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A 100-Year Review: Total mixed ration feeding of dairy cows[1]

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ABSTRACT

Total mixed rations (TMR) as we know them today did not exist in 1917. In fact, TMR are an invention of primarily the last half of the past 100 yr. Prior to that time many dairy herds were fed only forages, but dairy producers started moving toward TMR feeding as milk production per cow increased, herds became larger, freestall and large-group handling of cows became more common, and milking parlors became more prevalent. The earliest known reports in the *Journal of Dairy Science* of feeding "complete rations" or TMR may have appeared in the 1950s, but those studies were often reported only as abstracts at annual meetings of the American Dairy Science Association or in extension-type publications. The earliest full-length article on TMR in the journal was published in 1966. An advantage of feeding TMR as opposed to feeding forages supplemented with concentrates is the opportunity to make every bite of feed essentially a complete, nutritionally balanced diet for all cows. Nutritionally related off-feed (e.g., ingredient separation due to poor mixing, feed sorting by the animal, and so on), milk fat depression, and other digestive upsets were less likely to occur with TMR feeding. Feed mixer wagons, feed particle sizes, moisture content of diets, and other factors were not concerns before TMR feeding but are concerns today. Today, most dairy herds, especially larger herds in the United States and elsewhere, feed TMR.
Key words: total mixed ration, dairy cow

INTRODUCTION

Total mixed rations as we know them today did not exist in 1917. In fact, TMR are an invention of primarily the last half of the past 100 yr. The earliest known reports in the *Journal of Dairy Science* of feeding "complete rations" or TMR may have appeared in the 1950s (Harshbarger, 1952); however, this study and some others were reported only in abstract form at annual meetings of the American Dairy Science Association. One of the earliest full-length articles (McCoy et al., 1966) indicated advantages of feeding TMR as opposed to feeding forages supplemented with concentrates (referred to as grain mixes in some studies). More is said later about TMR feeding, but first we start with an overview of earlier dairy cattle feeding systems.

This article reviews what was reported primarily in the *Journal of Dairy Science* regarding the development and use of TMR feeding of dairy cows. Many nutritional aspects of feeding dairy cattle are not covered in this article because those subjects are covered by other authors in other articles of this special issue. Although TMR feeding is used in many research experiments reported in the journal, many of the techniques involved in areas related to TMR feeding are reported in extension and industry publications and are not necessarily reported in scientific journals. Some of that information is cited in the review-type articles referenced in this article. Appendix Table A1 presents a timeline of major developments related to TMR feeding as well as some factors that are not directly related to TMR feeding but are related to why the industry moved toward TMR feeding.

HISTORY OF THE DEVELOPMENT OF TMR FEEDING

Prior to the 1960s, most dairy herds in the United States were housed in stanchion or tiestall barns with concentrates added on top of the forages (i.e., top dressed). That is the system that I, my parents, and my grandparents grew up with, which covers back to before the start of the *Journal of Dairy Science*. Even during my earlier years (1970s) at South Dakota State University (**SDSU**), we often fed concentrates as a top dress in our research diets. Cows are ruminants and thus designed to utilize forages. Therefore, rations were based on forages—often pasture in the warmer months and hay or silage especially in the cooler seasons. As production per cow increased, it became apparent that cows needed additional nutrients, which were supplemented as concentrates. Several *Journal of Dairy Science* articles through the years (Coppock et al., 1981) attest to various methods of supplying additional

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concentrates. The earliest reference to guidelines for feeding grain appeared in a 1930 extension bulletin by Frazer (cited by Huffman, 1939). Greater refinements in concentrate feeding by many researchers came later. Often the amounts of concentrates fed were based on milk production, such as 1 kg of concentrate/3 kg of milk produced; modifications were based on fat content of the milk, differences due to breed, and additional allotments for growth of younger cows. Such refinements were being put into place by the early 1950s. Concentrates fed typically contained locally available grains (e.g., corn, oats, wheat, barley) plus a protein supplement source (e.g., soybean meal, cottonseed meal, linseed meal). There was often little concern about nutritionally balanced diets other than the need for protein; the need for various vitamins and minerals often got minimal or no attention.

