WHEY: COMPOSITION, PROPERTIES, PROCESSING AND USES

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INTRODUCTION

In the dairy industry, the term whey denotes the greenish translucent liquid that separates from clotted milk during manufacture of cheese or industrial casein. More generally, residual streams from liquid fractionation processes of other food systems (especially of other protein solutions) have been referred to as why on occasion, as in oilseed protein recovery processes (1) or in alkali extraction of protein from meat boning waste (2). This entry is concerned solely with the traditional dairy whey and similar wheylike byproducts of the modern dairy processing industry, using cow's milk as the principal raw material. With certain minor allowances for compositional differences, much of the information presented here is also relevant for whey resulting from processing of milk of other milking animals such as goats, buffaloes, sheep, etc. This article is geared towards the enlightenment of the athlete.

TYPE AND FORMS OF WHEY

The traditional whey is produced as a result of processes aimed at recovering casein, the principal protein of milk. Separation of casein from the rest of the milk (as in cheese-making or production of industrial casein and caseinates) is usually accomplished by acidification to PH 4.5-4.8 or through the action of rennet, a casein-coagulating enzyme preparation. In acid coagulation, the PH is lowered either by microbial fermentation of the milk sugar lactose into lactic acid or by direct addition of a mineral (phosphoric, hydrochloric, sulfuric, etc.) or an organic (lactic, citric) acids. The fermentation route is most often used in the production of cottage cheese, quarg and other fresh cheeses, while the direct acidification is typical for production of industrial casein and caseinate products; in both cases, the resulting why is referred to as acid whey. In contrast, sweet wheys are obtained in manufacture of most hard and semihard cheeses including Cheddar, Swiss, Gouda, Mozarella and many others for which the rennet coagulation principle is employed, as well as in production of industrial rennet casein. Since enzymatic clotting of milk by rennet occurs at pH 6.0 or higher, the lactic acid content of freshly obtained sweet whey is very low but may increase quickly if subsequent bacterial fermentation is not controlled by rapid pasteurization and/or by deep cooling. Approximately 9 L of whey will be obtained from 10 L of milk for every kg of cheese produced; this general ratios will vary somewhat depending on the type of cheese, fat content of the raw milk used and other factors. In high moisture fresh cheeses such as cottage cheese (where a portion of the original raw milk is returned to the cheese as cream dressing) the ratio may be as low as 6:1.

Either sweet or acid wheys can exist in various forms, depending primarily on whether any moisture has been removed in subsequent processing. Since whey contains on the average about 93-94% water, it is often desirable to remove some or most of its water for further handling. As discussed in more detail later, application of common food processing operations such as evaporation or drying results in concentrated, semisolid or dried forms of whey, the principal difference being the residual moisture content (Table 1). Liquid whey forms may be further processed by reverse osmosis (RO), ultrafiltration (UF), electrodialysis (ED), ion exchange (IE), lactose hydrolysis (LH) and other modern unit operations, now available to the whey processing industry, into many additional modified whey products useful as ingredients for other food processors.

Table 1. Proximate Composition Ranges for Major Whey Forms[a]

Whey Form	Total Solids, %	Total Protein, % (Nx6.37)	Lactose, %	Minerals, %Ash
Liquid unprocessed	6.0-7.0	0.4-0.8	4.4-4.9	0.5-0.8
Concentrated (RO)	20-25	1.2-3.0	14-20	1.0-3.0
Concentrated (evaporator)	40-60	4.0-8.0	26-48	3-8
Dried	96-97	10-13	70-75	7-12
Liquid UF permeate	4.0-5.5	0.1-0.3	3.9-4.8	0.3-0.8

[a] Orientation data based on various sources including refs. 3 and 4
[b] Except for fat recovery by centrifugation, common for many types of cheese whey (eg, Cheddar etc). Fat content of cottage cheese whey is negligible due to the use of skim milk.

OTHER BY-PRODUCTS OF MILK AND WHEY PROCESSING

The rapidly emerging use of UF for cheese-making and for further whey processing results in a wheylike liquid waste stream referred to as a UF permeate. Although in principle UF permeate is similar to whey in terms of its physical state and volume (its quantity being several-fold that of the desired UF retentate, the principal product of UF processing of milk or whey), the main compositional difference between the permeate and the traditional whey is due to the almost complete protein recovery in the UF retentate leaving the permeate virtually protein-free (Table 1). Minor compositional differences are normally observed between permeates from UF of milk and of the two types of whey, primarily due to the variations in the mineral fraction.

COMPOSITION AND PROPERTIES

Composition of Unprocessed Whey

Whey is a multicomponent solution of various water-soluble milk constituents in water; the dry matter of whey consists primary of carbohydrate (lactose), protein (several chemically different whey proteins) and various minerals. Fat content of the freshly separated liquid whey may be up to 0.5-1* depending on the type of milk used and the efficiency of the cheese-making operation. However, the valuable butterfat is usually recovered by whey centrifugation and returned to the cheese or processed into whey butter. Thus, the fat content usually reported for the various types of whey is typically below 0.1%. Fat content of most acid wheys from fresh cheeses such as cottage cheese or ordinary quarg is negligible as skim milk is used in the manufacture of these cheeses. The proximate composition of various wheys may show significant variations due to many factors including the pretreatment of the cheesemilk (heating, centrifugation, homogenization); the processing differences characteristic for the various cheeses (cultures used, mechanical handling, use of processing aids such as the yellow color, use of membrane processes); and the whey handling and pretreatment processes (pasteurization, preconcentration, recovery of casein fines). Average compositional data for cheese wheys of the sweet and acid types are shown in Table 2.

