Metabolizable Energy (ME) in the Lactating Cows: Improving How We Represent Supply and Requirements

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Introduction

Governed by the laws of thermodynamics, the field of bioenergetics seeks to understand how energy is captured, transformed, and then routed to support cell function, growth, lactation, reproduction, and survival (Weiss and Tebbe, 2019). The study of bioenergetics is arguably the most thoroughly documented and most storied pursuits in all of animal nutrition. Biochemists, physiologists, and nutritionists have all joined the journey with each bringing their unique perspective and important contributions. Nutritionists have historically sought to measure and describe the animal's requirements for energy and as well as the feeds which supply it (Blaxter, 1967). Although there are a number of different energy evaluation systems in the world they are unified in the fact that each estimates metabolizable energy (ME) supply by subtracting energy losses from gross energy (GE) (Azarfar et al., 2025).

Metabolizable energy is a pool that represents the energy that is available to the animal for all biological functions and physical activity. In modern dairy cows, over 60% of the ME consumed each day is used to synthesize milk, making the mammary gland the single most energy-demanding organ in her body. From a feeding standpoint, this underscores why even small imbalances in energy supply can rapidly show up in milk production, much before they can be seen in changes in body weight or body condition. In dairy farming productive efficiency can be defined as the yield of milk and milk components yield to the energy expended on maintenance, lactation and of returning the cow to the level of body condition that existed before the onset of lactation (Bauman et al., 1985). For nutritionists seeking to help dairy producers maximize productive efficiency of energy, understanding how ME is estimated, assumptions used, and knowing the key physiological and nutrition factors that influence it can provide valuable insights for making formulation adjustments. This paper will discuss factors that influence the supply and use 1) how the supply of ME is estimated and the factors that affect both ME supply and use, 2) some key assumptions in representing ME that may not always apply and how resulting challenges may be overcome, and 3) potential modifications to improve predictions and formulation practices.

Supply of Energy

Flow of Energy Through the Cow

Figure 1 outlines the flow of energy through the dairy cows. Data in the figure stem from a study aimed to estimate the among-animal variance in energy utilization in lactating Jersey cows (Carroll et al., 2024). The study included data from 15 energy balance experiments in which indirect calorimetry and total fecal and urine collection were used to measure energy intake, digestion, and the partition of energy. In all, 115 Jersey cows were used and they supplied a total of 560 animal-period observations, covering a range of days in milk, milk production, and dietary composition. Figure 2 also illustrates the contributions of among-animal variance observed in this study on key measures related to energy utilization. To generate this figure, statistical analyses were conducted to partition variance among animals, dietary treatments, and experiments, highlighting the role of inherent animal differences in energy metabolism.

Characterization of energy flow begins with gross energy (GE) which is measured by determining the heat produced when a feed is completely oxidized (Pond et al., 1995). Once the total GE consumed is measured, the energy lost in the feces can be quantified and subtracted from the GE consumed and the remaining energy is described as digestibility energy (DE). This is usually the single greatest loss of energy (Carroll study). Urinary and gas energy losses can then be subtracted from DE, giving us a measure of the remaining ME.