Starting in the 1960s, several concentrate feeding systems were developed in place of topdressing on forages (Coppock et al., 1981). Some of these were quite simple, whereas others were quite sophisticated. One of the earliest systems fed concentrates in relation to the amount of water consumed. A simple system gave cows wearing a magnet on a neck chain access to unlimited amounts of concentrates. More elaborate and accurate systems used computerized programing to determine how much and how often a cow could consume concentrates. Extensive research was conducted in this area during the 1960s and into the early 1980s, but these systems are less used today.

Another interesting aspect of feeding concentrates was density of the ingredients. Feeding was often based on volume by the "scoopful" with no regard to weight per volume. During the early 1960s when I was an undergraduate at the University of Illinois, increasing the amount of concentrates fed was becoming more popular; however, I was unsuccessful in convincing my dad, who was a very good dairy producer, of this until he learned it by accident. One summer we ran out of corn around the time we harvested oats. Rather than buy more corn to maintain our usual corn–oats–soybean meal blend, Dad switched to feeding only oats as the grain ingredient. Around the time he harvested corn he ran out of oats, so he immediately totally replaced ground oats with ground shelled corn but still put the same-sized pile of grain mix in front of the cows. Because corn is denser than oats (0.72 vs. 0.46 kg/L for corn and oats, respectively) and contains more energy per kilogram (3.12 vs. 2.78 Mcal of NE_L/kg; NRC, 2001), Dad was now feeding more grain mix and a grain mix with more energy. This resulted in approximately 74% more NE_L from the concentrate portion of the diet and an immediate increase in milk production from most cows. Increasing the amount of concentrates fed was becoming more popular in the 1960s; however, excess concentrates that led to insufficient amounts of effective fiber in the diets often resulted in milk fat depression and digestive upsets.

The increased use of milking parlors, starting primarily in the early 1960s, led to additional ration and cow handling systems. The first large-scale milking parlor was the Rotolactor, which is a predecessor to today's rotary parlors. It was developed by Borden in 1930 and installed in the Walker-Gordon Laboratories Farm in New Jersey, where it remained functional until 1971. However, it was not until herringbone-style parlors were developed in New Zealand in the 1950s that milking parlors started to become popular in the United States and elsewhere in the 1960s (Weimar and Blayney, 1994). When I worked as a herd tester in northern Illinois during the summer of 1962, only 1 of the 25 herds I tested used a milking parlor. Today virtually all dairy herds in South Dakota and elsewhere in the United States use milking parlors. Initially, for many herds, some or all of the concentrate was fed in the milking parlor, often as an enticement to get cows into the parlor. This meant that all forages were fed separately from all or some of the concentrates, which sometimes led to digestive upsets and other problems (Rakes, 1969; Coppock, 1977; Eastridge, 2006). Dairy producers soon found that high-producing cows did not have sufficient time in the milking parlor to consume the amount of concentrate needed and that milking time was faster and cleaner without concentrate feeding in the parlor. Thus, few if any dairy operations today include concentrate feeding in the parlor, which means lower costs when building a parlor. However, with the more recent advent of robotic milking systems, dairy producers sometimes feed concentrates in the stall as an incentive to get cows to come into the milking stall.

Another change in cow handling that occurred around the time of milking parlors was increased size of dairy herds. The advent of bulk tanks in the 1950s replaced handling milk in cans and encouraged increased herd size because bulk tanks were a major economic investment (Weimar and Blayney, 1994). For instance, when my parents built a new milk house to accommodate a bulk tank on our Illinois farm, we doubled our herd size to 40 cows. Meanwhile, 4 neighbors quit dairying. We continued with stanchion barns, but larger herd sizes nationwide led to group housing with freestalls or large lots, group feeding, and the advent of partial or total TMR feeding. However, even into the early 1970s, the average dairy herd size in the Midwest and many other areas was only 20 cows; larger herds of several hundred cows could be found in the West and Southwest. Today, herds of several thousand cows can be found in many areas of the United States, Canada, and elsewhere. The above information is paraphrased from many annual reports from the USDA Economic Reporting Service (e.g., USDA ERS, 2017) and is often reported in various popular publications such as *Hoard's Dairyman*.