Table 2. Average Composition Data for Sweet and Acid Types of Whey[a]

Component	Sweet Whey (pH 5.9-6.4)		Acid Whey (pH 4.6-4.8)
		g/L	
Total Solids		63.0-70.0	
Protein (N x 6.37)	6.0-8.0		6.0-7.0
Lactose	46.0-52.0		44.0-46.0
Fat	0.2-1.0		0.1-0.5
Calcium	0.4-0.6		1.2-1.6
Magnesium	0.08		0.11
Phosphate	1.0-3.0		2.0-4.5
Citrate	1.2-1.7		0.2-1.0
Lactate[b]	2.0		6.4
Sodium		0.4-0.5	
Potassium		1.4-1.6	
Chloride		1.0-1.2	

[a] From various sources including refs. 5 and 6.
[b] No lactate in uncultured rennet or mineral acid whey.

Lactose, the principal component of the whey apart from water, constitutes about 4.4-4.9% of they whey "as is" (almost 75% of the dry matter) depending on the whey type. Lower lactose content is usually found in the acid wheys due to the preceeding fermentation process in which some of the lactose is converted to lactic acid. Although lactose is the most abundant material of whey, the most valuable whey component is the whey protein, constituting approximately 0.7% of the whey (about 9-11% of the dry matter). In addition, whey may contain about 0.2-0.3% of nitrogenous matter denoted as nonportein nitrogen (principally inorganic compounds, urea etc): this is sometimes included with the true whey protein and reported as total whey protein (N x 6.38). The total protein fraction of cow's milk consists of about 20% whey protein and 80% casein. In milk of other mammals, this ratio may vary; eg, in human milk, the whey protein fraction constitutes almost 60% of the total protein. However, whey protein is neither acid nor rennet coagulable and thus, when the classical cheese-making processes are used, the whey protein will pass into they whey of either type. Finding suitable technological alternatives allowing recovery of whey protein in the cheese is one of the major concerns of the current cheese research; while this could increase the cheese yield by up to 5-10%, the cheese quality in many cases may be impaired by the inclusion of the whey proteins. Since about 50-60% of the whey proteins can be coagulated by heat, high heating of milk is now practiced for some types of fresh, acid coagulated cheeses such as quarg (7) or cottage cheese where the quality is not greatly compromised and the diminished rennet clottability is not a major problem. As a result, whey obtained from such cheese-making operations will contain mainly the heat noncoagulable whey proteins and its total protein content will be substantially lower, often around 0.4% (8). Table 3 shows the main components of the whey protein fraction of cow's milk, together with their relative content and heat stability characteristics.

Table 3. Composition and Thermal Characteristics of the Whey Protein Fraction[a]

Protein	Approx. Content, g/L whey	Total Whey protein, %	Denaturation Temperature, °C	Heat Precipitation Stability
α-lactalbumin	0.6-1.7	20	61	Quite Stable[b]
β-lactoglobulin	2.0-4.0	55	82	Labile
Serum albumin	0.2-0.4	5	66	Very labile
Immunoglobulins	0.5-1.0	8	72	Extremely labile
Proteose-peptones	0.2-0.4	12		Heat stable
Other (caseins, glycoproteins)	0.1	1		

[a] Adapted from various sources including refs. 5, 6, 9, 10.
[b] Due to its renaturation characteristics and despite its low denaturation temperature

In addition to lactose and whey protein, minerals constitute the third major component group of whey dry matter. The mineral composition shows the greatest variations between the two types of whey, together with pH and lactic acid content. Although the overall compositional values far each of the two types are dependent on many factors related to the cheese-making process, the main differences between the two types of wheys reflect the different casein coagulation pathways. IN addition to lower pH and higher lactic acid (and correspondingly lower lactose) content, the acid whey show substantially higher calcium and phosphorus contents cause by the solubilization of the calcium-phosphate complex of the casein micelle at the acid pH range, used for the acid coagulation of the casein. In contrast, the calcium removal from the casein micelle does not occur as a result of the rennet clotting at pH 6.0 or higher; thus, much of the milk calcium is retained in the cheese rather than being lost in the sweet whey. The differences in acidity as well as the higher calcium content of the acid whey appear to be the main reason for variations in physic-chemical properties of the two whey types, including the substantially lower heat stabilities of the dairy systems containing added UF retentates from acid wheys in comparison to sweet wheys (11); on the contrary, in the acidic pH range below 3.9 typical for whey beverages, high-calcium containing acid whey appears to be more resistant against heat-induced instability (12).

Composition of Modified Whey Products

Using some of the typical whey processing unit operations such as UF, ED, or IE, numerous modified whey products may be obtained. Table 4 lists some of these products and gives their basic composition. Since most of these whey modification processes are capable of handling both sweet and acid wheys, the compositional differences of the final products reflect the processing techniques used rather than the type of whey. Oftern, sweet and acid wheys are mixed together by the large whey processors for manufacturing of these modified products, resulting in a uniform final composition with minimal variations due to the individual processes used. Typically, most of the modified whey products available on the market today are manufactured by various fractionation processes aimed at separation of the undesirable components and thereby enrichment of the targe substance. The main exception is the enzymatically modified whey syrup where the constituent disaccharide lactose is converted to two monosaccharides, glucose and galactose, thus leaving the proximate composition virtually unchanged. Similar modification involving enzymatic breakdown of the whey proteins are currently in advanced experimental stage (14) with one of the main industrial application being the production of hypoallergenic baby formula (15).

