ENHANCING NET FOOD PRODUCTION BY USING LEFTOVER FEEDS FOR HIGH-PRODUCING DAIRY COWS

By

Morgan N. Mills

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

Animal Science - Master of Science

2024

ABSTRACT

Dairy cattle can convert human-inedible by-products, or leftovers, into food for humans. When cows are fed diets high in by-products, they can more than double the amount of food available for humans. Our goal was to evaluate the effects of feeding a diet of 70% by-products on milk production and net food production. Multiparous Holstein cows (n=31; 90 ± 23 DIM, 51 ± 8 kg milk/d, 730 ± 60 kg BW) were used in a crossover design of 2 diets. Diets were composed of 20% by-products (CON) or 70% by-products (BYP). BYP diet consisted of 25% corn silage, 18% corn gluten feed, 15% bakery waste, 10% whole cottonseed, 10% wet beet pulp, 8% wheat straw, and 13% supplements (DM basis). CON contained 36% corn silage, 13% haylage, and 25% corn grain. Data were analyzed using PROC GLIMMIX of SAS 9.4 with treatment, treatment sequence, and period as fixed effects and cow as random. Cows fed BYP consumed less DM (30.1 vs 30.9 kg/d, $P < 0.01$) and produced less milk (46.9 vs 49.1 kg/d, $P < 0.01$) with more fat (3.68 vs 3.55%, $P < 0.01$), less protein (3.07 vs 3.09%, $P = 0.01$), and less lactose (4.91 vs 4.95%, $P < 0.01$) than cows fed CON. Energy-corrected milk was decreased 3% ($P < 0.01$; 47.5 for BYP and 48.9 kg/d for CON). Cows fed BYP were considerably more efficient in converting human-edible feed energy into milk energy using Atwater energy values (171 vs 54%, $P < 0.01$). Cows fed BYP were also more efficient in converting human-edible feed protein into milk protein (202 vs 72%, $P < 0.01$). Adding more by-products in dairy cattle diets presents tradeoffs for sustainability with decreased production levels but increased net food production.

ACKNOWLEDGEMENTS

I would like to start off by thanking Dr. Michael VandeHaar for giving me the opportunity to study at Michigan State University. His continued advisement has been greatly appreciated and he has shaped me into the independent scientist that I am today. I would also like to thank my committee members Dr. Bradford, Dr. Rowntree, and Dr. White for supporting my research and education.

I am incredibly thankful to have had such a wonderful lab mate and close friend during my time in East Lansing. Sarah Naughton has been an integral part of everything that I have done here, and I would not have been able to successfully complete my program without her consistent support.

The undergraduate students that helped on my project were amazing and dependable, and I am extremely grateful for their help with collecting samples at the farm. They made those 5 am shifts more enjoyable. I would also like to extend my deepest gratitude to the farm staff at the MSU dairy for all their hard work not only with my project, but also with the countless other projects that they help to facilitate. Their expertise and guidance were integral to my time at the dairy farm.

I would also like to thank the amazing community at MSU, especially the dairy nutrition group in 2280. They never hesitated to help with any questions that I had, and I will always be thankful for their support. To my roommate Renee, thank you for all the late night ice cream runs that saved my mental health. A special thank you to Dr. Lock, who was not my advisor or on my committee, but who offered continuing moral support after an especially difficult event took place. I will never forget his compassion during a very sensitive time.

Finally, I would like to thank my family for supporting me after I made the difficult decision to leave Florida to continue my education. Thank you for always answering my phone calls and listening to me talk about cows. Also, to Mitchell, who I met in the middle of my project and since then has offered unending encouragement. All of your support means the world to me.

TABLE OF CONTENTS

LIST OF ABBREVIATIONS vi

CHAPTER 1: INTRODUCTION 1

CHAPTER 2: LITERATURE REVIEW 4
- Overview of Sustainability 4
- Current Efforts in Sustainable Agriculture 4
- Relevant By-product Feeds 6
- Ruminal Digestion 11
- Public Perceptions of the Dairy Industry 15
- Importance of Animal Agriculture 16
- Current Research on By-products and Net Food Production 18
- Conclusions 19

CHAPTER 3: MATERIALS AND METHODS 20
- Design and Treatments 20
- Data Collection and Analysis 21
- Statistical Analysis 24

CHAPTER 4: RESULTS 25
- Production 25
- Net Food Production 25
- Milk Fatty Acid Content 26
- Tables 27

CHAPTER 5: DISCUSSION 33
- Tables 40

CHAPTER 6: OVERALL CONCLUSIONS 42

REFERENCES 44

APPENDIX: DIGESTIBILITY 55

LIST OF ABBREVIATIONS

AA = Amino acid

AE = Atwater energy

BCS = Body condition score

BW = Body weight

BYP = By-product treatment

CLA = Conjugated linoleic acid

CON = Control treatment

DCGF = Dried corn gluten feed

DHA = Docosahexaenoic acid

DIM = Days in milk

DMI = Dry matter intake

DM = Dry matter

EAA = Essential amino acid

ECM = Energy-corrected milk

EPA = Eicosapentaenoic acid

FA = Fatty acid

FCM = Fat-corrected milk

GWP = Global warming potential

HE = Human-edible

HEAE = Human-edible Atwater energy

LSM = Least square means

MCP = Microbial crude protein

ME = Metabolizable energy

N = Nitrogen

NASEM = National Academies of Science, Engineering, and Medicine

NDF = Neutral detergent fiber

NEFA = non-esterified fatty acid

NRC = National Research Council

peNDF = Physically effective neutral detergent fiber

PLF = Precision livestock farming

RDP = Rumen degraded protein

RUP = Rumen undegraded protein

SCC = Somatic cell count

SEM = Standard error of the mean

TMR = Total mixed ration

VFA = Volatile fatty acid

WCGF = Wet corn gluten feed

CHAPTER 1: INTRODUCTION

The strategy of feeding by-products to livestock is not a new concept and dates back to the early 1800s as a method to dispose of waste (Coffey et al., 2016). Since then, by-products have been popularized as they are useful feeds to improve the nutritional quality of livestock diets. As the global population continues to grow and more land is needed for expansion of urban development, by-product feeds may prove to be of even more value to livestock nutritionists. With this approach, the same acre of land can produce food for humans and food for livestock, reducing competition and contributing to a sustainable animal agriculture industry.