The use of commodity by-products in dairy cattle diets was another change that started to occur in the 1990s or earlier, first in the southwestern states such as California and much later in other areas of the United States. Although dairy producers still depend heavily on traditional feed grains, protein supplements, silage, and hay, today most dairy diets contain at least some by-products such as food processing wastes as well as more traditional items such as distillers grains, cottonseed, and soy hulls. In some areas, by-product feeds compose a significant portion of the diet.

TMR FEEDING

Initially there were many versions of TMR feeding, mostly partial TMR versus complete TMR. Partial TMR usually was used with group housing and feeding when additional concentrates were fed in the parlor or via separate concentrate feeding stations. Several concentrate feeding systems were developed (Coppock et al., 1981) as described above.

A survey by the USDA National Animal Health Monitoring System (2014) indicated that almost 90% of large herds (>500 cows/herd) were fed TMR compared with <20% of small herds (30–99 cows/herd). Nationally, the trend toward TMR feeding occurred gradually rather than instantly. The first reports of TMR feeding in the *Journal of Dairy Science* were presented as abstracts at the national meeting of the American Dairy Science Association (Harshbarger, 1952), and the first journal article on TMR was published in 1966 (McCoy et al., 1966). The reviews by Coppock (1977) and Rakes (1969) pointed out that the advantages of the complete ration system far outweigh the disadvantages. These advantages and disadvantages of TMR, as paraphrased from Coppock (1977), are listed below. Many of these statements are still true today, although in some areas we know more than was known in 1977. Some of these items are further explained later.

Advantages of TMR Feeding

- No choice among feeds is permitted. Consequently, each bite consumed is a uniform, definable, and—as closely as one can make it—nutritionally complete diet. (See later discussion for further clarification.)
- High production with TMR was demonstrated in research trials and by dairy producers with large herds.
- Free-choice mineral supplements were unnecessary.
- Complete rations coupled with lactation groups permitted special formulation for high producers and other special groups. (Today we also know of special situations in which TMR feeding can be very effective, which is discussed below.)
- Complete rations fed ad libitum result in fewer digestive upsets in early lactation as cows are changed from high-forage diets to higher concentrate diets immediately postpartum. (This is verified in later discussions.)
- Nonprotein nitrogen compounds, especially urea, can be more easily and safely fed as TMR.
- A TMR with a forage base of silage serves to dilute and mask the flavor of unpalatable ingredients. This feature offers significant advantage because it increases the flexibility and minimizes the number and magnitude of constraints that must be imposed on least cost-formulated diets. In effect, one can make large changes in formulation as prices change without inducing an off-feed problem. Sudden changes in forage types are possible without depressing intake or milk production.
- Reduction in labor may accrue through TMR feeding.
- By providing a specific and obligatory ratio of forage to concentrate, one can prevent some cases of milk fat depression by ensuring that fiber in the consumed diet is adequate to maintain normal, nondepressed milk fat test. (Today, we would be inclined to say "forage NDF to concentrate" ratio rather than "forage to concentrate ratio" as a means of more precisely formulating diets.)
- It is not necessary to feed concentrates in the milking parlor.
- It is possible to mechanize a conventional tiestall barn for TMR feeding.
- The total diet can be formulated quantitatively.

Disadvantages of TMR Feeding

- Hay that is stored in baled or long form must be chopped before it can be blended with silage or grain.
- Mixer wagons that thoroughly blend ingredients are expensive, and electronic load cells are highly recommended to quantitate the blending process.
- Many barns may be designed for a single large group and are awkward to split into smaller groups.
- Experimental data are limited regarding sound recommendations for the number of cows per group and the exact ration specifications that will

permit efficient use of concentrates. (Research conducted since the time of that review article has answered some of these questions.)
- It may not be economically feasible to use TMR feeding in small herds, and TMR are less applicable for grazing systems.
- More mathematical calculations are necessary.