Table 4. Characteristic composition of major types of modified whey products[a]

Product	Total Protein, % (Nx6.37)	Lactose, %	Minerals, % Protein	Fat, %
Liquid WPC (10% TS)	3.3	5.5	0.8	0.3
Dried WPC (35% protein)	35.0	50.0	7.2	2.1
Dried WPC (80% protein)	81.0	3.5	3.1	7.2
Lactose, edible grade	0.1	99.0	0.2	0.1
Whey Powder, demineralized (70%)	13.7	75.7	3.5	0.8
(90%)	15.0	83.0	1.0	0.9
Lactose-reduced demin, whey powder	30.5	51.5	7.8	2.0
Regular Whey powder	12.5	73.5	8.5	0.8

[a] From refs. 3, 6, 13.

Properties of Whey and Whey Components

Although whey is a rather dilute aqueous solution of lactose, whey protein and some minerals, some physicochemical properties of unmodified wheys as determined by the individual system components are similar to those of water but others different rather substantially. As seen in the Table 5 summarizing available data in comparison to skim milk, some of the physical properties of the two materials (such as viscosity, surface tension, freezing point etc) are very similar as can be expected from the compositional similarities. The main difference between whey and skim milk is in the protein fraction, due to the removal of casein, which accounts for a major difference in heat stability of the two systems. In the absence of casein, whey protein will coagulate and precipitate from the solution upon heating above the whey protein denaturation temperature which varies depending on the type of protein and the heating time. As a general guideline, heating to more than 70°C will cause precipitation in whey systems above pH 3.9, the severity of the phenomenon being dependent on the heating time, temperature and calcium content.

If complete precipitation of the heat-denaturable whey protein is desired, the whey should be heated to at least 90°C with holding for several minutes. Whey systems containing little calcium (such as rennet whey or decalcified acid whey), will show less precipitation upon heating than regular acid whey, the main effect being increase in turbidity (20). At pH lower than 3.7-3.9 depending on the calcium content, whey proteins become highly resistant to heat-induced precipitation and even severe heating above 90°C for 20 min or more will not result in protein precipitation or turbidity increase(12,21). Heating of sweet or acid whey systems will enhance the already high foamability of whey (22), probably due to the effect of heat on some of the heat noncoagulable whey protein fractions, primarily the proteose-peptones.

Limited solubility and low sweetness are the most important properties of the main whey component, lactose, influencing many whey processing operations. Since the solubility of lactose is only about 20 g/100 g water at room temperature and 60 g/100 g water at 60°C, as compared with about 188 g/100 g and 235 g/100 g water for sucrose at the same conditions (23), whey concentration to more than about 36-38% total solids (TS) will result in formation of crystalline lactose. This is the principle of the lactose manufacturing process based on crystallization from highly concentrated whey, as well as the reason for specific processing steps aimed at avoiding formation of large lactose crystals in manufacture of dried whey, the Norwegian whey cheese mysost, table spreads based on whey (3,24,25), and other products containing high concentrations of lactose. To avoid the lactose crystal formation and/or to increase the sweetness of lactose-containing foods if desired, the lactose may be hydrolyzed to its two constituent monosaccharides, glucose and galactose. The hydrolysis may be accomplished enzymatically using either free or immobilized lactase (beta-galactosidase, EC.3.2.1.23) or by chemical hydrolysis through high temperature-low pH processes (26).

The main differences in physico-chemical properties of sweet and acid wheys are due to the varying content of mineral and acids. Both of these componental groups influence also the sensory properties of the two types of whey, particularly in terms of the saltiness and sourness that limit the use of unmodified whey as an ingredient in many foods. Calcium appears to be particularly important in terms of whey protein heat stability, while sodium and potassium are primarily responsible for the saltiness and, together with lactose, for the osmolality of the whey (18). The mineral content of whey can be modified by ion exchange, electrodialysis or certain specialized membrane processes (“nonafiltration”).

Optical properties of the whey and wheylike systems resulting from processing of milk are influenced by the content and type of protein present and by the most abundant whey vitamin, the riboflavin. The greenish color of most traditional whey systems, regardless of the processing conditions used, is caused by the water-soluble and heat-stable riboflavin. However, riboflavin is sensitive to light as well as to ionizing radiation treatments and whey systems exposed to these conditions will show fading of the green color (27). As a small molecule, riboflavin will be retained by reverse osmosis but not by most ultrafiltration membranes so that both wheys as well as UF permeates of milk or whey processing have the same color character. The cause of recently observed loss of color in UF processing of whey on a metallic membrane cast within a porous carbon tube (the CARBOSEP system) has been tentatively identified as adsorption of riboflavin on the carbon support (28); the affinity of riboflavin for various adsorbents as crystalline lactose or carbon has been known for some time (29). The turbidity of most industrially produced wheys is due to the casein fines content (30). Property clarified wheys are virtually transparent and, in visual appearance, not substantially different from good quality UF permeates. Turbidity measurements can be conveniently used as indication of the heat effects in various whey systems, since the heating may result in aggregation of the whey protein present into larger clusters (20) that will change the optical character of the heated whey system even if no precipitation will result. Yellow discoloration of whey may occur after prolonged heating, especially in concentrated whey systems due to the Maillard nonenzymatic browning reaction between the lactose and whey proteins. Yellowing may be also caused by the use of coloring in the cheese-making process; since the most common cheese color, the annato extract, is water soluble, much of it will remain in the whey after the curd separation.