Peters et al. (2016) evaluated ten distinct diet scenarios to determine which diet would have the highest carrying capacity in the United States. Carrying capacity is the amount of people that can be fed from an agricultural land base. A lacto-vegetarian diet consisting of plant-based foods and dairy was shown to be able to feed the most people with the available land at 807 million people and 260% of the total US population. In comparison, the carrying capacity for a traditional baseline diet mimicking the current eating habits of the United States reached 402 million people, or 130% of the country's population. Data such as this exemplifies the role of dairy cattle in a food system that can sustain a continually growing population.

The rumen of dairy cattle allows for efficient digestion of fibrous by-products, making these animals the perfect target for increasing levels of by-products in their diets. Many studies have evaluated the addition of higher levels of by-products in dairy cattle diets with varying results on production. Most studies with lower producing cows reported no differences in milk yields when cows were fed high by-product diets (Ertl et al., 2015; Ertl et al., 2016; Karlsson et al., 2018; Naderi et al., 2022), but some reported decreased milk yields (Erfani et al., 2023; Takiya et al., 2019). Fat concentrations increased in some, but not all, of the studies with varying results on protein and lactose concentrations as well (Ertl et al., 2015; Ertl et al., 2016; Karlsson et al., 2018; Naderi et al., 2022; Erfani et al., 2023). However, despite these differences in effects on milk production, all studies found that by utilizing high by-product diets, dairy cattle can improve net food production and produce more food for humans than the amount of human-edible food they consume (Ertl et al., 2015; Ertl et al., 2016; Karlsson et al., 2018; Naderi et al., 2022; Erfani et al., 2023).

Takiya and colleagues (2019) fed late lactation dairy cows a diet composed of 95% by-products, the highest amount that I have found reported in current literature. They observed a notable decrease of 3.6 kg/d in milk production and decreases in all milk components (Takiya et al., 2019). However, they also showed large increases in net food production (Takiya et al., 2019). Our goal was to do the same for high-producing cows in peak lactation. We hypothesized that a diet of approximately 70% by-products would be the most effective level of inclusion where we would observe no impact on milk production but a substantial improvement in net food production in peak lactation dairy cows.

Table 1.1. Comparison of Previous By-product Research Designs.

Study	Number of Cows	Breed	Parity	Stage of Lactation	Milk Production Level	By-products Used & Percent of Diet	Study Design	Days on Trial
Ertl et al., 2015	18	Holstein	Mutliparous (n = 13) and primiparous (n = 5)	108 ± 90 DIM	27.5 ± 5.1 kg/d	Corn middlings, beet pulp, rapeseed cake, soy cake, molasses (50% of diet)	Crossover	14 weeks
Ertl et al., 2016	20	Holstein	Mutliparous (n = 13) and primiparous (n = 7)	117 ± 113 DIM	26.2 ± 6.0 kg/d	Wheat bran and beet pulp (25% of diet)	Crossover	14 weeks
Karlsson et al., 2018	24	Swedish Holstein (n = 8) and Swedish Red (n = 16)	Mutliparous (n = 12) and primiparous (n = 12)	85 ± 13 DIM	38.6 ± 8.5 kg/d	Beet pulp, rapeseed meal, dried distiller's grain, wheat bran (45%,)	Crossover	12 weeks
Takiya et al., 2019	12	Holstein	Multiparous (n = 6) and primiparous (n = 6)	154 ± 20 DIM	42.6 ± 5.4 kg/d	Corn gluten feed, wheat straw, wheat middlings, hominy feed, molasses, porcine blood meal, post-extraction algae residue (95% of diet)	Crossover	40 days
Naderi et al., 2022	12	Holstein	Multiparous	112 ± 8 DIM	48 ± 2.3 kg/d	Corn gluten meal, cotton seed, corn bran, corn germ meal, corn grain screens, rice bran, barley malt sprouts, blood meal (26%, 65%, and 95% of diet)	3x3 Latin square	12 weeks
Erfani et al., 2024	12	Holstein	Multiparous	116 ± 12 DIM	42.7 ± 5.1 kg/d	Diet 1: rice bran, corn germ meal, wheat bran, barley sprout, broken corn (51% of diet) Diet 2: beet pulp, dried citrus pulp, canola meal, molasses (51% of diet)	3x3 Latin square	12 weeks
Current Study	31	Holstein	Multiparous	90 ± 23 DIM	50.1 ± 8.5 kg/d	Wheat straw, bakery waste, wet beet pulp, corn gluten feed, whole cottonseeds (~70% of diet)	Crossover	8 weeks

CHAPTER 2: LITERATURE REVIEW

Overview of Sustainability

Sustainability can be defined as the ability to provide for the present community while preserving resources for future generations. Although the term is commonly used to refer to environmental protection, in the context of policy, it can also refer to economic and social development as well (Kuhlman et al., 2010). The idea of sustainability dates back to the early 1700s when Hans Carl von Carlowitz, a German forestry scientist, suggested using sustainable forest management (Wilderer, P., 2007). Popularity of sustainability has grown exponentially since the 1970s and has even been the foundation for many governmental policies (Caradonna, J., 2022). In relation to animal agriculture, it must be noted that there are some additional considerations. A sustainable livestock production system mandates profitable production with the curtailment of negative environmental and social impacts, all while optimizing animal health and welfare (Wathes et al., 2008; FAO, 2024). Research and attention have been focused on sustainable farming systems now more than ever before.