The idea that each bite of diet is the same with a TMR is not entirely true. Sorting of feed ingredients is greatly minimized with TMR but not completely prevented. This aspect of TMR feeding can be valuable whenever one attempts to troubleshoot a herd characterized by a high incidence of some disorder. For instance, in an experiment designed to evaluate feed sorting, DeVries et al. (2007) indicated that cows rapidly adjusted their sorting behavior when subjected to a dietary change and exhibited more sorting for short particles and against long particles, NDF, and physically effective NDF when fed a low-forage diet. Many researchers do not report compositions of the starting TMR and the orts remaining in the manger, but when they do report such data (e.g., DeVries et al., 2007; Litherland et al., 2013) they show that the compositions of the starting TMR and the orts remaining in the manger were not identical. This was especially demonstrated in preliminary data for an experiment of ours evaluating wet distillers grains (Birkelo et al., 2004). One day we received a batch of spoiled wet distillers grains. Even though the diet was fed as a TMR, the next morning one cow had consumed all of her allotment except the spoiled wet distillers grains, and all she had to sort with was her tongue.

A cow's wisdom to select what it needs in order to consume a nutritionally balanced diet is not great. In 1927, Nevins (cited by Spahr, 1977) conducted an experiment in which cows were allowed to choose the quantity of feed consumed over the entire lactation. He found that, except for a short period after calving, cows consumed greatly in excess of their requirements. Cows differed markedly from each other and from one time to another in their selection of feeds. Milk production was not increased, and the idea of self-feeding cows cafeteria style was inadequate. More recently, Coppock (1977) observed a substantial difference in individual cow preference for corn silage versus alfalfa hay; preference for corn silage ranged from 23.6 to 77.7% in one study. The freedom to select a preferred forage is most serious when 2 forages such as corn silage and alfalfa are offered because the great difference in their protein and mineral contents severely limits the precision of concentrate formulation to match some "average" forage base and formulate nutritionally balanced diets. Using a cafeteria-style mineral feeder was likewise not accurate when cows were selecting minerals needed to supplement diets based on corn silage or alfalfa hay (Muller et al., 1977). For instance, cows sometimes selected large amounts of calcium when fed an alfalfa hay diet that already contained more than adequate amounts of calcium. Flavor preferences for certain feeds or carriers of feed supplements is also a factor that enters into cow feed choices (Coppock et al., 1981). Total mixed rations can eliminate, or at least greatly decrease, the feeding problems cited above.

Fewer digestive upsets and off-feed situations occur with TMR feeding (Hernandez-Urdandeta et al., 1976). This at least partially reflects the fact that each bite is more nutritionally balanced than when concentrates and forages are fed separately. Also, cows eat TMR diets more slowly than they would likely eat concentrates, and only a little concentrate can be consumed in a short time. These factors are also partially related to number of times fed daily, stocking density, manger barrier design (e.g., open bunk vs, headlocks), and social behavior of cows (Huzzey et al., 2006). Feeding more frequently minimizes effects of overstocking and social dominance of cows even though these are less of a problem with TMR feeding than when concentrates and forages are fed separately. The use of a barrier between adjacent cows, such as a headlock feed barrier, can further reduce competition at the feed bunk. There is some research evidence that milk production is increased and efficiency of converting ME to milk is improved in cows fed a TMR compared with cows fed the diet components in meals (Holter et al., 1977). In cases bordering on acidosis, several studies (e.g., Keunen et al., 2002; DeVries et al., 2008) indicated that cows can sort for variations in particle size to help minimize the acidosis situation. Also, TMR plus supplemental long hay can maintain DMI during incidents of, and recovery from periods of, low ruminal pH (Keunen et al., 2002; Kmicikewycz and Heinrichs, 2014).

Although stanchion or tiestall barns are less frequently used for dairy cattle housing today than in the past, TMR feeding can also be used in such facilities. A stationary mixer may be mounted on a conventional platform scale in the feed room so that diets can be mixed in that device quantitatively, and a self-propelled (sometimes automated) feed cart can be used to deliver the blended mix to the cows. I am aware of such a situation in a larger dairy herd (>1,000 cows) near our university's dairy herd that still maintains a 100-cow tiestall barn for special cows in addition to a separate freestall parlor system for the remainder of the herd. The tiestall barn uses the automated TMR feeding system.