Table 5. Some Physico-Chemical Properties of Whey in Comparison to Skim Milk (Orientation Data)

Property	*Whey*	*Skim Milk*	*References*
Viscosity (mPa.s)	1.2	1.5	16
Surface tension (dyn/cm)	42	48	16, 17
Freezing point (°C)	-0.530	-0.520	16, 18, 19
Stability against heat coagulation (standard pH)	Unstable	Stable	16
Stability against acid coagulation (no heat)	Stable	Unstable	16

INDUSTRIAL PROCESSING OF WHEY

Traditionally, whey has been known as a troublesome byproduct of cheese manufacturing and, because of its very high BOD (about 40,000 ppm) as one of the strongest industrial wastewater pollutants of any kind (31). The opportunities for using whey as a valuable resource have been recognized for some time, but so far, only very few countries (the Netherlands being the prime example) have established a record of nearly complete utilization of all available whey. However, the question of whey utilization as opposed to whey disposal is becoming increasingly important in view of more stringent ecological constraints together with dairy production controls in some of the important dairying regions of the world. Intensified research activities have resulted in many new approaches to industrial whey processing and the value of cheese whey as a raw material for various consumer products or industrial food ingredients is now being recognized. Some of the largest whey processing facilities in the world are capable of handling in excess of 5×10^6 liters of whey daily and may rely on suppliers of raw or RO preconcentrated whey from cheese manufacturers several hundred kilometers away. The main whey disposal problem continues to be the acid whey from production of cottage cheese and other fresh cheese products as the manufacturers are often located close to the main population centers (and thus outside of the main agricultural areas) and their whey production is not large enough to warrant separate whey processing facility. One of the possible solutions for these processors appears to be the production of high value consumer products based on whey, such as whey beverages and whey cheeses.

Consumer Whey Products

Whey cheeses and whey drinks are among the most traditional foods produced from whey. The use of whey as a beverage has been recorded in history since the time of Hippocrates (32), while traditional whey cheeses such as ricotta and mysost (24,33-35) have been popular in various parts of the world for centuries. These products usually require simple processing facilities and thus, in their traditional versions, may be suitable for small whey processors supplying primarily local markets. However, neither whey cheeses nor whey beverages (with a few exceptions) have been particularly successful on large scale, possible because of the limited consumer appeal outside of the traditional producing countries. Development of new technological approaches resulting in new types of high quality products remains one of the priorities in this regard.

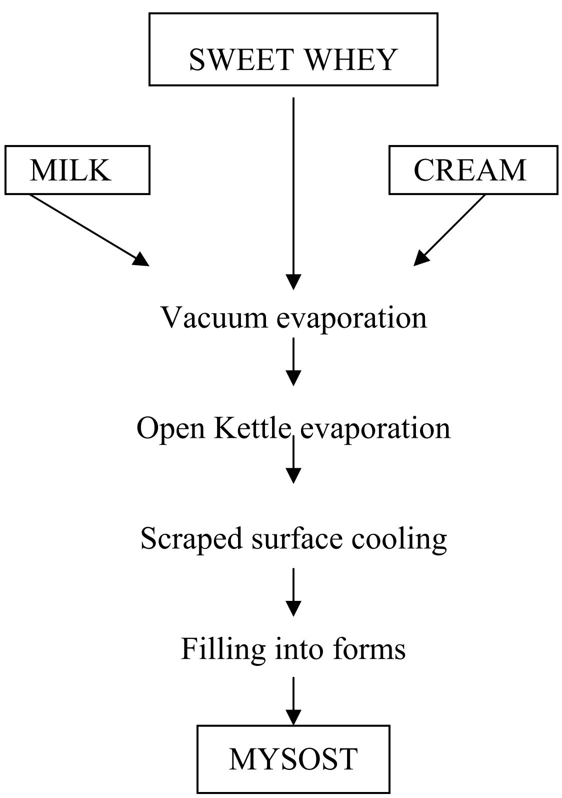

Figure 1. Main technological steps in the production of mysost whey cheese.