Current Efforts in Sustainable Agriculture

Precision Livestock Farming

The intensification and industrialization of farming has presented both social and environmental concerns. In agricultural systems this is due to the widespread application of fertilizers and pesticides, which contribute to the growth of toxic algal blooms in bodies of water (EPA, 2024). In livestock production systems, these concerns are related to greenhouse gas emissions and management of manure (Tullo et al., 2019; Lovarelli et al., 2020). Precision livestock farming (PLF) has been presented as an on-farm technique to improve sustainability efforts. PLF focuses on the utilization of technology to manage animals on farm; including all aspects of health and early warning of illnesses, feed/nutrient utilization, and welfare concerns (Lovarelli et al., 2020; Berckmans, 2017). These early notifications aid in a manager's decision making and influence the efficiency of the farm. Improved efficiency means fewer animals using fewer resources and results in reductions in environmental impacts (Rotz, 2020).

Genetic Potential

Milk production per dairy cow in the United States has increased exponentially in the last 100 years due to selective breeding (VandeHaar and St-Pierre, 2006). The average dairy cow in the United States produces approximately 11,000 kg of milk, or 2,820 gallons of milk, per year (USDA NASS, 2023). Although this growth in productivity has increased the amount of milk available for human consumption, it has also had some detrimental and unforeseen effects on dairy cattle. With selection of high-producing dairy cattle, fertility has decreased (Albarrón-Portillo and Pollot, 2013; Berry et al., 2015; Oltenacu and Broom, 2023). Additionally, even with the drop in DMI that is associated with early lactation, cows are consuming more feed to meet the energy requirements associated with producing higher quantities of milk (Gross, 2023). A sustainable solution to this issue is to select for animals based on a new trait, "Feed Saved". This trait is defined as actual vs. predicted intake and aims to reduce the amount of feed that cows consume, with no impacts on production performance (VandeHaar et al., 2016). This trait is imperative to sustainability efforts because of its impact on the amount of feed that is saved by reducing DMI, while cows are still producing high quantities of milk.

Feeding By-products

Some of the earliest instances of feeding by-products to animals were recorded in the early 1800s, when leftover grain products in mills were thought to have little nutritional value to humans (Coffey et al., 2016). As such, by-products are defined as the "secondary products produced in addition to the principal product" and typically have little use to humans (AAFCO, 2016). Almost all livestock species consume some by-products in modern animal agriculture, including, but not limited to: tallow, bakery waste, wheat middlings, corn gluten feed, almond hulls, brewer's grain, beet pulp, soybean meal, and more. In fact, even companion animals like cats and dogs eat animal by-products in kibble (Case et al., 2011). By-products have some advantages to being fed on farm, most notably due to being cost-effective sources of protein and energy while also potentially improving palatability (Van Soest, 1994). The biggest environmental benefit of feeding by-products is the ability to reduce waste from various agricultural industries (Bampidis & Robinson, 2006). If by-products were simply to be thrown away, they would inevitably end up in landfills. Already, approximately 30-40% of the food supply in the United States and 20% of the international food supply is wasted (USDA, n.d.; UN, 2023). Decomposition of food waste in landfills releases large quantities of methane, which has a global warming potential (GWP) that is 28x stronger than carbon dioxide (EPA, 2023). Currently, food waste contributes to 58% of methane emissions from landfills and would increase if by-products were thrown away instead of fed to livestock around the world (EPA, 2024).

Relevant By-product Feeds

Soybean Meal

Soybean meal is the leftover product after oil is extracted from the bean. Soybean oil is widely used in commercial vegetable oils used in households and is the most widely consumed oil in the world. There are different methods for oil extraction, which result in soybean meal of different nutrient compositions (Karr-Lilienthal et al., 2006). Extrusion is the process of mechanically pressing or crushing soybeans through a small opening to isolate the oil, and results in a soybean meal that is higher in fat content (Giallongo et al., 2015; AAFCO, 2016). Expeller soybean meal is produced after removing the oil from grinding the beans and then pressing the soybeans to expel the oil (NRC, 2021). The third variation, solvent-extracted soybean meal is the leftover after grinding soybeans and the application of hexane to remove the oil (Eastridge, 2007). Soybean meal is one of the most prevalent co-product feeds on dairy farms as it provides a critical source of protein but could also potentially be eaten by humans as tofu or other soy products. In our study, we considered soybean meal to be human-edible.

Cottonseeds

In the process of harvesting cotton for use in clothing manufacturing, cottonseeds are left over. When feeding livestock, cottonseeds can be fed whole, as a meal, or pelleted. The most impressive property of cottonseed as a feed is that it has a high protein and fat content, but also contains a high enough fiber content that makes it similar to forage effectiveness in the rumen (Arielli, 1998; Broderick et al., 2013). Feeding cottonseeds increases both milk fat content and FCM without altering milk yield (Depeters et al., 1985; Clark and Armentano, 1993). There is an associated depression in milk protein when feeding cottonseeds, which could be due to utilization of lysine (Coppock et al., 1986). The bioavailability of lysine may be low when feeding cottonseeds because of the gossypol content, which binds to the epsilon group of the amino acid (Blauwiekel et al., 1997). Gossypol is a compound produced by the plant as a natural defense against pests and although rare, has the potential to be toxic to ruminants (Blauwiekel et al., 1997). Because of the gossypol content, cottonseeds are not edible by humans.