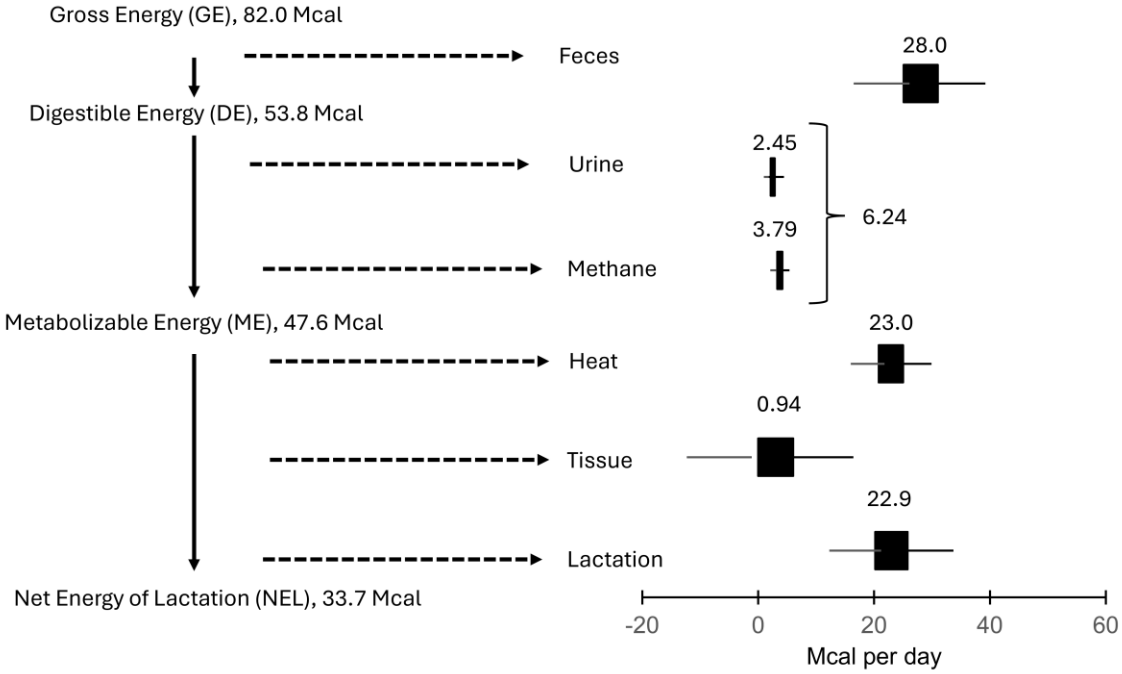

Figure 1. Illustration of energy flow and quantification of energy losses in lactating Jersey cows, values represent median while boxes represent 25th and 75th quartile and whiskers represent minimum and maximum observations (data from Carroll et al., 2024).

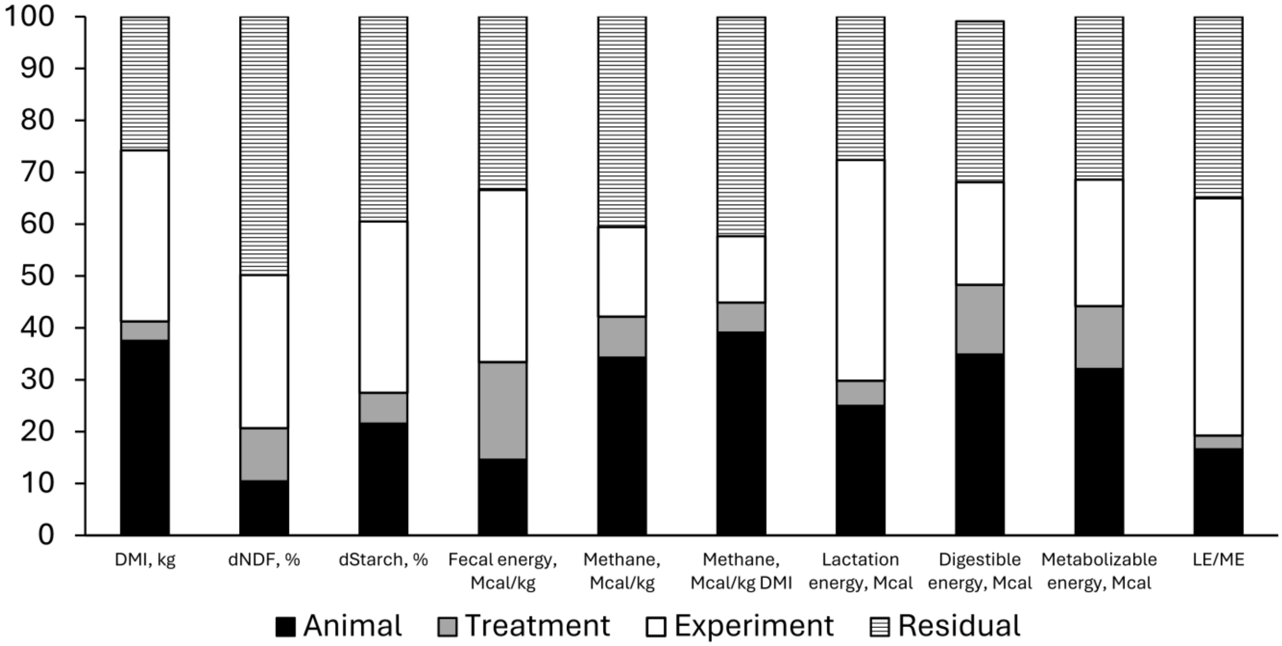

Figure 2. Analysis of sources of variance reported as the proportion (%) of total variation from differences sources. Sources was variation was analyzed for DMI, NDF digestibility (dNDF), starch digestibility (dStarch), fecal energy, methane energy, lactation energy, digestibility energy, metabolizable energy and conversion of metabolizable energy to lactation energy (LE/ME) (data from Carroll et al., 2024).