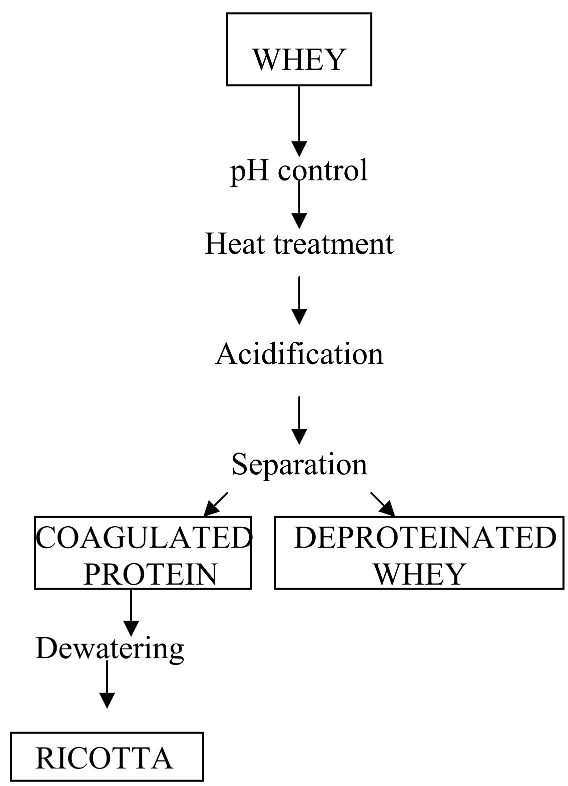

Figure 2. Main technological steps in the production of ricotta whey cheese

Whey Cheeses. There are two types of whey cheese: the Norwegian whey cheese myosost (also know as gjetost, primost, brunost, or Gudbrandsdalsost) and the Italian whey cheese ricotta (also ricottone). Figures 1 and 2 show schematically the basic processing steps used in production of these cheeses. The technology for mysost production is based on evaporation of water from the whole whey, followed by solidification of the evaporated mass under carefully controlled conditions to avoid growth of lactose crystals beyond sizes that would be recognized as grittiness upon product consumption (24). In contrast, the ricotta-type of whey cheese is based on the recover of the whey protein coagulum obtained by high heating of the whey raw material, often containing additional skim milk. As a result, the composition of the two products differs rather substantially, as shown in the Table 6. Since all traditional milk-based cheeses are manufactured by retaining casein and removing whey proteins and lactose, describing mysost or ricotta as a cheese may be a misnomer although allowed for in the modified FAO definition of cheese (36). The character of the protein-based ricotta is closer to the traditional cheese than the mysost, in which lactose is the most abundant component. From the standpoint of whey disposal, the mysost technology is much more suitable since it leaves no residue, while heat precipitation of protein from whey still results in a partially deproteinated whey stream almost as high in the BOD as the original whey. The BOD content of the deproteinated why is dependent primarily on lactose, which is not recovered by the ricotta process. More details about the whey cheese manufacture, properties and uses may be found elsewhere (eg, 33, 325,26).

Table 6. Illustrative Compositional Data for Ricotta and Mysost-Type Whey Cheeses[a]

	Ricotta type		Mysost type	
Component	Fresh	Pressed	Regular	Spread
Total solids, %	25	40	80	66
Protein, %	12	19	11.5	7.5
Carbohydrate, %[b]	4	5	36	46[c]
Fat, %	7	10	30	7.5

[a] Adapted from refs. 24, 34-36.
[b] Lactose only.
[c] May include additional carbohydrate sweeteners.

Whey Beverages. Incorporation of whey into various beverage and developments of whey drinks using numerous technological approaches have been attempted by large number of researchers. Extensive literature review exist (32,37) summarizing many of these attempts. However, there are still only a few truly successful whey beverages that can be found on market shelves in various countries. Virtually no products have established any major international reputation. Table 7 gives examples of whey beverage products known to enjoy some commercial success presently, as an illustration of the types of beverages that may be produced from whey.

Table 7. Examples of Commercially Available Whey Beverage Products, 1983-1988[a]		
Product Type	*Commercial Name*	*Country*
Whey with fruit juices	Djoez	Netherlands
	Taksi	Netherlands
	Big M	Germany
	Mango-Molke mix	Germany
	Latella	Austria
	Hedelmatarha	Finland
	Nature's wonder	Sweden, Canada, Germany
Drinkable yogurt with whey	Yor	Netherlands
	Interlac	Belgium
Soft drink (carbonated)	Rivella	Switzerland, Japan
[a] From ref. 33.		

Figure 3 shows diagrammatically the main technological pathways available for production of a whey beverage. Among these, the most often used approach appears to be mixing whey with fruit juices, thereby combining the nutritional benefits of high quality whey protein, calcium and riboflavin from why with the traditionally recognized source of various vitamins, the fruit. Nationally successful products of this type include the Taksi and Djoez drinks marketed in the Netherlands, and Austrian Latella, the Finnish Hedelmatarha, or the Swedish "Nature's wonder" which has shown some market potential even in international licensing agreements (Germany, Canada). However, frequent market failures of the less successful products in this category indicate that the seemingly simple technology of mixing cannot be applied without careful product and market development research. A typical quality problem found often in these products is a sediment formation, usually caused by the heat-labile whey proteins and their interactions with some of the truit components (as pectins) even below the pH range of 3.9-3.7 where whey protein should be heat-stable (38). Similarly, drinkable-yogurt type products have been developed (as Yor in the Netherlands or Interlac in Belgium) and, in view of the currently increasing popularity of yogurt-based drinks, should represent another avenue of success for further product development. Contrary to the precipitation in the fruit-juice-based products, the pectin can be used to stabilize these casein-containing beverages as in other fermented dairy products (39). It may be possible to use the same stabilization mechanism also in yogurt-type whey beverages based on UF retentate only, where the destabilization problem may be due to heat processing of the final product rather than due to the acid coagulability of casein (39). A third type of whey beverage that has been successfully marketed is the clear product based on whey UF permeate or heat-deproteinated whey. In fact, the main representative of this approach, the Swiss product Rivella, is the longest existing, and the most successful, of all whey beverage products. The popularity on the Swiss beverage market rivals that of Coca-cola. This carbonated product, made by mixing the clear deproteinated whey serum with a flavor extract of various herbs, represents a general thirst-quenching beverage rather than a nutritious, diary-based products such as fruit juice-based or the yogurt-based drinks. In this sense, the use of whey for Rivella production is similar to other industrial uses of whey, since the Rivella is manufactured by a specialized beverage company rather than a dairy processor.

