BURLEIGH DODDS SERIES IN AGRICULTURAL SCIENCE

Achieving sustainable production of milk

Volume 1: Milk composition, genetics and breeding

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Contents

Introduction

Milk and associated dairy products constitute the world's most important agricultural commodity by value, particularly if dairy ingredients in other food products are taken into account. The dairy sector provides livelihoods for 1 billion people and is key to enriching diets the world over, although global consumption of dairy still falls short of national dietary guidelines. At the same time, dairy production is also a significant user of land and other resources, and is responsible for 2.7% of total anthropogenic greenhouse gas (GHG) emissions. There is therefore an urgent need to improve the efficiency of dairy production so that it can meet the nutritional needs of a growing population in a more environmentally sustainable way.

The two volumes of *Achieving sustainable production of milk* address this challenge. Volume 1 starts by summarizing current research on the composition of milk, both as a source of nutrition and as a vital nutritional, nutraceutical or structural ingredient in many other food products. It also considers factors affecting the sensory quality of milk.

Part 1 The composition and quality of milk

Chapters 1–3 provide a comprehensive review of the most important components of milk, their nutraceutical and technological properties and uses as ingredients in further processing. As Chapter 1 indicates, the proteins of milk are its most important constituents from a nutritional and technological point of view. Milk and milk processing have been researched for many years and, today, milk proteins are probably the best characterized of all food proteins. In recent years, numerous new milk protein ingredients have been developed, making this a particularly active area of research. Written by one of the leading research groups in the field, Chapter 1 provides a comprehensive and authoritative overview of the composition and properties of the major and minor milk proteins, the methods used to prepare milk protein fractions in the laboratory and the production of milk proteins on an industrial scale. This topic is then explored in more detail in Chapter 3. Some of the factors determining milk protein synthesis are also further explored in Chapter 9.

Chapter 1 starts by briefly summarizing the various methods used in protein analysis, including polyacrylamide gel electrophoresis (PAGE), sodium dodecyl sulphate (SDS)-PAGE, lab-on-a-chip techniques, capillary electrophoresis and the more recent development of advanced proteomic approaches such as high-resolution two-dimensional electrophoresis, as well as multidimensional high-performance liquid chromatography.

Around 78% of milk proteins belong to a unique group of milk-specific proteins, the caseins. The review of key trends in casein research starts with factors affecting the microheterogeneity of caseins (such as genetic polymorphism) which has an important effect on processing properties. The chapter also summarizes what we know about the other distinct characteristics which determine the functionality and stability of caseins such as degree of insolubility, susceptibility to proteolysis, heat stability and amino acid composition. Caseins in milk have long been known to exist as large colloidal particles known as casein micelles which affect properties such as colour. The stability of milk and many of its technologically important properties are related to the properties of the casein micelles, which have, therefore, been the focus of considerable research. Chapter 3 looks at properties such as micelle formation, structure and function as well as degree of stability in response to milk processing operations.

Apart from the caseins, the remaining 22% of milk proteins are referred to as whey (serum) proteins. The major components of whey are β-lactoglobulin and α-lactalbumin. Other components include blood serum albumin, immunoglobulins and lactoferrin. Whey also contains many minor proteins and enzymes. The chapter looks at composition and functional properties of each of these components of whey including the proteose-peptone fraction of milk protein and caseinomacropeptide (CMP).

Finally, the chapter also discusses what we know about the minor proteins, enzymes and other components in milk, some of which have attracted considerable attention as nutraceuticals, a topic picked by in Chapter 2. These include:

- metal-binding proteins
- β_2-microglobulin
- osteopontin (OPN)
- vitamin-binding proteins
- angiogenins
- kininogens
- glycoproteins
- growth factors
- indigenous milk enzymes
- biologically active cryptic peptides (such as phosphopeptides, angiotensin-converting enzyme (ACE)-inhibitory peptides)
- non-protein nitrogen (NPN)

Chapter 1 concludes by summarizing key methods in the laboratory-scale preparation of whey and casein proteins as well as the preparation of industrial milk protein products using membrane and other technologies. Whey protein products, for example, are key ingredients in several growth areas of the food industry, such as infant formulae, clinical nutrition and sports nutrition. They include sweet whey, whey powder, demineralized whey, whey protein concentrates, serum protein concentrates, whey protein isolates, and enriched and isolated whey protein fractions. The casein market is dominated by products produced by renneting or acid precipitation of milk. However, casein-derived ingredients manufactured using membrane filtration, such as milk protein concentrates (MPC) and micellar casein concentrates, now have a significant presence in the global market for casein. The chapter also reviews liquid/gelled casein concentrates, β-casein and hydrolysates. The topic of dairy-derived ingredients is discussed in more detail in Chapter 3.