Bakery Waste

Bakery waste comes from a variety of sources, including unsold bakery products from supermarkets or damaged goods from food production factories. Due to the diverse products that can make up bakery waste, the nutrient composition can be highly variable between different producers of the feed (Waldroup et al., 1982; Slominski et al., 2004). However, bakery waste has a high concentration of energy and therefore can be used as a partial replacement of cereal grains in livestock diets (Humer et al., 2018). The substitution of bakery waste for grains at 15% and 30% of diet DM in dairy cattle diets resulted in linear increases of milk and ECM yields (Kaltenegger et al., 2020). At the same substitution rates, milk fatty acid composition was also affected with increases in oleic and conjugated linoleic acid (CLA) content (Khiaosa-ard et al., 2022). CLAs have relevance to human nutrition, with antiobesity, antidiabetic, antihypertensive, and anticarcinogenic properties (Koba and Yanagita, 2014). Bakery waste could probably be eaten by humans but given that it was refused from the human food supply once, it would only be considered human-edible if we had nothing else to eat.

Wheat Straw

Dietary forage is an important component of dairy cattle diets because it contributes essential physically effective NDF (peNDF). peNDF is responsible for stimulating rumination by contributing to the formation of the rumen mat, which is essential for promoting fiber digestibility (Yang and Beauchemin, 2006; Zebeli et al., 2012). Wheat straw is a source of peNDF and is the by-product of harvesting wheat for flour production. Particle size of wheat straw is important both for maintaining the formation of the rumen mat and to discourage cows from sorting, as they tend to favor shorter particles (Leonardi and Armentano, 2003). When comparing long straw and short straw treatment diets, cows fed short straw tended to produce more milk, suggesting that cows that sort against longer straw pieces consumed inadequate peNDF, which in turn could have impeded milk production (Coon et al., 2018). Strategies to improve fiber digestion of wheat straw include pre-treating it with alkali. However, research has shown that there is no difference in milk production with pre-treated wheat at up to 30% of diet DM; at 40% diet DM, there was a significant drop in intake and milk production (Haddad et al., 1998). Wheat straw has almost no available nutrients for humans and is considered human-inedible.

Beet Pulp

Beet pulp is a source of nonforage fiber and is leftover after extracting sucrose from sugar beets to make table sugar. The pulp can be fed either wet or dried, though it is more typical to feed in its dried and pelleted form as it can be difficult to store the wet product on farm. Beet pulp is approximately 40% NDF, but it is unique because it has a high concentration of soluble fiber in the form of pectic substances (Voelker et al., 2003a). In some studies, DMI decreases with increasing beet pulp concentration of diets; however, this result has varied between different studies (Swain and Armentano, 1994; Clark and Armentano, 1997; Voelker et al., 2003a). No changes in milk yields were observed with substituting high-moisture corn for beet pulp; however, there was a quadratic effect observed for both FCM and fat content with the highest values at 6% beet pulp inclusion (Voelker et al., 2003a). With further processing, perhaps beet pulp might have some value as food for humans, but it is mostly fiber and is considered human-inedible.

Soyhulls

Early in the oil extraction process of soybeans, the hulls are removed. They are about 8% of the DM of the beans and used to be ground into soybean meal as a way to dispose of them due to their low value (NRC, 2021). Today, soybean hulls are ground and pelleted to be used as feed for livestock. There has been some discrepancy between in vitro and in vivo digestion of soyhulls which could be attributed to the fine particle size, causing quick passage through the rumen and inadequate digestion (Ipharraguerre and Clark, 2003; Drackley, 2000). Upon replacing corn grain with soyhulls, no impacts on milk yields or milk components were observed (Ipharraguerre et al., 2002; Boerman et al., 2015). It has been suggested that as much as 30% of diet DM can be composed of soyhulls without any negative impacts in milk production, diet digestibility, or ruminal fermentation (Ipharraguerre and Clark, 2003). Because soyhulls are mostly fiber, they have little nutrient value for humans and are considered human-inedible.

Corn Gluten Feed

The production of ethanol results in many by-products, one being corn gluten feed. To obtain this feed, the corn is first steeped in sulfurous dioxide; the steepwater is then condensed to make corn steep liquor (NRC, 2021). The germ is then isolated, and the hull and bran are removed to further isolate the starch. Finally, the bran is pressed, and the corn steep liquor is added back to create corn gluten feed which can be fed wet or dry (NRC, 2021). There are some nutritional differences between wet corn gluten feed (WCGF) and the dried version (DCGF). The levels of protein and fiber digestibility are slightly lower in DCGF than WCGF (Schroeder, n.d.). However, despite these differences in digestibility, there was no difference in milk yield or DMI when lactating cows were fed either WCGF or DCGF at 27% of diet DM, but milk fat content was lowest when cows were fed DCGF (Bernard et al., 1991). With increasing concentrations of WCGF at 20, 30, and 40% of diet DM, there were observed depressions in milk yield, DMI, and digestibility but increased milk fat with increasing WCGF content (Staples et al., 1984). Because corn gluten feed is mostly fiber and the leftovers from fermentation, it is considered human-inedible.

Considerations of Previous By-product Research

When reviewing research investigating the effect of one by-product type on production levels or digestibility in dairy cattle, it is important to consider the limitations of such studies. When substitutions are made in favor of a by-product, results may be heavily influenced on what ingredient is being replaced. For example, replacing forage for by-products may have potentially positive effects on milk yields simply due to a reduced NDF concentration of the treatment diet, not necessarily because of the addition of by-products. This can also be said for the replacement of grains where reducing starch in the diet can reduce milk yields, and this effect may not be entirely dependent on the addition of by-products. However, such reviews on different types of by-products still provide foundational knowledge on the value of these ingredients in diets as long as the results are being interpreted in the proper context.