Grazing systems present another challenge for TMR feeding as one is dealing only with a partial TMR. It is difficult to accurately formulate partial TMR with grazed nutrients, but many studies have used partial TMR with grazing (Bargo et al., 2002). Depending on prices for feeds and milk, TMR feeding alone was often but not always more profitable than grazing with partial TMR feeding (Tozer et al., 2003).

With the use of TMR feeding came additional considerations such as particle size, moisture concentration, mixing systems, ingredient separation, and order of adding ingredients to the mixer batch. Each of these factors involved research, trial, and error, and many of the findings are reported in extension-type or manufacturer publications and not necessarily in scientific journals.

Particle Size

Particle size is one area that has received considerable attention. The Penn State shaker box system (Lammers et al., 1996) and the relative proportions of the diet that should be in each size category have become important management tools for dairy producers and researchers. The shaker box system shows the importance of having sufficient but not excessive amounts of larger particles, can indicate over- or undermixing, and can point out problems with nutritional management of diets that otherwise have acceptable nutrient compositions (Maulfair and Heinrichs, 2013). This can be a major consideration when dry hay is a part of the TMR. For example, the shaker box system can help determine just how much cutting is needed to get particles down to a sufficient size for adequate mixing of a TMR but not so small as to cause acidosis (Keunen et al., 2002; Kmicikewycz and Heinrichs, 2014), other digestive upsets, and milk fat depression (Bhandari et al., 2007).

Mixing

The TMR feeding systems led to the creation of mixer wagons and several factors related to the feeding process. Mixing time, order of adding ingredients to the mixer wagon, and style of mixer wagon can become factors. The following information is gleaned from several extension and industry presentations, many of which are unpublished. For instance, extending mixing time—sometimes unintentionally, such as the operator starting the mixer but then getting distracted with other tasks—can decrease particle size to the point that milk fat depression and other health problems may occur. Adding ingredients needed in small amounts (e.g., premixes of vitamins or minerals) too early can result in uneven distribution of those ingredients. Mixer wagon manufacturers often recommend the most desirable order of adding ingredients to prepare the TMR. Heavier ingredients sink and lighter ingredients float. When applied to feeds, for instance, corn silage is 33% denser than alfalfa silage, and the mineral mix can be 2 or 3 times denser than the protein or grain mix. Generally, low-density ingredients with long particle length such as hay should be added first, followed by high-density ingredients with small particle size that will sink. Most vertical mixer wagons allow the incorporation of unprocessed hay that should be added as the first ingredient, but the mixing time should be carefully controlled to ensure that the particle length is not excessively reduced. Although horizontal mixer auger wagons equipped with knives also allow for the incorporation of unprocessed hay, the uniformity of mixing may be better when hay has been previously processed.

Moisture Content of the TMR

The amount of moisture in the diet can influence optimal DMI and ingredient separation. A diet containing less than 45% DM may restrict DMI because of gut fill limitations (Lahr et al., 1983). Insufficient DM content can occur when feeding large amounts of ensiled forages and when feeding large amounts of wet by-products, such as wet distillers grains (Schingoethe et al., 2009). Conversely, a diet that is too dry, which can occur with large amounts of hay and concentrates, may increase ingredient separation and decrease total DMI. Exceptions to diet moisture content limiting DMI may occur with grazing situations (Bargo et al., 2002). Research studies (DeVries and Gill, 2012; Litherland et al., 2013) and industry observations (S. Emanuele, private consultant, unpublished data) indicate that providing some of the liquid as sugars such as molasses may be more effective in decreasing feed sorting than water alone. This may partially be due to coating fibrous products such as cottonseed and may actually increase ruminal fermentation (Mullins and Bradford, 2010). Thus, effects of sugars such as molasses and possibly lactose in whey products (DeFrain et al., 2006) may be partially attributable to stickiness as well as a source of fermentable sugars and moisture. In recent years, researchers have indicated that optimal DM content of diets should be greater than 45% and less than 60% DM.

