other possible uses include production of demineralized whey for food and infant formula applications and the production of whey beverages.

Food Uses

There are many food applications for the various forms of whey and whey products (Table 6). These uses may be based on the unique characteristics of whey, such as Maillard reactions between whey proteins and lactose that contribute to flavor and browning in baked goods, or they may be based strictly on economic advantage, such as in ice cream manufacture in which up to 25% of the SNF

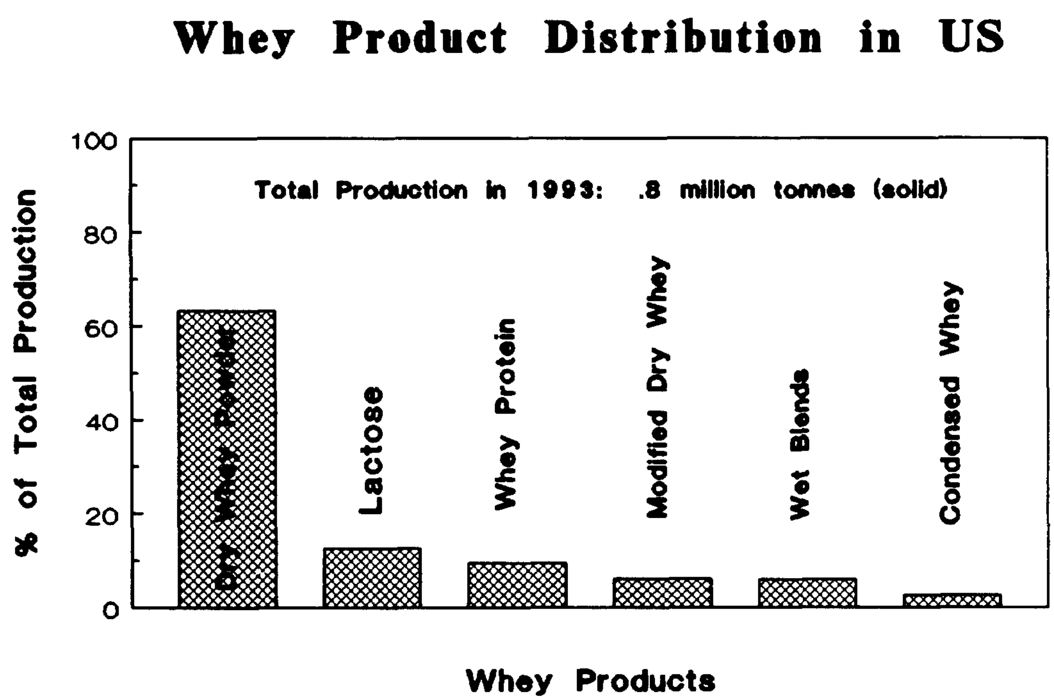

Figure 4. Production of whey products in the US in 1993.

TABLE 6. Food uses of whey and whey permeate.

Sweet whey	Ice cream and toppings, baked goods, icings, fudge, candy coatings, caramels, chocolates, other candies, margarine, cheese foods, gravy mixes, snack foods, fruit juices and beverages, soups, infant foods, puddings, meat products, and whey cheese (mysost)
Acid whey	Fruit-flavored beverages, fermented dairy products, cheese, cheese powders, dips, spreads, baked goods, salad dressings, sherbets, sausage, and processed meats
Whey permeate	Whey beverages

may legally be replaced by whey (81). The UF milk permeate may be returned to cottage cheese in the form of dressing, preventing it from entering the waste stream and providing a required feed stream (128). Fortunately, the whey nutritional profile fits current consumer preferences for more protein and less fat (19).

Often whey is demineralized before food use (44) to overcome salty flavor defect of some whey and to correct electrolyte imbalances that may render whey unsuitable for infant formula. Almost 65% of the demineralized whey permeate produced is used in infant formula (7). It also results in improved solubility, decreased sourness, and increased perception of sweetness (41). Demineralized acid whey can be used for sweet whey applications, such as producing whey powders (7).