Ruminal Digestion

Rumen Microbiome

Dairy cattle are able to supply much of their energetic requirements through ruminal fermentation. The rumen has a distinct microbial population that is active in the degradation of feedstuffs, providing volatile fatty acids (VFA) to sustain the animal in a symbiotic relationship (Bickhart and Weimer, 2018). VFAs contribute up to 80% of the total energy required by cattle, the most common forms being acetate, propionate, and butyrate (Wolin, 1979; Owens and Basalan, 2016). Carbon molecules are lost during the fermentation of carbohydrates to acetate and butyrate, and these carbons are used in making methane by methanogens in the rumen (Hungate, 1966; Morgavi et al., 2010). Higher concentrations of acetate and butyrate in the rumen are associated with high forage diets resulting in increased enteric methane production, whereas a higher concentration of propionate is indicative of a high grain diet and lower enteric methane formation (Hungate, 1966; Morgavi et al., 2010).

Protein Turnover

Protein nutrition is vital for maintaining many metabolic functions of the animal, such as growth, fertility, and lactation. Protein is classified as rumen degraded and undegraded protein (RDP and RUP, respectively; NRC, 2021). RUP bypasses the rumen and is mostly digested and absorbed in the small intestine, whereas RDP is broken down in the rumen. RDP is imperative to sustain the microbial population of the rumen, and the microbes produce microbial crude protein (MCP), a high quality metabolizable protein source (NRC, 2021). Inadequate levels of RDP in dairy cattle diets reduce fiber digestibility and DMI (Schwab and Broderick, 2017). RDP and RUP are supplied in tandem to achieve optimal metabolizable protein supply, if one source is predicted to decrease the other would need to be increased (NRC, 2021). However, it was noted in the 2021 version of the NASEM that recommendations for dairy cattle should be based on individual AA requirements rather than total protein as AA are the true building blocks for tissue and metabolic functions within the body. When EAA are fed and absorbed at the requirement of the cow, the efficiency for protein use is maximized and therefore the excess urinary N is decreased causing for fewer environmental concerns regarding N pollution (Schwab et al., 2003; NRC, 2021

Starch Utilization

Diets high in starch benefit milk production in high-producing dairy cows (Boerman et al., 2015). Starch is a highly digestible component of feeds and is an excellent source of energy. However, starch digestion is dependent upon the source of starch (corn, wheat, barley, etc.) and the processing of the feed (Oba and Allen, 2003; Moharrery et al., 2014; NRC, 2021). For example, the 2021 version of the NRC designates that dried fine ground corn grain has a digestibility value of 0.92, high moisture fine ground corn grain a value of 0.96, and steam flaked corn grain a value of 0.94. The digestibility of starch has also been shown to decrease as DMI increases and as passage rate increases (Voelker et al., 2003b; Ferraretto et al., 2013; de Souza et al., 2018). Amylolytic microbes in the rumen help to breakdown starch and produce propionate, a VFA that is a precursor for gluconeogenesis in the body (Reynolds, 2006). By increasing the fermentability of starch through feeding high moisture corn, Bradford and Allen (2004) saw increased plasma glucose and NEFA concentrations but no changes in plasma insulin or glucagon concentrations. Any declines in starch fermentation within the rumen are made up by increases in digestion in the small intestine, which may be more energetically efficient for the animal as intestinal cells are directly absorbing glucose compared to the production of VFAs in the rumen and use of the propionate to make glucose in liver (Owens et al., 1986; Voelker et al., 2003b).

Fiber Digestion

Although diets high in starch can provide energy to dairy cows, starch can also reduce fiber digestibility (Firkins et al., 2001; Ferraretto et al., 2013; Souza et al., 2018; NASEM, 2021). Voelker and colleagues (2003b) suggested several reasons for why this reduction occurs: reduction of ruminal pH from rapidly fermentable starch, lowered mastication, and decreased saliva buffer flow. Similar to starch, neutral detergent fiber (NDF) digestion is highly variable depending on the source and the time of harvest (NRC, 2021). NDF digestibility is negatively associated with lignin concentration, which is the indigestible portion of forages and increases in concentration as the plant matures.

Fiber is also important for maintaining proper gastrointestinal function, more specifically the formation and maintenance of the rumen mat. The rumen mat is responsible for physically keeping the particles in the rumen and enhancing rumination (Firkins, 1997). Shorter retention times decrease digestibility of NDF because there is a small window of time for ruminal microbes to break down bonds within the forages (NRC, 2021). Other contributors to retention time include particle size and DMI. Coarsely chopped forages are inhibited from passing through the rumen by the rumen mat, and therefore the retention time is increased. Conversely, forage fragility and the rate of reduction of particle size greatly contributes to a faster retention time and decreased NDF digestibility (Poppi et al., 1981; Kammes and Allen, 2012). DMI has been found to be negatively correlated with both retention time and NDF digestibility (Riewe and Lippke, 1970; Oba and Allen, 1999). Although not studied widely, Lee and associates (2011, 2012) also postulated that insufficient RDP, which is essential for the fibrolytic microbes, greatly decreases ruminal NDF digestibility.

Effects of Different By-products on Digestion

Microbial digestion within the rumen is advantageous to dairy cattle because it allows for the production of VFAs and other nutrients from otherwise indigestible feeds (Hungate, 1966; Bickhart and Weimer, 2018). By-product feeds have low nutritive value for humans and most monogastric animals; the ruminant digestive tract provides a clear advantage to digest and utilize these feeds. However, different by-product feeds have different compositions, thus altering their effect on digestion and nutrient utilization. By-product feeds with rapid rates of ruminal degradation could result in low ruminal pH and even acidosis (Batajoo and Shaver, 1998). Acidosis is caused by the excessive feeding of non-structural carbohydrates and highly fermentable forages (Plaizier et al., 2008). Ruminal acidosis causes a toxic environment for microbes, effectively terminates the population, and impairs milk production and health of the cow (Plaizier et al., 2008). Because high fiber by-product feeds are often fed in place of high starch grains, their inclusion reduces the risk of acidosis. Voelker et al. (2003b) showed that addition of sugar beet pulp reduced the risk of ruminal acidosis even though NDF digestibility was increased and starch digestibility was not decreased; the reduced acidosis was likely simply the result of feeding less starch. In addition to a reduction in acidosis, another advantage of replacing dietary starch with high fiber by-products is that baseline fiber digestibility will increase. Starch reduces fiber digestibility about 0.6 percentage units per 1% added starch (NASEM, 2021). Therefore, replacing starch with fibrous by-products can increase digestibility of the fiber already present in the diet and, if the by-product has high fiber digestibility, the energy supply per kg of feed may not be nearly as high as a high starch diet.