It is important to regularly check the DM content of moist dietary ingredients and adjust proportions of ingredients fed on a DM basis as necessary to maintain nutritionally balanced diets. For example, with the SDSU herd, we switched from a batch of corn silage containing 43% DM to a batch containing 29% DM but did not immediately change proportions of each ingredient in the TMR on an as-fed basis. The result was insufficient dietary fiber, which led to milk fat depression.

This was confirmed a few days later with our monthly DHI herd test. Around the same time, our SDSU dairy processing plant manager called the farm because the milk received did not contain sufficient amounts of fat to skim off of the milk for making ice cream.

Moisture and flavor of diets from ingredients such as corn silage can be effective in masking flavors of unpalatable ingredients, such as when anionic salts are added to transition diets (DeVries et al., 2008). It also makes it easier to incorporate commodity by-products (Grasser et al., 1995; Schingoethe et al., 2009) into diets and to change formulations without greatly affecting feed intake. Total mixed ration feeding has made it easier to incorporate many such ingredients into diets than would be possible with forage–concentrate feeding systems.

Grouping of Cows

The use of TMR feeding allows a dairy to group cows into many categories based on nutritional needs (Weiss, 2017). A recent survey by the USDA National Animal Health Monitoring System (2014) indicated that 63% of large dairies feed different rations according to lactation number, stage of lactation, or production level. Grouping first-lactation cows separately from older cows places less stress on first-lactation cows and possibly results in better health and production. Having separate groups for prefresh and fresh cows has several benefits but may be less economically feasible in smaller herds because of the small groups involved. Computerization of ration formulation makes formulating various dietary groups easy. One may not fine-tune formulations to the individual cow as one could with individual feeding, but within economic practicality one can come close.

TMR Feeding of Young Stock

It is logical to assume that TMR feeding can be used with growing herd replacement animals as well as with the milking herd and dry cows. Many of the same principles listed for the milking herd also apply to growing animals of various sizes and ages. In some cases, such as when dealing with grazing animals, one may supplement with a partial TMR. For research studies with young stock, TMR feeding minimizes feed sorting, which can improve precision and accuracy of a study. For instance, in a calf starter experiment of mine comparing 3 different protein supplements, weight gains with all 3 diets were similar (Stake et al., 1973). However, 1 protein supplement was less palatable than the other 2, so the calves ate less of that protein supplement but consumed more hay. In the next experiment (Schingoethe et al., 1974), all 3 protein supplements were fed as pelleted complete diets, which allowed us to get a true measure of the feeding value of each of the protein supplements.

SUMMARY

The TMR feeding of dairy cows evolved during the last half of the past 100 yr. It allows one to feed nutritionally balanced diets more accurately because sorting and separation of ingredients is minimized. Feeding TMR allows one to incorporate commodity by-products and specialty—sometimes unpalatable—ingredients into diets. Cows have fewer digestive upsets and fewer problems with milk fat depression and other health problems because they are consuming a nutritionally balanced diet all the time. Feeding TMR allows the feeding of larger groups of cows faster and more economically than feeding forages and concentrates separately, but it comes with some costs. Mixer wagons and feeding management (e.g., monitoring particle size, moisture content of the diet, and order of adding ingredients to the mixer batch) must be considered.

FUTURE DIRECTIONS

Total mixed ration feeding is here to stay, especially as the dairy industry continues to move to larger dairy herds. Larger herds allow the opportunity to further refine diet formulations to meet specific nutritional needs of specific groups of cows. Currently, many dairies may group cows into a few specific production groups, transition cows, and younger cows. With larger herds, it may become economically feasible to fine-tune grouping and ration formulations even further. The increased use of robotic milking systems adds new challenges and opportunities for feeding the herd. Concentrate feeding in the robotic stall somewhat goes against the premise of TMR feeding. However, as milking parlors get more automated with robotic components, TMR feeding in dairies will not be complicated with some concentrate feeding tied to the milking system.

REFERENCES

Bargo, F., L. D. Muller, J. E. Delahoy, and T. W. Cassidy. 2002. Performance of high producing dairy cows with three different feeding systems combining pasture and total mixed rations. J. Dairy Sci. 85:2948–2963.