Many whey beverages are available, but they are more popular in Europe than in the US. These beverages have been reviewed by Kravchenko (58), who divided them into groups: whey-based fruit beverages, thirst-quenching carbonated beverages, dairy-type beverages (fermented and unfermented), and alcoholic beverages (of relatively little importance to the market). These beverages are marketed for health buffs and athletes based on the vitamin and soluble protein content of the beverages (32) and the presence of *Bifidobacterium* species in the fermented products. Manufacture of these beverages has been covered in detail (48). The major hurdle to developing a market seems to be identifying marketable flavor blends and maintaining quality control.

Animal Feed

In the past, a good deal of the whey produced during cheese making was returned to the farms for use as animal feed. Increased transportation costs, the alternate use of soybeans, and delivery of milk to the factory by independent truckers rather than by the farmer (who would reclaim the whey for animal feeding) have decreased this use; however, with increased sewage costs and interest in lowering feed costs, this route is being reexamined.

Whey is a good source of protein, lactose, and minerals. Even permeate, concentrated whey, and mother liquor can be used. A 29% savings in feed costs has been calculated for swine (72). Ironically, lactating dairy cows must have only limited whey consumption so that they consume enough dry matter to support lactation. Use of whey as feed may be suitable for small dairies that lack the scale of operation for manufacture of other whey products. The animal feed operation for many dairies is simply a defensive move to cut whey disposal costs when cheap land spreading of whey is no longer an available option. Transportation costs for shipping liquid whey to animal feeders can be prohibitively high.

An alternative to feeding liquid whey is to use whey-based feed blocks, which have high palatability and may be used to deliver medications and dietary supplements. Feed blocks can be made from concentrated whey (50 to 55% total solids) plus additives (14).

Land Spreading

Many think spreading whey on land is purely a disposal route, but whey has value as a fertilizer. Whey is nontoxic; improves soil texture; contains the plant nutrients nitrogen, phosphorous, and potassium in proper proportions; and gives residual fertility. However, whey must not be applied in excess, and the annual limit is about 5 cm/yr (72). Spreading of whey on land is no longer an option for many dairies because of recent environmental regulations.

Hydrolyzed Lactose Whey Syrups

An area that has received a great deal of research attention (but little commercial success) in the last decade is the use of whey to produce hydrolyzed lactose whey syrups (18). This topic has been thoroughly reviewed recently (31, 33, 37, 124, 125).

Splitting the lactose molecule into galactose and glucose was expected to solve the whey surplus problem; hydrolyzed lactose would make its way into food and feed products and have added value as a fermentation feedstock relative to unhydrolyzed whey. With sufficient hydrolysis, crystallization is no longer a problem in foodstuffs. In some applications, such as breadmaking, hydrolyzed lactose produces an even more desirable product than does sucrose (80). With a taste twice as sweet as lactose (124), hydrolyzed lactose syrup is a lower calorie sweetener than whey or lactose and is especially useful in applications in which additional sweetener had previously been necessary, such as chocolate milk (72). Lactose-intolerant humans and animals can ingest hydrolyzed lactose with no difficulty. Organisms that are unable to ferment lactose may be able to ferment hydrolyzed lactose (16), allowing a wider variety of possible fermentation products. Potential uses for hydrolyzed lactose syrup include syrups, baked goods, meats, sausages, fruit beverages, fermentations, animal feed, dietetic foods, whey cheese, beverages, candies, chewing gum, frozen desserts, ice cream, yogurt, wine, beer, canned fruit, canned vegetables, puddings, and salad dressings. Despite these advantages, markets that were expected to materialize in the mid-1980s for this technology have not done so, primarily because of competition from other sweeteners (126).

The technology to produce hydrolyzed lactose syrup is well developed and used to produce lactose-hydrolyzed milks for lactose-intolerant individuals. Zadow (124, 125) and Crabtree (22) have reviewed current methods of lactose hydrolysis. Either chemical hydrolysis at low pH and high temperatures or enzymatic hydrolysis may be used. The chemical method is economical for protein-free streams such as permeates, but severe conditions cause excess browning in whole wheys or milks (21). For this reason, enzymatic hydrolysis is usually the method of choice.