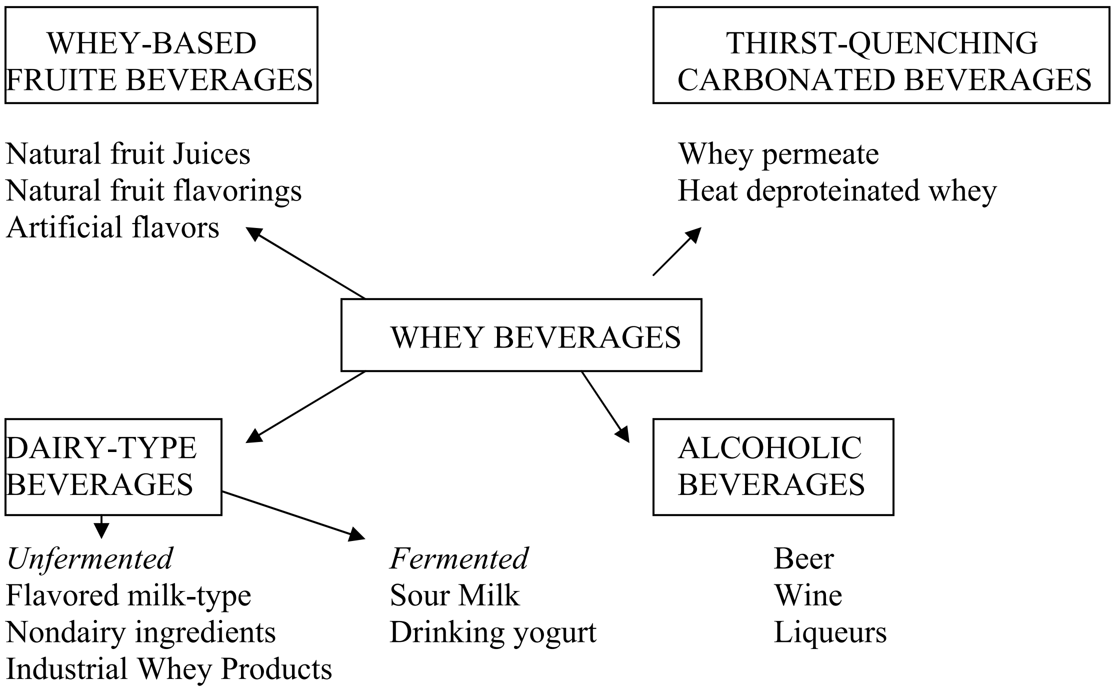

Figure 3. Alternative technological pathways for production of whey-based beverages.

Industrial Whey Products

Processing of whey into various industrial products has become the most attractive alternative to whey disposal. This includes the drying of whey, which may have been viewed earlier as a process merely reducing the disposal problem by some 90% (by removing the constituent water), since utilization of the dry whey often has been unprofitable. Significant research efforts worldwide have resulted in many new alternative technological approaches and uses for the industrial whey products and they whey processing industry is nowadays one of the most rapidly developing segments within the dairy field. In addition to the traditional dairy products made from whey (concentrated or dried whey, lactose, whey butter, partially delactosed whey and heat-precipitated whey protein), many now whey-based products are now available as ingredients for the food industry; these include whey protein concentrates, blends of whey or whey protein with other non-dairy sources, demineralized whey, lactose hydrolyzed whey products, fractionated and enzymatically modified whey protein products for specialized food, pharmaceutical and other nonfood uses, as well as various products of the whey fermentation processes including biomass, food grade or fuel alcohol and methane. Some of the representative industrial whey products are listed in Table 4.

Whey Protein Products. The most valuable component of whey is the whey protein. The oldest process for production of a whey protein concentrate (WPC) consists of heating of whey and recovery of the heat-precipitable whey proteins as an insoluble high-protein product (usually refered to as "traditional lactalbumin"). In the modern whey processing industry, various membrane-based separation technologies are being used to produce WPCs with much improved functional properties, in particular regarding good water solubility. The predominant technology for production of modern WPCs is the ultrafiltration, often combined with diafiltration (repeated washing of the retentate by adding water during the UF process) to remove addition lactose and ash and thereby increase protein content of the final product. The typical protein content of the "ordinary" WPC, produced by simple UF as with up to 80% protein are now being produced for many food ingredient uses. The modern WPCs have some important functional properties differentiating them from other food protein ingredients, such as high solubility (including solubility in acidic systems), foaming properties, and heat coagulability combined with high water binding in the heat-denatured state. Since whey protein from cows milk is similar to human whey protein, one of the main applications of the WPCs is in the production of baby formulas. Enzymatic modifications and/or fractionation techniques to separate the individual whey proteins are being developed to counteract the possible allergenicity of the most abundant whey protein, the beta-lactoglobulin (15), and to maximize the functionality of the individual whey protein fractions (10,40). Other technological alternatives that have been suggested for whey protein recover include the use of chemical precipitants—especially various biopolymers as pectin, carrageenan or carboxymethylcel-lulose—as well as ion exchange resins or gel filtration (4,10). In general, whey protein is considered to be nutritionally one of the best proteins for human food use, while its versatile functional properties make it a valuable ingredient for the modern food industry.