Apart from the nutritional value of milk, milk-borne biologically active compounds such as proteins, peptides, lactoferrin, enzymes, lipids and carbohydrates have been shown to be increasingly important for physiological and biochemical functions that affect human metabolism and health beyond nutrition. In recent decades, major progress has been made in the science, technology and commercial applications of the many bioactive components in bovine milk and colostrum. Chromatographic and membrane separation techniques have been developed to fractionate and purify these components on an industrial scale. Production of bioactive milk ingredients by fractionation has thus emerged as a lucrative new sector for the dairy industry.

Building on Chapter 1, Chapter 2 provides a comprehensive review of bioactives in milk and research on their nutraceutical properties. Ingredients include bioactive proteins such as caseins, whey proteins such as α-lactalbumin and β-lactoglobulin, and enzymes such as lactoperoxidase and lysozyme, as well as bioactive peptides and bioactive lipids such as conjugated linoleic acid (CLA), phospholipids and cholesterol. The chapter also discusses bioactive carbohydrates such as lactose and oligosaccharides, other bioactive compounds such as growth factors, cytokines, nucleosides and nucleotides as well as bioactive minerals and vitamins.

The chapter starts by looking at bioactive proteins, beginning with caseins. Digested or catabolized caseins produce a variety of bioactive peptides, including antihypertensive and immuno-stimulating peptides. Many bioactive compounds are generated from different casein (CN) fractions, including casomorphins, casokinins, phosphopeptides, immunopeptides, isracidin, casocidin, casoxins and casoplatelins. As research shows, these exert different bioactive functionalities such as reduction of hypertension (ACE inhibitory), mineral-binding, immunomodulatory, antimicrobial and antithrombotic activities as well as pain management (with opioid agonist/antagonist properties).

The chapter then reviews individual whey protein components and their hydrolysed peptide fragments which exhibit various bioactive properties including opioid agonist, antimicrobial and antiviral actions, immune system stimulation, anticarcinogenic activity and other metabolic functions. The chapter reviews recent research on nutraceutical properties and potential applications of α-lactalbumin, β-lactoglobulin, lactoferrin, immunoglobulins, glycomacropeptide (GMP) (including caseinomacropeptide (CMP), the non-glycosylated form of GMP). As an example, α-lactalbumin hydrolysates and their specific peptides have been shown to have antihypertensive, antimicrobial, anticarcinogenic, immunomodulatory, opioid and prebiotic properties. Similarly, β-lactoglobulin from milk has proven to be an excellent source of peptides with a wide range of bioactivities, such as antihypertensive, antimicrobial, antioxidative, anticarcinogenic, immunomodulatory, opioid, hypocholesterolemic and other metabolic effects.

After reviewing enzymes such as lactoperoxidase and lysozyme, the chapter goes on to discuss bioactive peptides. There are more than 200 biologically and functionally active peptides that exist in milk and dairy products. Bioactive peptides affect functions in the body such as gastrointestinal, cardiovascular, endocrine, immune and nervous systems. The chapter summarizes the wealth of research on antihypertensive (ACE inhibitory) peptides with applications in the control of blood pressure, antioxidative peptides, antithrombotic peptides, hypocholesterolemic peptides with the potential to reduce blood cholesterol levels and opioid peptides (with opiate-like effects which influence pain, mood and appetite). The chapter also reviews mineral-binding peptides including phosphopeptides, caseinophosphopeptides (CPPs) and calcium-binding phosphopeptides (CCPs) with the ability to improve the absorption of minerals such as calcium, before going on to cover anti-appetizing peptides, which can help to reduce energy intake and promote a healthy body composition with less body fat due to their positive effects on satiation/satiety. Other peptides include antimicrobial peptides (such as lactoferricins) which are able to modulate inflammatory responses in addition to killing microorganisms, immunomodulatory peptides with the potential to boost immune cell function and cytomodulatory peptides able to suppress cancer cell activity.

Chapter 2 then assesses bioactive lipids such as CLA, phospholipids, cholesterol and minor lipids (which include gangliosides, glycolipids, glycosphingolipids and cerebrosides as well as alkylglycerol). It goes on to survey research on bioactive carbohydrates such as lactose (which affects the adsorption of minerals and vitamins), lactose-derived compounds (including lactulose, lactitol, lactobionic acid and galacto-oligosaccharides) and oligosaccharides.