Bhandari, S. K., K. H. Ominski, K. M. Wittenberg, and J. C. Plaizier. 2007. Effects of chop length of alfalfa and corn silage on milk production and rumen fermentation of dairy cows. J. Dairy Sci. 90:2355–2366.

Birkelo, C. P., M. J. Brouk, and D. J. Schingoethe. 2004. The energy content of wet corn distillers grains for lactating dairy cows. J. Dairy Sci. 87:1815–1819.

Coppock, C. E. 1977. Feeding methods and grouping systems. J. Dairy Sci. 60:1327–1336.

Coppock, C. E., D. L. Bath, and B. Harris Jr.. 1981. From feeding to feeding systems. J. Dairy Sci. 64:1230–1249.

DeFrain, J. M., A. R. Hippen, K. F. Kalscheur, and D. J. Schingoethe. 2006. Feeding lactose to increase ruminal butyrate and the metabolic status of transition dairy cows. J. Dairy Sci. 89:267–276.

DeVries, T. J., K. A. Beauchemin, and M. A. G. von Keyserlingk. 2007. Dietary forage concentration affects the feed sorting behavior of lactating dairy cows. J. Dairy Sci. 90:5572–5579.

DeVries, T. J., F. Dohme, and K. A. Beauchemin. 2008. Repeated ruminal acidosis challenges in lactating dairy cows at high risk and low risk of developing acidosis: Feed sorting. J. Dairy Sci. 91:3958–3967.

DeVries, T. J., and R. M. Gill. 2012. Adding liquid feed to a total mixed ration reduces feed sorting behavior and improves productivity of lactating dairy cows. J. Dairy Sci. 95:2648–2655.

Eastridge, M. L. 2006. Major advances in applied dairy cattle nutrition. J. Dairy Sci. 89:1311–1323.

Grasser, L. A., J. G. Fadel, I. Garnett, and E. J. DePeters. 1995. Quantity and economic importance of nine selected by-products used in California dairy rations. J. Dairy Sci. 78:962–971.

Harshbarger, K. E. 1952. Self-feeding a ground hay and grain ration to dairy cows. J. Dairy Sci. 35:501. (Abstr.)

Hernandez-Urdandeta, A., C. E. Coppock, R. E. McDowell, D. Gianola, and N. E. Smith. 1976. Changes in forage-concentrate ratio of complete feeds for dairy cows. J. Dairy Sci. 59:695–707.

Holter, J. B., W. E. Urban Jr., H. H. Hayes, and H. A. Davis. 1977. Utilization of diet components fed blended or separately to lactating cows. J. Dairy Sci. 60:1288–1293.

Huffman, C. F. 1939. Roughage quality and quantity in the dairy ration, a review. J. Dairy Sci. 22:889–890.

Huzzey, J. M., T. J. DeVries, P. Valois, and M. A. G. von Keyserlingk. 2006. Stocking density and feed barrier design affect the feeding and social behavior of dairy cattle. J. Dairy Sci. 89:126–133.

Keunen, J. E., J. C. Plaizier, L. Kyriazakis, T. F. Duffield, T. M. Widowski, M. I. Lindinger, and B. W. McBride. 2002. Effects of a subacute ruminal acidosis model on the diet selection of dairy cows. J. Dairy Sci. 85:3304–3313.

Kmicikewycz, A. D., and A. J. Heinrichs. 2014. Feeding lactating dairy cattle long hay separate from the total mixed ration can maintain dry matter intake during incidents of low rumen pH. J. Dairy Sci. 97:7175–7184.

Lahr, D. A., D. E. Otterby, D. G. Johnson, J. G. Linn, and R. G. Lundquist. 1983. Effects of moisture content of complete diets on feed intake and milk production by cows. J. Dairy Sci. 66:1891–1900.

Lammers, B. P., D. R. Buckmaster, and A. J. Heinrichs. 1996. A simplified method for the analysis of particle sizes of forage and total mixed rations. J. Dairy Sci. 79:922–928.