Public Perceptions of the Dairy Industry

Improving the sustainability of the dairy industry is an important avenue for research because of public perceptions. Consumers are more likely to view plant-based dairy alternatives as more sustainable when compared to traditional cow's milk (McCarthy et al., 2017; Schiano et al., 2020). Consumers are also less likely to purchase traditional dairy products because they are placing more emphasis on animal welfare, with over half of respondents in a survey indicating that they are concerned with dairy welfare in the United States (Wolf et al., 2016; McCarthy et al., 2017; Schiano et al., 2020;). Although plant-based dairy alternatives account for only 16% of total milk sales in the United States, these products have seen more growth in sales in the past 5 years than traditional cow's milk, with oat milk sales increasing 4000% (UC Davis, 2022; Son and Lusk, 2023). This data illustrates that despite accounting for a small portion of total milk sales, the growing popularity of plant-based dairy alternatives pose a threat to traditional cow's milk sales. Reports from the USDA also show that sales of organic foods have seen 50% increases from 2011 from 2021, suggesting that some consumers are making the decision to purchase products that they perceive to be environmentally friendly and healthier options (USDA, 2024).

Consumers are also concerned about other sectors of animal agriculture. The meat industry has been in the spotlight for beef's impact on greenhouse gas emissions, and a large portion of consumers indicated that they would be willing to curtail eating meat in order to limit their impact on the environment (Sanchez-Sabate and Sabate, 2019). The influx in plant-based dairy alternative sales could also be attributed to the health concerns surrounding animal products (Thorning et al., 2016). A number of health professionals and organizations believe that animal products, which are typically high in saturated fats, lead to high blood cholesterol concentrations and increased risk of coronary heart disease (Maijala, 2000; Estrup et al., 2019; CDC, 2023). Suggestions to decrease the risk of these adverse health effects include choosing low-fat dairy options or abstaining from animal products altogether (CDC, 2023).

Importance of Animal Agriculture

Despite the public perception of animal agriculture, meat and dairy products can contribute to a healthy diet and lifestyle. As plant-based dairy alternatives are labeled as "milk", it can be easy for consumers to expect that these products are nutritionally equivalent to traditional cow's milk. In fact, when traditional cow's milk was compared to dairy alternatives, it was found that cow's milk offers the most protein, fat, calcium, and micronutrients such as B vitamins, iodine, potassium, and phosphorus (Chalupa-Krebzdak et al., 2018; Walsh and Gunn, 2020; Collard and McCormick, 2021). Cow's milk also contains conjugated linoleic acid, a fatty acid that is only found in foods from ruminants and has demonstrated health benefits including reducing the risk of cancer, atherosclerosis, and diabetes as well as having positive effects on immune function (Rainer and Heiss, 2004). In addition, lauric acid, a saturated fatty acid found in milk, can have positive effects on the amount of high-density lipoproteins that are present in the blood, illustrating that saturated fats in milk can have complex effects on health (Pereira, 2014). In an extreme model where animals were removed entirely from the food production system, total food production would increase due to the availability of arable land, this food system would ultimately fail to meet the nutritional requirements of the global population (White and Hall, 2017). Moreover, Peters et al. (2016) showed that more people can be fed per unit of land when they consume a lactovegetarian than a strictly vegan diet. When animals are excluded from the food system, there is a risk for the food supply to become deficient in calcium, vitamin A, vitamin B_{12}, eicosapentaenoic acid (EPA), docosahexaenoic acid (DHA), arachidonic acid, and various amino acids without the inclusion of proper alternatives in the diet (White and Hall, 2017; White and Gleason, 2023). However, there would theoretically be an increase in the amount of energy in diets which could result in increased risk of obesity (White and Hall, 2017; White and Gleason, 2023).

Animal agriculture produces milk, eggs, and meat that sustain the nutritional requirements for the global population. However, some animals can also provide other resources like wool that is used in clothing production. Other than these processing livestock creates by-products that can be used in other production systems. Organ meats that are not typically consumed by the public in the United States are utilized in pet food manufacturing, providing pets with essential amino acids (Thompson, 2008). Meat and bone meal sourced from cattle or pigs is commonly used in broiler diets to provide high-quality protein (Karakas et al., 2001). Cattle hides are typically used to create leather furniture and clothing and can be used in the creation of glues. Animals have also been used in the production of pharmaceuticals, most notably with the isolation of insulin from bovine or swine pancreas to be used in the treatment of diabetes mellitus (Pillai and Panchagnula, 2001).

Current Research on By-products and Net Food Production

In 2018, a study was conducted that evaluated the effects of replacing cereal grains (wheat, barley, and oats) and soybean meal with sugar beet pulp, dried distiller's grain, and rapeseed meal in high-producing Swedish Holstein and Swedish Red dairy cows. Results showed that there was no treatment effect on DMI or milk yield but that there was a significant increase in the efficiency of using human-edible energy and protein sources when cows were fed high concentrations of by-products (Karlsson et al., 2018). Similarly, the replacement of cereal grains (barley, triticale, corn, and rye) with wheat bran and sugar beet pulp in high-forage diets fed to mid-lactation Holstein dairy cows resulted in no significant differences in milk yields, milk components, or DMI (Ertl et al., 2016). Again, this study showed that cows fed diets high in by-products were more efficient in using human-edible energy and protein (Ertl et al., 2016).