Enzymes from *Aspergillus* and *Kluyveromyces* species are most commonly used; the fungal enzymes are particularly suitable for acid whey (having an acid pH optima). These enzymes are, however, inhibited by galactose and thus cannot achieve the degree of hydrolysis of yeast enzymes that are suitable for sweet wheys at neutral pH (124, 125). Bourne et al. (10) suggested that selective crystallization be used to remove lactose from the reactor effluent so that lactose could be recycled to the reactor without free galactose, allowing greater hydrolysis. The kinetics of the hydrolysis are nonlinear, especially >50% hydrolysis, so the minimum degree of hydrolysis necessary for a given product should be the goal (69). The enzyme process is not inexpensive, primarily because of the high costs of enzyme. The cost can be reduced by using immobilized enzymes (5, 6, 105, 114) or whole cells (35).

In addition to the high processing cost, hydrolyzed lactose and whey syrups have some disadvantages. Extensive hydrolysis is necessary to prevent crystallization of lactose in storage (125). The hydrolysate does not dry well and therefore must be used as syrup, which may be a disadvantage, although costly drying is not needed, and the syrup is easier to handle in food processing. The syrup does not have sufficiently reduced water activity to prevent contaminant growth, so care must be taken during storage (73, 125). Transport of syrup is more costly than for lactose powder because of the increased weight. Also, demineralization may be necessary to allow replacement of sucrose in some products (124), but demineralization raises costs, sometimes unacceptably (46).

Several nutritional concerns have been addressed by recent studies. High blood galactose concentrations are implicated in cataract formation. However, when galactose is ingested along with glucose, as it would be in hydrolyzed lactose milk and whey syrups, only a small rise in blood galactose, well within normal levels, occurs in healthy adults. However, for diabetics or elderly people, the concentrations may rise much higher, indicating that reduced-galactose products would be appropriate for these groups (8, 26). Earlier concerns over increased risk of ovarian cancer were demonstrated to be unfounded (26).

The real cause of lackluster commercial performance of this technology is the absence of a strong market. One large commercial installation in Australia, a Sumitomo immobilized enzyme plant, failed in the mid-1980s because of the closing of its expected market, a pet food manufacturer. The technology worked well, but the market did not exist. Harju (37) suggests first producing hydrolyzed whey as animal feed as one approach to this problem. Feeding studies show growth and cost benefits and that animals that are usually intolerant of high amounts of whey, such as swine, are able to benefit from larger amounts of hydrolyzed whey. After production is running for this purpose, additional markets can be pursued without risking large amounts of capital.

In the US, hydrolyzed lactose faces overwhelming competition from corn sweeteners. The situation is less threatening in Europe, Australia, and New Zealand where no established corn syrup supply exists. The US applications may be limited to in-house processes (124, 125), such as those being used for cottage cheese whey, which is demineralized, hydrolyzed, and then used in ice cream, resulting in a profitable use while eliminating waste costs (43). However, a US company, which produced hydrolyzed whey to grow baker's yeast (33), stopped production recently because corn syrup was a cheaper substrate.

Miscellaneous Uses of Whey

Although some of the miscellaneous uses of whey may seem far-fetched as solutions to the whey surplus problem, it would be imprudent to neglect them. Quite recently oligosaccharides were thought to be undesirable side products of lactose hydrolysis; currently the possibility for wide use of them in health foods seems likely.

Polyurethane foams with flame-retardant characteristics, comparable with commercially available sucrose-based foams, have been formed from whey (110). Thermosetting resins based on Maillard polymer formation in whey permeate have demonstrated excellent adhesive characteristics for binding solid lignocellulosic materials (109). Whey has been used as a binder for waste ore fines to allow pelletization and recovery of otherwise wasted material (13). These are only a few of the less studied applications for whey and whey permeates.