Nutrient Digestibility and Digestible Energy (DE)

In the study of (Carroll et al., 2024) fecal energy losses represented the single greatest loss of energy (28.0 Mcal/d or 34 % of the total GE intake); this also holds on commercial farms. This lost energy is in the form of nutrients in undigested feed. Of the nutrients reported, NDF not only had the lowest digestibility (46.6 ± 3.1 %) but the greatest variation. With NDF frequently often suppling as much as 20 % of the DE these data underline a long standing challenge and opportunity to increase energy availability by improving fiber digestion (Van Soest, 1994). Many of our nutrition models such as NASEM (2021), assume that digested NDF contains 4.2 Mcal/kg but this assumption may not always stand. In fact Stypinski et al. (2023) directly measured the energy content of NDF in a small number of feeds and observed it to be 4.0 Mcal/kg. In a follow-up, whole-animal energy balance study by Stypinski et al. (2024) NDF was observed to contain slightly more energy (4.1 Mcal/kg) but still less than assumed by NASEM (2021). Thus, when comparing NASEM (2021) predictions to live animal observations, it was not surprising that NASEM (2021) overpredicted both GE and DE. Although these studies observed the energy of content to be less than assumed by NASEM, in reality some variation even greater than what is assumed is also likely. One example is a feed containing a high concentration of lignin, a component that contains 6.0 Mcal/kg of energy (Voitkevich et al., 2012). Thus, in cases in which feeds contain a high concentration of lignified fiber, the energy measured may be greater than what is actually available to the animal. Overall, future nutrition models should consider representing energy on an ash, lignin-free, possibly even CP-free basis.

In the United States, starch commonly supplies more the 35% of the total DE intake of dairy cattle. Compared to NDF, starch possesses much higher digestibility and also has a lower variation in digestibility. Starch digestibility is affected by factors like grain type (e.g., barley vs. corn) and processing methods (e.g., dry-rolled vs. high-moisture corn). Average starch digestibility often ranges from as low as 77% to over 96%, and when formulating a diet, incorporating feed-specific starch digestibility coefficients can improve DE estimation accuracy. Although sugar is considered in the NASEM model it is accounted for in the in the residual organic matter (ROM). Representing sugars, organic acids, glycerol, and soluble fiber, this fraction is assumed to have an enthalpy of 4.0 Mcal/kg which is less than starch (4.2 Mcal/kg). In some diets sugar can provide a large amount of energy but on a per gram basis, starch supplies more than sugar (Azarfar et al., 2025). Directly speaking, the longer chains of glycosidic bonds found in starch result in a higher concentration of energy than sugar. In practice the energy contributed by these sources also depends on how they affect the nature of ruminal fermentation and the overall diet composition (Heldt et al., 1999). For example, starch also favors the production of the more propionate, a key gluconeogenic precursor, while sugars tend to favor butyrate production in the rumen (Oba and Kammes-Main, 2023; Piantoni and VandeHaar, 2023). Overall, the efficiency of energy capture is generally greater when feeding starch. In NASEM (2021) sugar containing ROM is assigned a constant digestibility of 96%, but its enthalpy is estimated at 4.0 Mcal/kg, which is lower than the assumed enthalpy of starch (4.2 Mcal/kg). This adjustment accounts for the nutritional differences between starch and ROM.

Urine and Gas Energy

Metabolizable energy is estimatedby subtracting model predictions of energy losses in urine and methane from DE. Carroll et al. (2024) reported that together, these sources of energy losses represented 6.24 Mcal/d (7.6% of the total GE intake). Energy losses from urine averaged 2.45 Mcal/d (2.99 % of the total GE intake).The equation used by NASEM to predict urinary energy losses was adopted from Morris et al. (2021b) in which urinary nitrogen was used to predict urinary energy. This approach was deemed as an accurate way to predict ME losses, especially when dietary protein varies. Moe et al. (1972) noted that when assessing energy utilization of diets, the supply of protein is also considered. This is because when protein is fed in excess, energy is required to process and excrete N to support metabolic transformations, synthesis of urea, and excretion by the kidneys (Reed et al., 2017). However, relative to popular belief energy needed to excrete N is small, approximately 14.6 kcal/g of N (Morris et al., 2021b).