Another study conducted in 2019 evaluated the effects of feeding a diet composed of 95% by-products on milk production and net food production in late lactation Holsteins. Results showed that feeding a high-byproduct diet did not affect DMI but did decrease milk, fat, and protein yields compared to the control diet (Takiya et al., 2019). Net food production was calculated on three different scales: an extreme scenario where humans could eat everything that is "edible" (thrift), a moderate scenario where humans could eat only the things they wanted to (choice), and a land use scenario where land could be used to produce soybeans and corn alongside alfalfa hay (land use). In all scenarios, recoveries of human-edible ME and protein increased significantly although with different extents (Takiya et al., 2019). Thrift and land use scenarios exhibited recoveries in ME and protein that were 5-50% higher and 700-2,000% higher in the choice scenario for cows fed the by-product diet (Takiya et al., 2019).

Though the aforementioned studies both exhibited large increases in efficiency levels for the cows fed by-product diets, there are differences in the ways that these efficiencies were calculated, thus changing the scales of how efficient the cows are. Both Karlsson and Ertl calculated net food production by subtracting the human-edible inputs from the human-edible outputs, however Ertl reported minimum and maximum human-edible nutrient scenarios. In contrast, Takiya calculated net food production through the ratio of human-edible outputs to human-edible inputs. Nonetheless despite these differences, it is clear to see the potential of dairy cows to produce more human-edible nutrients through milk production than what they consume.

Conclusions

As ruminants, dairy cows have the ability to contribute to a sustainable future for animal agriculture by consuming human-inedible feedstuffs and converting them into nutritious foods to sustain an ever-growing global population. Current research has proven that despite different calculations, dairy cows can produce more edible food for humans than what they eat through the production of milk. Takiya (2019) showed that an extreme diet containing 95% by-products, although efficient at producing human-edible nutrients, reduced milk production in late lactation cows. Therefore, we propose that a more moderate diet composed of approximately 70% by-products can also increase net food production for humans with no negative consequences on milk production or components.

CHAPTER 3: MATERIALS AND METHODS

Design and Treatments

Multiparous lactating Holstein cows at the Michigan State University Dairy Cattle Teaching and Research Center were used in a crossover design study of high compared to low by-product diets from January to March of 2023 (n=31). Mean DIM, milk yield, and BW for all 31 cows were 90 ± 23 d, 50.1 ± 8.5 kg/d, and 725 ± 56 kg at the beginning of the study. Cows were blocked by DIM in the preliminary period, ECM/BW$^{0.75}$, and whether or not they were housed on the north or south side of the barn at the beginning of the study. Within block, cows were then randomly assigned to 1 of the 2 treatment diets. All experimental procedures were approved by the Michigan State University Institutional Animal Care and Use Committee.

In our study, half the cows were fed a common diet for a 7-d preliminary period, control diet for 21-d, common diet for 7-d, and high by-product treatment diet for the final 21-d of the study; the other cows received diets in the opposite order. The high by-product diet consisted of approximately 70% by-product feeds and the control diet consisted of approximately 20% by-products. Both diets were fed to cows as a TMR. Feeds were bought in bulk at the beginning of the study and were sampled each week. By-products were chosen to be locally sourced from Michigan, with the exception of cottonseeds. Bakery waste was purchased from ReConserve (Battle Creek, MI), wet beet pulp from Michigan Sugar Company (Bay City, MI), corn gluten feed from Caledonia Farmer's Elevator (Caledonia, MI), and wheat straw from University Farms (East Lansing, MI). The ingredient and nutrient compositions of each diet are presented in Table 3.1.

Cows were milked three times daily at 500 h, 1300 h, and 1900 h. All cows were housed in tiestalls and only had access to their own feed and water ad libitum. Stalls were bedded with sawdust and cleaned after the 1300 h milking. Orts were recorded daily before feeding, and feed was offered once daily at 900 h.

Table 3.1. Ingredient and nutrient composition of diets.

Ingredient, % of DM	CON	BYP
Corn Silage	36.0	25.0
Alfalfa Haylage	12.9	-
Ground Corn	24.0	-
Bakery Waste	-	15.0
Wet Beet Pulp	-	11.5
Corn Gluten Feed	-	16.9
Wheat Straw	-	7.5
Cottonseeds, Whole	10.0	10.0
SoyPlus	8.0	5.0
Protein/Vitamin/Mineral Premix[1]	9.1	9.1
Nutrient Composition		
NDF	29.6	37.1
Forage NDF	19.5	15.9
Starch	30.8	20.0
CP	16.8	17.0
RDP	10.7	10.8
RUP	6.4	6.4
Ether Extract	4.6	4.0

[1] Protein/Vitamin/Mineral Premix contained 35.1% CFE Distillers (Caledonia Farmers Elevator, Caledonia, MI), 12.6% sodium sesquinate refined, 11.2% calcium carbonate, 9.36% Soybean meal 47.5 Solvent, 9.01% Spectrum AgriBlue (Perdue Animal Nutrition, Salisbury, MD), 6.12% Ion Plus 48.5, 4.25% Urea 281 CP, 2.71% MIN-AD (MIN-AD Inc., Winnemucca, NV), 2.44% salt white, 2.16% calcium phosphate di, 1.69% potassium chloride red, 1.58% magnesium oxide, 0.81% magnesium sulfate $7H_2O$, 0.52% CFE Selenium 600 (Caledonia Farmers Elevator, Caledonia, MI), 0.15% Energizer 2 40 Tallow, 0.10% zinc sulfate H_2O 89, 0.09% Micro 5, 0.05% Vitamin E, 0.03% Manganese Sulfate H2O, 0.02% Copper Sulfate 5H2O, < 0.01% Vitamin A, < 0.01% Vit D_3 500 (Baltivet, Dubingai, Lithuania)