WHEY FERMENTATIONS

Whey fermentation has long been an interesting subject for the dairy industry (42, 54, 124). Whey in many forms can be used as a feedstock for many different fermentations. Although whole wheys or whey permeates are usually chosen as substrates, concentrated whey permeates and the mother liquor from lactose crystallization process may also be used to support fermentations (93, 96, 121). As is true for other applications, the use of these lactose-containing streams as fermentation feedstocks are influenced by governmental policies on waste disposal. As costs increase and regulations prohibit release of high BOD streams to community waste treatment centers, the pressure to use the whey in other ways will certainly increase (54).

As shown in Table 7, a wide range of products can be obtained from whey fermentations, including single-cell protein (SCP), methane, alcohols (ethanol, butanol), organic acids (lactic, acetic, propionic, and citric), vitamins, and biopolymers (xanthan gum). As genetic engineers clone genes for desired products into lactose fermentors, the list of possible fermentation products will increase (55).

However, whey is not always an economical or even a feasible feedstock for industrial fermentations. Whey and, in particular, whey permeate are low in organic nitrogen sources needed for the growth of many industrial microorganisms. Most whey fermentations use supplementation to achieve good growth and productivity (2, 17, 20), but immobilized cells may have high productivity even in plain whey permeate because of high cell density and reduced growth requirements (97, 121). Also, hydrolysis of whey proteins in whole whey can provide a complex nitrogen source suitable for promoting growth, eliminating or reducing the need for expensive supplements (84). Demineralization of some wheys may be required for optimal fermentation (57), but some yeasts grow on salt whey (27). Also, lactose is not a fermentable or preferred carbon source for many microorganisms. Hydrolysis of lactose certainly can solve this problem, but increases process costs. The low lactose concentration in whey makes product recovery difficult and sometimes uneconomical. Furthermore, most of the surplus whey is available from small and medium plants, which often do not provide the economy of scale of other fermentation feedstocks, such as corn dextrose. The advantage of being a low cost feedstock also disappears when high value, high purity products are considered.

Presently, none of the existing whey fermentation processes are widely used in the dairy industry. In addition to technological considerations, the decision to produce a fermentation product from whey lactose is often market-driven and heavily dependent on specific plant situations. Here, we only discuss some fermentation products and new technologies that offer unique opportunities to the dairy industry.

Methane

During production of methane or biogas via fermentation, several species cooperatively convert lactose to methane (113). Defined seeding cultures have been proposed to overcome some of the inherent complexity in these systems (117). Despite numerous studies showing the technical feasibility, methane production is not a highly desirable use of whey. The process is slow to initiate, has a relatively high chance of souring because of the high BOD of the whey wastes, and has a low reaction rate. Therefore, Yang et al. (122) suggested that methane production be used as a last resort for whey disposal; other higher value products from whey should be considered first.

Several commercial methane plants, however, are in operation in the US, using sweet and acid whey and sweet whey permeate

TABLE 7. Selected whey fermentations.

Product	Organism	Medium	Reference
SCP[1]	*Kluyveromyces fragilis, Rhodopseudomonas sphaeroides/Bacillus megaterium*	Sweet whey permeate	(90)
	Kluyveromyces marxianus	Acid whey permeate	(67)
	Candida pseudotropicalis	Whey plus YE[2]	(34)
	Various yeasts	Whey plus YE	(94)
Alcohol	*K. fragilis*	Concentrated cottage cheese whey permeate	(30)
	K. marxianus	Acid whey permeate	(106)
Bakers yeast	*Saccharomyces thermophilus* followed by *Saccharomyces cerevisiae*	Sweet whey permeate plus corn steep liquor	(15)
Lactic acid	*Lactobacillus delbrueckii* ssp. *lactis*	Acid whey permeate plus YE	(68)
	Homolactic acid bacteria	Unsupplemented acid whey	(64)
	Lactobacillus helveticus	Supplemented whey permeate	(17)
Acetic acid	*Streptococcus lactis* ssp. *lactis* and *Clostridium formicoaceticum*	Whey permeate plus YE	(101)
Propionate	*Propionibacterium acidipropionici*	Whey permeate	(121)
Polysaccharide	*Propionibacterium* sp.	Supplemented sweet whey	(23)
Oil	*Apiotrichum curvatum*	Whey permeate	(123)
	Various fungi	Deproteinized cheese whey	(1)
	Candida curvata	Whey permeate	(29)
Enzymes	*Aspergillus niger*	Lactose	(59)
β-Galactosidase	*Candida pseudotropicalis*	Whey plus YE	(34)
Acetone-butanol	*Clostridium acetobutylicum*	Whey permeate plus YE	(28)
Lysine	Mutant *Escherichia coli*	Whey	(99)
Vitamin B_{12}	*Propionibacterium* sp.	Acid whey	(47)
	Propionibacterium shermanii	Sweet whey plus YE	(66)
Citric acid	*A. niger*	Whey permeate	(100)
L-Ascorbic acid	Mutant *Candida norvegensis*	Sweet whey permeate	(12)
Glycerol	*K. fragilis*	Whey permeate	(50)
	K. marxianus	Supplemented whey permeate	(88)
Anthocyanins	*Ajuga reptans*	Supplemented whey permeate	(11)
Insecticides	*Bacillus thuringiensis*	Unsupplemented sweet whey	(92)
Xanthan gum	*Xanthomonas campestris*	Hydrolyzed whey permeate plus YE	(65)
	Adapted strain of *X. campestris*	Supplemented whey medium	(95)