Lactose Products. As lactose is the predominant whey component, any protein recovery operation not accompanied by some lactose processing alternative will result in a large lactose disposal problem. Traditionally, lactose has been recovered as an article of commerce by crystallization from highly concentrated whey (typically to 65-50% T.S.), with or without prior whey protein removal. Crystallizing lactose from unmodified whey will result in partially delactosed whey residue which can be dried to obtain a product with sufficiently high protein content to be valuable as skim milk replacement in certain applications. When the whey protein is removed before the crystallization process either by heat precipitation or by ultra-filtration, yield of both products can be maximized and the rate of lactose crystallization optimized (23), but the residual mother liquor from the lactose crystallization process could constitute a disposal problem. However, presently about 70% of the 22 U.S. lactose producing plants are reported to be using UF permeate as the raw material for lactose manufacture (41). Lactose of edible grade or better can be produced also by spray-drying of highly purified deproteinated and demineralized whey. Since world market for lactose is rather static, new opportunities for lactose utilization must be found if lactose production were to increase substantially.

Hydrolysis of lactose into its two monosaccharide constituents, glucose and galactose, will result in increased sweetness of the mixture, as well as reduced lactose crystallization problems in concentrated food systems (as ice cream). Thus, lactose hydrolysis in whey or in the various lactose streams obtained during the whey processing operations is one of the options available to increase the functionality of lactose-containing whey-based food ingredients. Sweetening syrups can be produced by lactose hydrolysis in purified lactose streams for use in canning, as brewing adjuncts or for other applications (26). Lactose hydrolysis in whey or whey UF permeate for use in manufacture of whey drinks will decrease the caloric content the final product as well as the required sweetener addition when using some of the high potency noncaloric sweeteners (42). Lactose can be further modified chemically to obtain useful food or industrial ingredients such as lactitol, lactulose or lactosyl urea (43); however, the raw materials for these lactose derivatives is usually the isolated lactose rather than the whole whey.

Whole Whey Products. The most common industrial whey product is spray-dried whey and its numerous variants. When drying is not an easy process because of the high lactose content and, in the case of acid whey, the high content of the nonvolatile lactic acid. For a typical spray-drying operation, the whey is first concentrated by multi-stage vacuum evaporation to more than 50% TS. Preconcentration by RO to ca 20-28% TS, the maximum concentration achievable in an economically feasible process, is often practiced to increase the capacity of the evaporator and/or to bring the raw material from a distant supplier to the central drying facility. To produce a nonhygroscopic whey powder, the lactose should be left to crystallize for at least 24 h before the spray-drying operation, otherwise noncrystalline, unstable and highly hygroscopic lactose glass will be formed in the drying process. Sometimes, the whey proteins are also purposely heat-denatured before the spray-drying to minimize a potential for protein deposition on the heat-transfer surfaces resulting in processing difficulties. As a result, the hygroscopicity, solubility, and other functional properties of whey powders may differ substantially depending on the processing conditions. Other drying procedures traditional for the dairy industry, such as drum drying, are seldom used because of the great operational difficulties and the inferior quality of the final product.

In addition to regular whey powders, products with modified lactose, protein, or mineral content can be produces using lactose crystallization, membrane processing, demineralization by IE or ED, or blending the liquid whey with other nondairy protein sources including soy, pea and other vegetable proteins as well as the bran or other food materials. A recent U.S. patent (44) claims that wet grinding of dry cereal or oilseed protein sources (soy, rapeseed, oats) in whey or whey UF permeate followed by spray-drying of the blends will result in improved functional properties, especially higher resistance towards lipid rancidity development in the dry product. Other whole whey products include sweetened and/or lactose-hydrolyzed concentrated whey as in “in-house” ingredient in ice cream and other dairy products, and highly concentrated whey in the form of semisolid “lick-blocks” for cattle feeding purposes.

Fermentation Products From Whey. Since whey and the UF whey permeate contain a relatively high content of a carbohydrate that is fermentable by certain microorganisms, whey has been a traditional substrate for fermentation processes including the production of antibiotics, lactic acid, or biomass. However, these established processes of the past have been replaced to a large degree by more economical alternatives including direct chemical synthesis. Recent developments of modern processing approaches, as well as the preference of natural over synthetic ingredients may revitalize the interest in various fermentation processes based on whey. Production of lactic acid is one of the examples where modern technology (45) and the back-to-nature philosophy may make the traditional fermentation route (4) successful again. Likewise, production of food-grade alcohol from whey for use in dairy-based liqueurs have been successfully developed in Ireland (46). In New Zealand and other countries, whey fermentation into industrial alcohol in large commercial installations appears to be profitable (47). Use of liquid whey as the medium for bulk propagation of lactic starter cultures for "in-house" use is well established in many dairy processing plants. Further fermentation of whey for various whey-based beverages is a natural possibility especially for production of whey wine or whey beer, even though lactose is not fermentable by many common yeasts without special pretreatments. Alcoholic whey based beverages have been described in literature (32,37,38) but their commercial success is not well documented apart from the manufacture of whey beer in Germany during the period of scarcity in the World War II. In the nonfood area, whey has been used as a substrate for biomass production by yeast fermentation (the "wheast" process) for bacterial fermentation into lactic acid with continuous neutralization to produce fermented ammoniated concentrated whey (FACW) for ruminant feeding (49), or as a source of biogas generated in anaerobic waste treatment installations (50). However, these processes may be considered more as alternatives for whey disposal rather than profitable opportunities for manufacture of industrial whey products.