The chapter concludes with a review of other bioactive compounds in milk such as growth factors (including epidermal growth factor, IGF-I and IGF-II (insulin-like growth factor), FGF1 and FGF2 (fibroblast growth factor), TGF-β1 and TGF-β2 (transforming growth factor), BTC (β-cellulin) and platelet-derived growth factor). It also covers cytokines (which include chemokines, interferons, interleukins and lymphokines), as well as main milk hormones: gonadal hormones (oestrogens, progesterone, androgens), adrenal (glucocorticoids), pituitary (prolactin, growth hormone) and hypothalamic hormones (gonadotropin-releasing hormone, luteinizing hormone-releasing hormone, thyrotropin-releasing hormone and somatostatin). After discussing nucleosides, nucleotides and polyamines, it reviews organic acids (such as lactic acid, citric acid, pyruvic acid, uric acid, orotic acid, nucleic acid and neuraminic acid). The final group of bioactive ingredients surveyed are bioactive minerals and vitamins, from calcium, phosphorus and potassium to trace minerals such as iron, zinc, iodine, selenium and manganese, as well as vitamins. Particularly, riboflavin (B_2) and vitamin B_{12}. In each case the chapter provides a valuable summary of key clinical research.

Building on both Chapters 1 and 2, Chapter 3 concludes the first group of chapters by looking at the range of dairy-derived ingredients for use in dairy and non-dairy foods, as well as non-food products. These ingredients range from commodity ingredients, such as milk and whey powder, to milk protein ingredients, such as caseins, caseinates, whey protein ingredients, MPC and milk protein hydrolysates. Lactose and lactose derivatives, including lactulose, lactobionic acid and the prebiotic galactooligosaccharides, and milk fat globule membrane (MFGM) material fractions are also produced as ingredients. This chapter reviews the main dairy-derived ingredients and their physical and nutritional functionalities and range of applications. The focus is primarily on ingredients produced on an industrial scale. The chapter shows how scientific and technical innovations have created a new range of products driven by the demand for dairy ingredients for nutritional products for infants and the elderly, performance nutritional snacks and ingredients with nutraceutical properties in preventing or managing a range of chronic diseases.

As highlighted in Chapter 2, milk proteins in particular not only are a source of amino acids, but can also confer immunity and are a carrier of calcium phosphate, which is essential for bone growth. In addition, some milk proteins contain bioactive sequences which may be released upon hydrolysis during digestion. The proteins in the MFGM are also known to have antimicrobial and antiviral properties. In addition to the main carbohydrate lactose, milk also contains smaller amounts of oligosaccharides. These are known to aid the development of the intestinal flora of the neonate, which provides important anti-infection properties and is an important factor stimulating postnatal development. Since they have a high value, milk proteins have received extensive attention with respect to preparing functional ingredients. Desired functionality may either be physical (in improving process functionality or product quality), nutritional or nutraceutical. Techniques used include selective precipitation, membrane filtration and chromatography. In addition, enzymatic hydrolysis of proteins may be used to improve physical, nutritional or nutraceutical functionality.

The chapter starts by reviewing techniques for refining casein and caseinates as well as their wide range of applications. As an example, sodium and potassium caseinate are excellent emulsifiers and foamers, and also have high heat stability, strong water-binding functionality and excellent nutritional properties. They are therefore widely applied in coffee creamers and other high fat products, cream liqueurs, bakery products, whipped toppings, soups, sauces, ice cream, meat products, and infant and clinical nutrition.

The chapter also looks at the preparation of whey protein concentrates and isolates using techniques such as ultrafiltration, as well as fractionated whey protein ingredients (such as α-lactalbumin, β-lactoglobulin and lactoferrin) developed for the infant formula industry. The chapter then discusses processing of MPCs used for standardization of cheese milk, protein fortification of yogurt, ice cream mixes, and clinical and infant nutrition products. Because micellar calcium phosphate is largely retained in the micelles during ultrafiltration, MPCs contain high levels of encapsulated bioavailable calcium, thus making them interesting ingredients for nutritional products.