[1]Single-cell protein.

[2]Yeast extract.

as feedstocks (45). The first plant to supply all of the power to a dairy went on-line in 1984 at a Foremost Dairy cultured products facility [Lemoore, CA (82)]. Continued commercialization depends on world oil prices to determine the economic feasibility.

SCP

Kilara and Patel (54) have reviewed the production of SCP from whey. This fermentation may take place on the farm where UF concentration of milk is performed with increasing frequency. Fungi are used to avoid excess nucleic acid content, which would be toxic in the end use of SCP, animal feed.

Oils (Lipids)

Various yeasts accumulate lipids and oils when grown under high ratios of carbon to nitrogen. Production of lipids has been suggested to be more profitable than SCP and is especially appropriate for countries with little domestic vegetable oil production, such as New Zealand (25).

Alcohols

Saccharomyces cerevisiae does not ferment lactose. However, adapted *Kluyveromyces fragilis* strains can produce high ethanol yields and concentrations (30). Extractive ethanol fermentation increases the reactor productivity by several fold (24). Although the market for fuel ethanol is huge, ethanol production from whey fermentation may not be economically attractive because of the low lactose concentration in whey and competition from corn as a feedstock (122). Potable ethanol may have a better economic return because it can be used as the substrate for vinegar production. There is also interest in butanol production from whey, but the commercial potential is not high. Acetaldehyde production, instead of ethanol production, from yeast fermentation of whey has been suggested (111).

Lactic Acid

There has long been an interest in lactic acid production from whey fermentation. Lactic acid and its salts are used in foods and as specialty chemicals. The potential market for lactic acid derivatives encompasses the production of propylene oxide, biodegradable polylactic acid polymers, propylene glycol, and acrylic fibers. The lactic acid market worldwide is now only ~27 million kg/yr, but could exceed 500 million kg/yr in 10 yr if the polylactic acid market develops (62).

In 1993, Ecological Chemical Products Company (Adell, WI) (Ecochem) brought a 9 million kg/yr lactic acid plant on-line (4). This plant consumes the whey from 10 dairies and is in actuality only the trial operation for a much larger facility that is planned. The lactic acid produced will be used for polylactic acid production. Successful marketing of this biodegradable polymer could lead to a huge demand for lactic acid (62).

In addition to the polylactic acid market, fermentatively produced lactic acid (~50% of total lactic acid production) is used in foods as an acidulant and preservative. Sodium lactate may be economically produced from whey fermentation and used in fermented meat products.