According to Carroll et al. (2024), energy losses from methane averaged 3.79 Mcal/d (4.62 % of the total GE intake). Interestingly, the among animal variation in methane production is large (Figure 2), and even increased when methane is expressed per unit of DMI. When estimating gas energy losses to derive ME, the current NASEM

(2021) only accounts for methane. This is generally appropriate because other energy containing gasses such as hydrogen production are normally found only in trace amounts. However, this is not the case when some additives are used to reduce enteric methane production. For example, 3-Nitrooxypropanol has been shown to reduce enteric methane production but also result in a small increase hydrogen gas production (Lopes et al., 2016). Energetically, although gaseous energy losses are reduced when methane production is reduced, increases in hydrogen gas represents small but measurable losses of energy. For example, in a study designed to test the effect of a bromoform-containing feed additive, methane energy losses were reduced from 4.06 to 3.26 Mcal/d but hydrogen gas losses increased from 0.0 to 0.17 Mcal/d (Sherwood et al., 2025). When taken together, feeding the additive resulted in a net reduction of gaseous energy losses and this reduction was observed to have a positive effect on ME supply and also the efficiency of converting DE to ME. Consequently, when trying to reduce gas energy losses by feeding supplements that reduce methane, future nutrition models should probably consider accounting losses in hydrogen when predicting ME.

Utilization of Metabolizable Energy for Maintenance and Milk

The energy left after the losses of fecal, urinary, and gas energy, called ME is either lost as heat or incorporated into “products” which in the case of the dairy cow, is milk, conceptus, and body tissues (Reynolds, 2000). In the NASEM (2021), efficiency of how ME is converted into these products is denoted by k with different subscripts. Those discussed here include the conversion of ME into NE for maintenance (k_m =0.66) and lactation (k_L= 0.66) (Moraes et al., 2015; NASEM, 2021). For information related to the conversion of ME into NE for lactating cow tissue gain (k_g = 0.75), and milk production from tissue energy loss (k_T = 0.89) readers are referred to NASEM (2021).

Use of metabolizable energy for maintenance

Metabolizable energy for maintenance (MEmaint) represents is the energy required to support 1) nutrient digestion and absorption and 2) internal work for existence. This is equal to the heat produced when an animal is fed in the state of maintenance (Moe et al., 1972; Carroll and Kononoff, 2024). Net energy maintenance (NEmaint) refers to energy only needed to support internal work for existence and is equal to the heat produced while an animal is in a fasted state. The efficiency of converting MEmaint to NEmaint, denoted as k_m and in NASEM (2021) assumed to be the same and k_L (0.66), and NELmaint is assumed to be 0.1 Mcal × kg body weight$^{0.75}$. This was increased from 0.08 Mcal × kg body weight$^{0.75}$ in the NRC (2001) report. Recent evidence supports the change in NEmaint (Morris and Kononoff, 2021; Carroll and Kononoff, 2024) and these studied also serve as evidence that the current requirements are equally applicable to Jersey’s. However, it is also thought that NELmaint in cows may vary as much as 8 – 10 % (NRC, 1989).

Use of metabolizable energy for milk synthesis

In NASEM (2021) the efficiency of use of ME for milk production is denoted as k_L. and assumed to be 0.66. In a respective analysis of data collected at Beltsville, (Moraes et al., 2015) reported that efficiency of converting ME into NE for milk synthesis (k_L) has increased over time (0.60, 0.62, and 0.69 in 1963 to 1973, 1974 to 1983, and 1984 to 1995). While the observed increase were most likely and largely driven by genetic improvement, these authors also noted that k_L was also positively correlated to milk yield and dietary fat. The positive association with dietary fat has long been known (Andrew et al., 1991) but not accounted for in the current NASEM (2001) model. In the evaluation of modern Jersey cows (Carroll et al., 2024) observed k_L to be substantially higher (0.73). In addition to the reasons listed above, the higher k_L could also be higher because the Jersey cows were producing a higher concentration of milk fat (5.49%) and the synthesis of this milk component requires less energy than milk protein (Morris et al., 2021a). Moe et al. (1972) reported that k_L varied among animals by as much as 9 %, while more recently Carroll et al. (2024) also observed that k_L varied substantially among animals. It should be noted that mathematically when NEmaint is increased, k_L will also increase because these coefficients are inherently positively correlated (Moe, 1981). In a recent study evaluation residual feed innate (RFI), k_L was observed to increase from 0.601 to 0.69 in low and high feed efficient cows. Overall, there does appear to be substantial evidence to increase k_L even more than 0.66 in our models to better represent contemporary animals. Alternately, nutrition models could be modified to compute variable efficiencies which could be based upon animal and/or feed-based factors known to affect k_L.