Milk protein hydrolysates from caseins and whey proteins are a class of milk protein ingredients that have attracted more and more interest in the last few decades. Milk protein hydrolysates can be divided into three main categories based on their designated application: hydrolysates or specific peptides with biological activity, hydrolysates for consumers with specific nutritional needs and hydrolysates for improved protein functionality. As an example, and as discussed in Chapter 2, antihypertensive peptides are one of the most well-known categories of milk peptides with biological activity, manufactured by enzymatic hydrolysis of milk protein ingredients or fermentation by proteolytic bacteria. The chapter also discusses the three main categories of milk protein hydrolysates designated to address specific nutritional needs: milk protein hydrolysates used as ingredients in hypoallergenic infant milk formulae developed for infants that suffer from cow's milk protein allergies; low-phenylalanine hydrolysates for consumers that suffer from phenylketonuria; and mildly hydrolysed milk proteins for easier digestion developed either for infants or for the elderly. Finally, hydrolysis of whey proteins can increase their processing functionality such as solubility, viscosity, surface activity, emulsifying and foaming ability, as well as increase thermal stability.

The carbohydrate fraction of milk has also been a rich source of ingredients such as lactose and lactose derivatives. Lactose is a widely used carbohydrate in food products in baking and confectionery, but also as an excipient in pharmaceutical products. In addition, lactose can also be converted into functional ingredients such as lactulose, lactitol and lactobionic acid used in sweetener and other applications. Furthermore, prebiotic galactooligosaccharides (GOS) can be produced from lactose and have found wide application, particularly for infant nutrition products. In each case, Chapter 3 reviews the key processing steps in developing ingredients on a commercial scale. Finally, building on Chapter 1, the chapter reviews the preparation and use of MFGM material fractions. MFGM material has useful properties for emulsion stabilization and controlling protein interactions and has therefore been used in ice cream, evaporated milk, cheese and processed cheese, and nutritional products.

Whilst the first group of chapters concentrates on ingredients derived from milk, the following two chapters discuss milk itself, starting with the key issue of spoilage. As Chapter 4 shows, milk spoilage is essentially a result of inadequate control of the growth of microorganisms, combined with the activity of enzymes which have found their way into milk from production and processing environments. As the chapter shows, psychrotrophic, thermophilic or thermoduric and spore-forming microorganisms (PTS) can contaminate milk, grow in chilled bulk tanks and survive heat treatments to reduce shelf life. They also produce thermotolerant lipolytic and proteolytic enzymes that can survive the pasteurization process to cause spoilage. Spoilage microorganisms can be classified by their heat resistance (thermoduric) as well as their preferred growth temperature as psychrotrophic, mesophilic or thermophilic, with thermoduric psychrotrophs a particular challenge.

The chapter summarizes what we know about conditions favouring growth and survival. It also reviews sources of contamination such as the mammary glands, the external surfaces of the udder and teats, the farm environment (e.g. bedding), milking equipment and personnel, as well as tankers and the transport chain through to the processor. Based on this foundation, the chapter then describes best practice in monitoring and prevention of contamination by spoilage bacteria. Preventing spoilage is a question of preventing contamination through hygiene and sanitation, proper cooling and understanding the conditions specific to the processes leading to the wide variety of dairy products and ingredients. Control measures on the farm include mastitis control, udder hygiene, milking routine, environmental sanitation (including feed and bedding), tank and truck sanitation, processing conditions and equipment sanitation. Udder hygiene and teat preparation (cleaning and drying) are considered critical points. However, the concentration of spores in silage and feed during housing periods is now regarded as having significant impact on the spore load of milk. The chapter concludes by identifying future trends in this area, including the prospect of better detection and typing methods for identifying problem areas as well as improved technologies for ensuring milk quality all along the value chain. It also identifies the need for more research in areas such as determining critical points in the origin of spore formers on the farm as well as in the processing plant and the synergistic effects of combining control technologies.

Chapter 5 builds on Chapter 4 by first reviewing the causes of off-flavours in milk and the importance of good management practices (including herd size, milking routine and bedding) in determining levels of mesophilic and thermophilic spores in milk. It also looks at good practice in monitoring for and identifying different categories of off-flavour and their likely causes, as well as ways they can be prevented. As the chapter shows, preventing absorbed off-flavours generally involves good cow nutrition (appropriate feeds, balanced rations) and management (ventilation, health monitoring, manure management) practices. Preventing bacterial off-flavours hinges on good training of staff that prepare teats for milking and proper maintenance of equipment, temperature control, proper selection of application of cleaning and sanitizing chemicals, and prompt milk processing. Preventing chemical off-flavours involves keeping milk away from light, reactive metals, and excessive agitation and using appropriate processing controls. Preventing delinquency off-flavours relies on attentive care by all who handle milk, from cow to consumer. Finally, the chapter reviews techniques for instrumental and sensory shelf life testing.