Acetic Acid and Calcium Magnesium Acetate

Currently, there is much interest in producing acetic acid and calcium magnesium acetate (CMA) from biomass by fermentations. Acetic acid is an important raw material in chemical and food (vinegar) industries. The yearly production of acetic acid in the US is ~1.6 billion kg. One untraditional use of acetic acid is to produce CMA as a noncorrosive road deicer. Acetate deicers, including potassium acetate and sodium acetate, are also used in place of glycols and urea in airport runway deicing. At present, commercial production of glacial acetic acid is exclusively by petrochemical routes. Consequently, those acetate deicers are more expensive than road salt or urea (118, 120). At its current price of ~$715/tonne, CMA cannot compete with rock salt except for use in environmentally sensitive areas or on bridges where corrosion costs make it cost effective. The present CMA market is <10,000 tonnes/yr, but 9 to 13 million tonnes of road salt are used annually in the US and Canada. If the cost of CMA could be brought down significantly, a much larger market would develop.

Bench-scale investigation has indicated that the acetate may be produced economically from cheese whey via an anaerobic fermentation using a coculture of *Streptococcus lactis* ssp. *lactis* and *Clostridium formicoceticum* with a ~95% yield (102, 118). A continuous, immobilized cell (biofilm) reactor that provides high cell density and high productivity can be used to reduce the fermentation costs, and a two-step extraction process can be used to reduce the energy costs in product recovery (121). Estimated cost of the product is ~$220/tonne, less than one-third of its current price. This process may be commercialized in the near future.

Propionate

Propionic acid is used in the production of feed and food additives, herbicides, and chemical intermediates. The calcium, sodium, and potassium salts of propionic acid are used widely as food and feed preservatives. The US production of propionic acid was ~45,000 tonnes in 1981 (85) but has dramatically increased recently with an expanding market. For example, Union Carbide will expand its propionic acid capacity by 54 million kg from its present 68 million kg/yr.

Until recently, almost all propionic acid was produced from petrochemicals. Because of consumer demands for natural food ingredients, commercial interests in producing propionic acid or calcium propionate from whey lactose by fermentation are high (20, 61, 79, 121). The price for synthetic propionic acid is at ~$.84/kg, but propionate produced by fermentation can be labeled as a natural product and sold at a much higher price (~$4.4/kg). The entire broth of the fermented whey containing propionate is dried to the final product for food use, mainly in bakery products. The fermentation is thus a zero emission process and is economically attractive (121).

Xanthan Gum

Xanthan gum is a bacterial polysaccharide that is uniquely suited for various food and cosmetic thickening and stabilizing applications. Xanthan gum is also used as a lubricant, emulsifier, and mobility control agent in the oil-drilling industry. The worldwide consumption of xanthan gum is ~23 million kg/yr; annual growth rate is 5 to 10%. Presently, commercial xanthan gum is produced from glucose or dextrose by batch fermentation with the bacterium *Xanthomonas campestris*.

Production of xanthan gum and other polysaccharides from whey lactose has been recently examined by Schwartz (95). Whey lactose must be hydrolyzed first before it can be fermented by the commercial bacterial strain (65). Mutants and genetically engineered strains that can directly ferment lactose are available, but they produce much lower amounts of xanthan gum from lactose than from glucose.

The major cost in producing the gum is the recovery step by alcohol precipitation. Drying the whole broth for some food applications would lower the cost substantially. Whey does not offer a cost advantage over glucose, but can be substituted for glucose, making use of a waste stream while producing a high value product. A commercial product derived from direct whey lactose fermentation and whole broth drying requires a use level 10- to 15-fold higher than that for pure xanthan gum (54). High use levels, which will be a problem in many food applications, can be attributed to the low xanthan concentration in the product.

A new recovery method for xanthan gum based on UF has been recently developed (63). Without alcohol precipitation, xanthan gum containing broth can be readily concentrated to ~15% (wt/vol). This new recovery method should make hydrolyzed lactose whey an attractive feedstock to produce xanthan gum.

Process Considerations

Fermentation. For any of the described fermentations to be a desirable use of whey, the reactor must have high productivity and yield so that the process can be economically feasible. However, many fermentations are limited by the low product concentration and low productivity because of strong product inhibition. Recently, we (61, 122) have developed a novel spiral-wound fibrous bed bioreactor for continuous immobilized cell (biofilm) fermentations. The bioreactor has the following advantages, which make it suitable for many fermentations, including whey-based fermentations; simple start-up, high stability for long-term operation (up to 1 yr has been demonstrated), easy scale-up, high cell density, high reactor productivity but little cell growth so that nutrient requirements are minimized, and high yields. Several fermentations, including ethanol, lactic acid, propionic acid, and acetic acid, have been demonstrated using this reactor (97, 120, 121). Cell recycle membrane bioreactors also have high cell density and productivity (86, 106), but, in contrast with our bioreactor, often have long-term operational difficulties from membrane fouling (20).