Final Thoughts

Future advances in the energy systems should attempt to shed further light on how the variation in nutrient enthalpies affects estimates of predicted and observed outputs in digestible energy. This is particularly important when feeding heterogenous chemical components such as NDF which support a large portion of DE and ME supply. Likewise, recent interest and attention related to cattle feeding and the environment has spurred application of methods to reduce gaseous losses, and these effects may have direct implications on energy utilization of dairy cattle. Thus, factors such as differences in the conversion or DE to ME or increases in hydrogen gas production should be integrated into future energy systems. Finally nutrients may be used with variable efficiencies to support lactation. Although nutrients such as fat appear to enhance the efficiency of k_L the notion has not been directly integrated into models, and other nutrients remain relatively unexplored.

Summary

- Milk production drives ME demand. In modern dairy cows, over 60% of daily ME intake goes directly toward milk synthesis. Small imbalances in ME supply can rapidly impact milk yield before changes in body weight or condition become apparent.

- Fiber digestibility is critical. NDF has the lowest digestibility and usually has the greatest variation among nutrients. Improving fiber digestibility offers one of the largest opportunities to enhance digestible energy (DE) and overall ME supply on-farm.

- Starch vs. sugar energy contribution. Starch provides more energy per gram (4.2 Mcal/kg) than sugar (4.0 Mcal/kg) and tends to favor propionate production in the rumen, improving efficiency of energy capture. Diet formulation should account for grain source, processing, and starch digestibility coefficients to improve accuracy.

- Methane mitigation can enhance ME supply. Enteric methane typically accounts for ~4.6% of gross energy losses. Feed additives that reduce methane losses may also slightly increase the efficiency of converting DE into ME but future models should also account for associated hydrogen production.

- Reconsidering efficiency coefficients. Current NASEM (2021) models assume kL = 0.66 (efficiency of converting ME to milk energy), but recent studies in modern genetics and diets suggest in some cases this may be closer to 0.73. Incorporating variable efficiencies based on animal factors, genetics, and diet composition could improve diet formulation accuracy and milk production predictions.

References

Andrew, S.M., H.F. Tyrrell, C.K. Reynolds, and R.A. Erdman. 1991. Net energy for lactation of calcium salts of long-chain fatty acids for cows fed silage-based diets. Journal of Dairy Science 74:2588–2600. https://doi.org/10.3168/jds.S0022-0302(91)78437-3.

Azarfar, A., H. van Laar, P.J. Kononoff, J. Dijkstra, D.L. Morris, S. van Gastelen, A.L. Carroll, A. Bannink, W.F. Pellikaan, and J.W. Spek. 2025. Estimation of dietary metabolizable energy content in dairy cattle using the measured dietary content of digestible nutrients: A meta-analysis. Journal of Dairy Science 0. https://doi.org/10.3168/jds.2025-26796.

Bauman, D.E., S.N. McCutcheon, W.D. Steinhour, P.J. Eppard, and S.J. Sechen. 1985. Sources of Variation and Prospects for Improvement of Productive Efficiency in the Dairy Cow: A Review. Journal of Animal Science 60:583–592. https://doi.org/10.2527/jas1985.602583x.

Blaxter, K.L. 1967. The Energy Metabolism of Ruminants. Hutchinson, London.

Carroll, A.L., and P.J. Kononoff. 2024. Derivation of the maintenance energy requirements in Jersey cows differing in body condition score. Journal of Dairy Science 107:8034–8043. https://doi.org/10.3168/jds.2024-24940.

Carroll, A.L., M.L. Spangler, D.L. Morris, and P.J. Kononoff. 2024. Partitioning among-animal variance of energy utilization in lactating Jersey cows. Journal of Dairy Science 107:7734–7743. https://doi.org/10.3168/jds.2024-24740.

Heldt, J.S., R.C. Cochran, G.L. Stokka, C.G. Farmer, C.P. Mathis, E.C. Titgemeyer, and T.G. Nagaraja. 1999. Effects of different supplemental sugars and starch fed in combination with degradable intake protein on low-quality forage use by beef steers. Journal of Animal Science 77:2793. https://doi.org/10.2527/1999.77102793x.

Lopes, J.C., L.F. de Matos, M.T. Harper, F. Giallongo, J. Oh, D. Gruen, S. Ono, M. Kindermann, S. Duval, and A.N. Hristov. 2016. Effect of 3-nitrooxypropanol on methane and hydrogen emissions, methane isotopic signature, and ruminal fermentation in dairy cows. Journal of Dairy Science 99:5335–5344. https://doi.org/10.3168/jds.2015-10832.