Part 2 Genetics, breeding and other factors affecting quality and sustainability

The next group of chapters in Part 2 looks at ways of balancing milk yield and quality with other factors affecting the sustainability of milk production. Chapter 6 gives an authoritative overview of some of the key developments in breeding dairy cattle in recent decades. As the chapter shows, there has been a large increase in the productivity of dairy cows over the last half century, with the yield per cow more than doubling. This is substantially due to the use of genetic selection in dairy cattle breeding programmes. Early gains were achieved through progeny test schemes supported by artificial insemination (AI) and embryo transfer (ET) technologies. AI and ET technologies made possible a strong international trade in genetic material, resulting in the large-scale introduction of Holstein Friesian genes into many dairy populations throughout the world. The chapter also covers the use of multiple ovulation and ET and juvenile *in vitro* fertilization and ET to further improve breeding efficiency.

The chapter then reviews the development of genomic selection which has resulted in halving of the generation interval and doubling of the rate of genetic gain. An example is the DGAT1 mutation with a significant effect on milk fat and other milk constituents. Initial results found a relatively low number of individual quantitative trait loci (QLT) useful in in marker-assisted selection. Subsequent studies based on increasingly dense marker panels have revealed that most of the observed genetic variation on quantitative traits is due to a large number of genes, each with a small effect. This resulted in a shift to the use of all marker information across the whole genome in a single analysis to predict breeding values, using single-nucleotide polymorphism chips to genotype individuals for numerous genetic markers.

Finally, the chapter shows that genomic selection is opening powerful new opportunities to select for more complex traits such as phenotypes associated with feed efficiency, methane production, fertility and health traits that have previously been difficult or expensive to measure, but which are important to the sustainability of dairy production. Accuracy of trait prediction is determined by the size of the reference population, or the number of bulls and cows for which both genotype and phenotype are known. This has pushed countries to increase the size of reference populations and to share their data. Many breeding programmes still lack good phenotypic information about non-production traits and, as a result, genetic change remains dominated by an increase in yield, in spite of an increased selection emphasis on other traits. More intensive measurement of a wider range of traits is needed in dedicated resource herds, and these can serve as a training population to allow for genomic selection of bulls.

Chapter 6 provides a context for Chapter 7. As it notes, up until recently most of the emphasis of breeding in dairy cattle was for traits such as milk production, fat and protein content. Inclusion of secondary or 'functional' traits in breeding objectives only began to develop in the 1990s. Although there is a nearly complete consensus about the economic importance of functional traits such as fertility, health and longevity, genetic evaluation and inclusion of these traits in selection indices has been hindered by factors such as difficulties of definition and measurement, low heritability and negative correlations with milk production.

The chapter reviews progress in breeding for functional traits which started with efforts to compute genetic evaluations for a range of traits, using different models, for inclusion in a selection index. The chapter also reviews the range of studies of the heritability of key functional traits: fertility and calving traits, health traits such as susceptibility to mastitis, hoof disorders, udder oedema, milk fever, retained placenta, metritis, ketosis, lameness, cystic ovaries and displaced abomasum, as well as growth rate and longevity. The chapter also looks at alternative approaches such as evaluation and selection of traits that are genetically correlated with 'functional' traits, but are more amenable to genetic evaluation, or crossbreeding breeds that are superior for production to breeds with economically higher genetic levels for secondary traits. The chapter also reviews what we know about genetic parameters and genetic and phenotypic trends for these traits. Finally, the chapter discusses methodologies for detection and analysis of the actual segregating genes that affect functional traits, including mapping and identification of quantitative trait loci related to functional traits.

Chapter 8 builds on Chapter 6 by looking in more detail at ways of improving breeding efficiency in dairy cattle whilst maintaining high milk production. As noted earlier, for decades genetic selection of dairy cattle was largely performed with a focus on traits relating to milk production with a corresponding decline in fertility. This is despite the importance of high reproductive efficiency to sustainable dairy farming, and the fact that reproductive failure is the primary reason for culling dairy cows in many countries. As the chapter shows, many factors, either independently or through their interactions, can influence reproductive efficiency. The main factors affecting reproduction can be broadly grouped into four categories, namely human (managerial), animal (intrinsic and extrinsic), nutritional and environmental.