Litherland, N. B., D. N. L. da Silva, W. P. Hansen, L. Davis, S. Emanuele, and H. Blalock. 2013. Effects of prepartum controlled-energy wheat straw and grass hay diets supplemented with starch or sugar on periparturient dairy cow performance and lipid metabolism. J. Dairy Sci. 96:3050–3063.

Maulfair, D. D., and A. J. Heinrichs. 2013. Effects of varying forage particle size and fermentable carbohydrates on feed sorting, ruminal fermentation, and milk and component yields of dairy cows. J. Dairy Sci. 96:3085–3097.

McCoy, G. C., H. S. Thurmon, H. H. Olson, and A. Reed. 1966. Complete feed rations for lactating dairy cows. J. Dairy Sci. 49:1058–1063.

Muller, L. D., L. V. Schaffer, L. C. Ham, and M. J. Owens. 1977. Cafeteria style free-choice mineral feeder for lactating dairy cows. J. Dairy Sci. 60:1574–1582.

Mullins, C. R., and B. J. Bradford. 2010. Effects of a molasses-coated cottonseed product on diet digestibility, performance, and milk fatty acid profile of lactating dairy cattle. J. Dairy Sci. 93:3128–3135.

NRC. 2001. Nutrient Requirements for Dairy Cattle. 7th rev. ed. Natl. Acad. Sci., Washington, DC.

Rakes, A. H. 1969. Complete rations for dairy cattle. J. Dairy Sci. 52:870–875.

Schingoethe, D. J., G. L. Beardsley, and L. D. Muller. 1974. Evaluation of commercial rapeseed meal and Bronowski variety rapeseed meal in calf rations. J. Nutr. 104:558–562.

Schingoethe, D. J., K. F. Kalscheur, A. R. Hippen, and A. D. Garcia. 2009. Invited review: The use of distillers products in dairy cattle diets. J. Dairy Sci. 92:5802–5813.

Spahr, S. L. 1977. Optimum rations for group feeding. J. Dairy Sci. 60:1337–1344.

Stake, P. E., M. J. Owens, and D. J. Schingoethe. 1973. Rapeseed, sunflower, and soybean meal supplementation of calf rations. J. Dairy Sci. 56:783–788.

Tozer, P. R., F. Bargo, and L. D. Muller. 2003. Economic analyses of feeding systems combining pasture and total mixed ration. J. Dairy Sci. 86:808–818.

Weimar, M. R., and D. B. Blayney. 1994. Landmarks in the U.S. dairy industry. Agric. Inf. Bull. No. 694. USDA Economic Research Service, Washington, DC.

Weiss, W. P. 2017. Grouping similar cows has its benefits. Hoard's Dairyman 162:192.

USDA ERS (Economic Research Service). 2017. Dairy data. Accessed March 11, 2017. www.ers.usda.gov/data.

USDA National Animal Health Monitoring System. 2014. Dairy Cattle Management Practices in the United States, 2014. USDA, Washington, DC.

APPENDIX

Table A1. Milestones in the TMR feeding of dairy cows

Date	Milestone	Reference
1930	Grain (concentrate) feeding guidelines are first published.	Frazer, cited by Huffman, 1939
1930	The first milking parlor is developed.	
1950s	Bulk tanks rather than cans become the major method for handling milk on the farm.	Weimar and Blayney, 1994
1952	TMR feeding is first reported at American Dairy Science Association meetings.	Harshbarger, 1952
1960s	Increased emphasis is placed on feeding more concentrates.	
Early 1960s	Milking parlors start becoming popular.	
1960s	Development of individual cow concentrate feeding systems begins.	Coppock et al., 1981
1966	First journal article in *Journal of Dairy Science* reporting research with TMR feeding is published.	McCoy et al., 1966
Late 1960s	First mixer wagons are developed.	
1970s	A noticeable move is made toward freestall and large-group housing of dairy herds as herds become larger.	
1990s	Use of commodity by-products as feeds increases.	
1996	Penn State shaker box system is developed for determining sizes of particles in diets.	Lammers et al., 1996
2014	About 90% of large dairy herds use TMR feeding.	USDA National Animal Health Monitoring System, 2014