Separation. The cost of product purification is also critical in determining the economic potential of whey fermentations. We have developed a two-step extraction process to recover and concentrate efficiently the carboxylic acids, including lactic, acetic, and propionic acids, from dilute solutions (115, 119). An aliphatic amine is used to strip the acid, followed by back extraction with an alkali solution, resulting in a concentrated organic salt solution and regenerated extractant (115). The organic acid in the dilute fermentation broth can be recovered as an organic salt and concentrated to a level close to its solubility in water with extremely low energy input. Such extraction methods can be integrated with the fermentation itself in a technique known as extractive fermentation, removing the problem of product inhibition and improving reactor productivity (60, 112). Improvements such as these in fermentation technology and product recovery techniques are necessary to make fermentation a profit-generating use of whey lactose.

Waste Reduction. As mentioned earlier, one major motive for whey utilization is to eliminate or reduce the whey disposal problem facing many cheese makers. Thus, any process to use whey should consider its potential for waste reduction. In fact, whey fermentations may not be economically viable if a significant waste stream is generated from the process. Thus, whole fermented whey should be used as the product to achieve zero emission from the plant. Fermentation should be considered as a method to modify the properties and functionality of whey lactose to add to its value and market demand.

CONCLUSIONS

The dairy industry has a whey surplus problem. Any use for whey seems to meet the goal of keeping it out of the waste stream, but the experience of the industry with lactose hydrolysis demonstrates that this is not necessarily the case. With lactose hydrolysis, the

TABLE 8. Comparison of various products from 50,000 kg of whey permeate (5% lactose).

Product	Quantity	Unit price	Value	Use	Market and production
			($)		
Lactose	1500 kg	$.44/kg	660	Food; pharmaceutical	95,000 tonne/yr
Methane	780 m^3	$.176/$m^3$	138	Energy	On-site use
Ethanol	1340 L	$.40/L	536	Fuel	Very large
CMA[1]	3000 kg	$.66/kg	1980	Road deicer	<10,000 tonne/yr; potentially large
K-Acetate (50%)	6250 L	$1.06/L	6625	Airport runway deicer	~20 × 10^6 L/yr
Lactic acid	2250 kg	$2.2/kg	4950	Food, chemical, and polylactides	~30 × 10^6 kg/yr; potentially large
Ca-propionate	1500 kg	$4.4/kg	6600	Natural food preservative	Small, but good
Xanthan gum	1750 kg	$11.0/kg	19,250	Food thickener	~20 × 10^6 kg/yr
TOS[2]	1250 kg	$17.6/kg	22,000	Food; pharmaceutical	6000 tonne/yr; potentially large

[1]Calcium magnesium acetate.

[2]Transgalactosylated oligosaccharides.

industry was pushed by available enzyme technology into selling itself on a product for which a market did not really exist. Fortuitously, oligosaccharides may develop into a high value product that can use the same enzyme technology and potentially have a large market. This application is the type about which the industry should become excited: turning ~$.40/kg of lactose into a high value food additive or pharmaceutical. Alternatively, products such as lactic acid and acetate deicers, which have the potential to become commodity chemicals and make a significant impact on the whey surplus, would be worthy of industry resources to develop.

Table 8 summarizes some current and potential products from whey lactose. For the present and near future, none of the current or new uses of whey is likely to consume all of the surplus whey lactose. The optimal choice for product development and whey utilization by each individual cheese maker is dependent on the plant size, available technologies, and market situations. No single universal solution currently exists for the whey disposal and utilization problem, and certainly no single solution meets all future needs. Continued development of multiple new technologies, innovative applications for those technologies and the development of markets for the resulting products will allow the industry to capitalize on, rather than suffer from, the present lactose surplus.

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