Looking first at managerial factors, the chapter shows that poor oestrus detection efficiency is a primary cause of reduced reproductive efficiency in dairy herds. In herds using AI, accurate detection of oestrus is extremely important for reproductive success. Other factors include identification of non-pregnant cows as soon as possible after breeding, feeds and feeding, disease management (e.g. vaccination) and environmental management (e.g. heat abatement during hot summers) which can have major impacts on reproductive efficiency. The chapter also looks at the relative importance of animal factors such as breed, genotype and age as well as nutritional factors. Inadequate energy intake during the early postpartum period is common in high-producing dairy cows, resulting in negative energy balance, with mobilization of fat and high concentrations of non-esterified fatty acids (NEFA). High NEFA concentrations have negative effects on oocyte function and embryo quality which likely contribute to subfertility in dairy cows.

With this foundation, the chapter reviews the various strategies that can be used to improve reproductive efficiency in dairy herds. Since poor oestrus detection efficiency is a major factor decreasing reproductive inefficiency, the first strategy should be to improve oestrus detection efficiency. Other strategies include oestrus synchronization and synchronization of ovulation (OvSynch), the use of voluntary waiting periods, shortening the dry period to minimize negative energy balance and techniques to minimize embryo loss such as use of supplemental exogenous progesterone and boosting endogenous progesterone. Although high-protein diets have a detrimental effect on fertility, supplemental fats and specific polyunsaturated long-chain fatty acids have positive effects.

The final chapter in Volume 1 looks at ways of improving nutritional efficiency in cows to both optimize milk quality and improve sustainability. As Chapter 9 shows, the conversion of feed nitrogen into milk nitrogen often has only 20% efficiency which results in significant losses of nitrogen to the environment, contributing to the degradation of air and water systems. The chapter considers the two nitrogen-utilizing systems in the cow: the rumen microbiota and ruminant tissues. The more efficient both the rumen and tissue systems are, the lower the urinary nitrogen excretion. The rumen microbiota considerably alters feed inputs producing microbial protein for digestion and metabolism. Rumen fermentation of feeds provides energy (primarily from carbohydrates) and nitrogen (primarily from protein) for microbial protein synthesis. A balance of rumen-available carbohydrate and rumen-degradable feed protein results in efficient microbial protein synthesis, minimizing nitrogen wastage from the rumen. The proportion of essential amino acids and total metabolizable protein absorbed from the small intestine then determines the efficiency of tissue utilization of protein for milk protein synthesis and maintenance. Absorption of an ideal proportion of essential amino acids improves efficiency of milk protein synthesis, enabling a reduction of total protein in the diet. Both efficiency of nitrogen utilization in the rumen and nitrogen utilization by the mammary gland influence nitrogen losses.

The chapter reviews approaches to estimating rumen microbial protein synthesis, the protein and energy requirements of dairy cows and the use of milk urea nitrogen to assess the nitrogen efficiency of dairy cows. It then considers the development of nutritional systems which account for rumen microbial synthesis, rumen-degradable and -undegradable feed protein, and endogenous protein supplies of amino acids based on utilization of feed inputs. The goal of precision protein feeding programmes is to capture as much dietary nitrogen into milk nitrogen as possible and reduce urinary nitrogen losses. It is now possible to significantly reduce dietary crude protein and maintain reasonable milk production levels in dairy herds. Forage quality, appropriate protein and energy supplements are necessary to ensure adequate rumen-available energy and nitrogen for microbial protein synthesis. Nutritional systems are thus evolving which account for rumen microbial synthesis, rumen-degradable and -undegradable feed protein, and endogenous protein supplies of amino acids based on utilization of feed inputs. Accurate prediction of essential amino acid supply to the mammary gland by ration models will facilitate improved conversion of feed nitrogen to milk protein nitrogen, reducing urinary nitrogen. Future work will more fully describe influences of feed nutrients on rumen fermentation, better characterize endogenous protein supplies and incorporate hindgut models of nutrient utilization to improve the precision of ration formulation models. Efficient grouping of cattle combined with more precise ration formulation will further influence the performance of nutritional models to reduce environmental pollution from dairy farms.

Summary

As the wealth of material in Volume 1 shows, research is continuing to improve our understanding of what a rich resource bovine milk is in meeting the nutritional and wider health needs of a growing population, as well as an important ingredient in a wide range of other food products. It also shows what is being done to preserve milk quality and yield whilst, at the same time, making milk production more efficient, whether in terms of developments in breeding for functional traits such as reproductive efficiency or management strategies for optimizing nutrition to reduce environmentally damaging waste. Other aspects of sustainability are discussed in Volume 2.

Index