Whey Disposal and On-Farm Utilization

Although whey has become much too valuable to be disposed of on a large scale, there are still many smaller and isolated cheese manufacturing operations where whey disposal can be a major economical and/or ecological burden. Where industrial whey processing or manufacture of high value consumer products is not feasible, other methods of whey disposal must be selected, based mainly on the associated cost. The "down-the-drain" approach is certainly the most wasteful although not always the most expensive alternative, especially when municipal or existing industrial waste treatment facilities are located nearby and the volume of whey to be discarded is not great. Spraying the whey onto fields is still being practiced by many isolated cheesemakers in rural areas, sometimes relying on sophisticated approaches with time-controlled application schedules such as developed in New Zealand to maximize the potential fertilizer value and to minimize soil salinity and acidity problems inherent in these techniques (51). Direct feeding of whey to agricultural animals, especially pigs, appears to be one of the most profitable on-farm uses of whey (52). When the whey feeding is combined with methane production from the animal excreta for use as a fuel in a cheese factory located nearby, a truly ecologically enclosed industrial system can be developed as evidenced by several commercial installations in Switzerland.

NUTRITIVE VALUE AND USES OF WHEY

As a by-product of dairy processing, cheese whey contains about 50% of all the nutrients found in milk. The most valuable whey components from the nutritional standpoint are the whey proteins, the water-soluble vitamins (especially riboflavin), and some of the nutritionally important minerals. Acid whey is a particularly good source of calcium with its content approaching that of regular cow's milk. Whey protein from either sweet or acid whey is one of the best proteins for human food use, due to its balanced amino acid profile and superior digestibility (53). Dried cheese whey composition can be compared to that of regular wheat flour (31) in terms of the proximate composition and some of the micronutrients. In addition to the unquestionable value of the whey protein, calcium and riboflavin, some sources also emphasize the beneficial effects of the high (L +) lactic acid content of whey produced with certain dairy cultures (53).

The use of many industrial whey products as ingredients in various foods is based not only on the nutritional qualities but also on the desirable functionality of some of the products. With the high lactose and protein content, dried whey is an ideal substrate for the nonenzymatic Maillard browning reaction in foods where such color development is desired, as in breaded meat or fish products or in toasted bread. As one such example, dipping into solutions of lactose or cheese whey was shown to be effective for uniform brown color development in French fried potatoes (54). Lack of sweetness in lactose is advantageous in many applications of whole or modified whey ingredients, especially when used in meat products, processed cheese foods, gravies, soups, sauces, salad dressings etc. Whey protein is ideally suited for fortification of various foods both because of its nutritional quality and its functional attributes including bland taste compatible with most food flavors and solubility in aqueous food systems (55). Many additional uses of whole whey and whey-based traditional or modern food ingredients have been suggested in the various reviews available on the subjects (eg, 4,56,57). Inclusion of whey protein in cheese --- either by varying the cheese processing technology or by reincorporation of the protein recovered from the whey --- is one of the important research subjects concerning whey at the present time. Several alternative technological pathways can be used for incorporation of the heated whey protein precipitate into fresh cheeses such as quarg and quarg-based food products (7) in which the cooked flavor and quality impairment, often encountered in traditional cheeses, need not be a problem. This option is especially attractive for fresh cheese plants where whey from production of other cheese varieties is available.

Although food use of whey and whey based products is the most desirable whey disposal alternative, various nonfood uses of whey also have been proposed, including incorporation into foamed insulation materials for the construction industry or use as a binder for iron ore pellets (58). Enzymatic modifications of whey proteins for use in the pharmaceutical industry may follow the successes predicted for the casein (14). Rapid advances in biotechnology will likely discover new opportunities for conversion of whey into valuable industrial food or nonfood materials such as biosorbents, biopolymers, stabilizer gums, flavoring or coloring compounds, bacteriocins or fat substitutes as the recently approved Simplesse developed from whey protein and egg white (59). With its high lactose content, surplus dried whey could be used as a quick source of energy in international hunger-relief programs, however, the prevalence of lactose intolerance in most third world countries make such use difficult without careful development of foods that can be tolerated by the lactose malabsorbers. Recent investigations in this regard

(60) indicated that incorporation of whey into high solid indigenous foods could be possible as these foods appear to be better tolerated by lactose malabsorbers than more liquid products (61).

The possibilities for treating whey as an opportunity rather than a problem have increased dramatically in the recent years. In one of the newest industrial dairy installations in California, all whey produced in the cheesemaking section is completely utilized on site in a variety integrated processes, leaving no residue to dispose of (62). With continued technological developments, the emerging scarcity or inexpensive dairy ingredient sources and the increasing emphasis on ecologically responsible industrial processes, the image of whey is rapidly changing from that of a bothersome by-product to a highly prized resource.

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