Moe, P.W., W.P. Flatt, and H.F. Tyrell. 1972. Net energy value of feeds for lactation. Journal of Dairy Science 55:945–958. https://doi.org/10.3168/jds.S0022-0302(72)85601-7.

Moraes, L.E., E. Kebreab, A.B. Strathe, J. Dijkstra, J. France, D.P. Casper, and J.G. Fadel. 2015. Multivariate and univariate analysis of energy balance data from lactating dairy cows. Journal of Dairy Science 98:4012–4029. https://doi.org/10.3168/jds.2014-8995.

Morris, D.L., T.M. Brown-Brandl, P.S. Miller, W.P. Weiss, R.R. White, and P.J. Kononoff. 2021a. Factors that affect heat production in lactating Jersey cows. Journal of Dairy Science 104:346–356. https://doi.org/10.3168/jds.2020-18976.

Morris, D.L., J.L. Firkins, C. Lee, W.P. Weiss, and P.J. Kononoff. 2021b. Relationship between urinary energy and urinary nitrogen or carbon excretion in lactating Jersey cows. Journal of Dairy Science S0022030221004367. https://doi.org/10.3168/jds.2020-19684.

Morris, D.L., and P.J. Kononoff. 2021. Derivation of the maintenance energy requirements and efficiency of metabolizable energy utilization for dry and lactating Jersey cows. Journal of Dairy Science 104:9726–9734. https://doi.org/10.3168/jds.2020-20056.

NASEM. 2015. Nutrient Requirements of Beef Cattle, 8th Revised Edition. National Academies Press, Washington, D.C.

Oba, M., and K. Kammes-Main. 2023. Symposium review: Effects of carbohydrate digestion on feed intake and fuel supply. Journal of Dairy Science 106:2153–2160. https://doi.org/10.3168/jds.2022-22420.

Piantoni, P., and M.J. VandeHaar. 2023. Symposium review: The impact of absorbed nutrients on energy partitioning throughout lactation. Journal of Dairy Science 106:2167–2180. https://doi.org/10.3168/jds.2022-22500.

Pond, W.G., D.C. Church, and K.R. Pond. 1995. Basic Animal Nutrition and Feeding. 4th ed. Wiley, New York.

Reed, K.F., H.C. Bonfá, J. Dijkstra, D.P. Casper, and E. Kebreab. 2017. Estimating the energetic cost of feeding excess dietary nitrogen to dairy cows. Journal of Dairy Science 100:7116–7126. https://doi.org/10.3168/jds.2017-12584.

Reynolds, C.K. 2000. Measurement of energy metabolism. Page 22 in Feeding Systems and Feed Evaluation Models. M.K. Theodorou and J. France, ed. 978-0-85199-346-1.

Sherwood, S.C., A.L. Carroll, K.K. Buse, and P.J. Kononoff. 2025. Methane production and whole-animal energy utilization in lactating Jersey dairy cows fed a bromoform-containing feed additive. Journal of Dairy Science 108:5832–5846. https://doi.org/10.3168/jds.2024-26032.

Stypinski, J.D., P.J. Kononoff, and W.P. Weiss. 2023. Evaluation of gross energy concentration of neutral detergent fiber contained in feed and fecal samples. JDS Communications 4:251–254. https://doi.org/10.3168/jdsc.2022-0345.

Stypinski, J.D., W.P. Weiss, A.L. Carroll, and P.J. Kononoff. 2024. Effect of acid detergent lignin concentration for diets formulated to be similar in neutral detergent fiber content on energy utilization in lactating Jersey cows. Journal of Dairy Science 107:5699–5708. https://doi.org/10.3168/jds.2023-24318.

Van Soest, P.J. 1994. Nutritional Ecology of the Ruminant. 2nd ed. Comstock Pub, Ithaca.

Voitkevich, O.V., G.J. Kabo, A.V. Blokhin, Y.U. Paulechka, and M.V. Shishonok. 2012. Thermodynamic properties of plant biomass components. heat capacity, combustion energy, and gasification equilibria of lignin. J. Chem. Eng. Data 57:1903–1909. https://doi.org/10.1021/je2012814.

Weiss, W.P., and A.W. Tebbe. 2019. Estimating digestible energy values of feeds and diets and integrating those values into net energy systems. Translational Animal Science 3:953–961. https://doi.org/10.1093/tas/txy119.