Data Collection and Analysis

BW were measured for each cow 3 d per week. Body condition was scored by 3 trained investigators on a 5-point scale in 0.25 increments at the beginning and end of each period during the week that cows were fed the common diet, and again after the end of the last treatment period. Daily milk yield was recorded automatically at each milking using Afimilk software (Kibbutz Afikim, Israel). Milk samples were collected for 6 consecutive milkings per week for component analysis. Samples were stored with preservative (Bronolab W-II liquid, Advanced Instruments, Norwood, MA) at 4°C until analysis. Individual milk samples were analyzed by CentralStar Cooperative, Inc (Grand Ledge, MI) for fat, true protein, lactose, and SCC concentrations by mid-infrared spectroscopy (AOAC, 1990, method 972.160). Milk yield and component concentrations for each milking were summed for a daily total and to calculate ECM and milk component yields. Energy-corrected milk was calculated as: ECM = [(0.324 x kg milk) + (12.816 x kg milk fat) + (7.129 x kg milk protein)].

Samples of each diet ingredient and TMR were collected once weekly and stored at -20°C until composited by treatment period and dried. Apparent total tract digestibility was determined for the study. Samples of all feed ingredients and orts from each cow were collected daily for 5 d at the end of period 2 in each study. Samples of feed ingredients were composited for the 5 d, and orts were composited by cow for the 5 d. Feces were collected from each cow through palpation of the rectum or during defecation every 15 h over the same 5 d, resulting in 8 samples/cow. Feces were stored at -20°C until they were dried and composited on an equal DM basis. Diet ingredients, orts, and feces were dried at 55ºC for 72 h in a forced-air oven to obtain DM. Dried samples were then ground with a Wiley mill (6-mm screen; Arthur H. Thomas, Philadelphia, PA). All samples were analyzed by Cumberland Valley Analytical Services (Waynesboro, PA) for CP (method 990.03; AOAC, 2000), starch (Hall, 2009), and fat (method 2003.05; AOAC, 2006). NDF and indigestible NDF were determined according to Van Soest et al. (1991) modified to use Whatman 934-AH glass microfiber filters with 1.5-µm particle retention (Cytiva, Marlborough, MA). Indigestible NDF, estimated as NDF residue after 240 h in vitro fermentation, was used as an internal marker to predict fecal output (Cochran et al., 1986).

Energy calculations for net food production on a human nutrition basis used Atwater factors of 4 kcal per gram of protein, starch, soluble fiber, and sugar, and 9 kcal per gram of fat where Feed AE = 0.04(%CP + %Starch +%SolFiber + %Sugar) + 0.09(%Fat). Atwater factors were used in this study to place values for net food production on a human nutrition scale, as these are used to calculate calories on nutrition labels (Atwater and Bryant, 1900). Nutrient concentrations are expressed as a percent of DM. This equation was utilized for all ingredients in each diet and summed together to create an Atwater Energy (IntakeAE) value for each diet. IntakeAE was calculated by the equation: DMI*FeedAE. Milk Atwater Energy (MilkAE) was calculated using the equation: 4(Lactose Yield) + 4(Protein Yield) + 9(Fat Yield). We calculated net production of Atwater energy as: MilkAE/IntakeAE. Similarly, we calculated net production of protein as: MilkProtein/IntakeProtein. To evaluate net food production on strictly a human-edible basis, we assumed that corn grain and soybean meal (100%), the corn grain of corn silage (45% of DM) and the leaves of alfalfa (30% of DM) were human-edible (HE). The modified equation for the human-edible energy for each ingredient was: 0.04(%CP + %Starch +%SolFiber + %Sugar) + 0.09(%Fat) * %human-edible. Ingredients in each diet were summed together to create a human-edible Atwater Energy value (IntakeHEAE) and a human-edible protein value (IntakeHEProtein). We used these values to calculate HEAE net production as MilkAE/IntakeHEAE and net HE protein production as: MilkProtein/IntakeHEProtein. From feed analyses by Cumberland Valley Analytical Services (Waynesboro, PA), we found that corn silage was 32.8% starch. Considering that we assumed 45% of corn silage to be corn grain, we can calculate that the corn grain portion of corn silage was (0.328/0.45)*100 = 72.8% starch. The average starch content of 71,000 samples of high-moisture corn in NASEM (2121) was

70.9% with a standard deviation of 2.4%. The starch content of the dry corn used in our study was 75.1%. Thus, our assumption on grain content being 45% seems reasonable.

Milk samples analyzed for fatty acid composition were collected at 12 consecutive milkings at the end of each period and stored at -20°C until composited. Samples were composited based on milk fat yield for each period. Milk lipids were extracted, FAME-prepared, and analyzed by gas chromatography (Lock et al., 2013; Bales et al., 2024). Yields of individual FA (g/d) within milk fat were calculated using milk fat yield and FA concentration of the last 5 days of the period to determine yield on a mass basis using the molecular weight of each FA while correcting for glycerol content and other milk lipid classes (Pantioni et al., 2013).

Statistical Analysis

All data were analyzed using the Glimmix model of SAS (version 9.4; SAS Institute, Cary, NC) according to the following model:

$$Y_{ijk} = Cov + \mu + T_i + P_j + S_k + e_{ijk}$$

where Y_{ijk} = independent variable, Cov = fixed effect of covariate, μ = overall mean, T_i = fixed effect of treatment (i = 1 to 2), P_j = fixed effect of period (j = 1 to 2), S_k = fixed effect of treatment sequence (k = 1 to 2), and e_{ijk} = residual error. Normality of results was tested using the Shapiro-Wilk test, box plots, and homogeneity of variances. The covariance structure variance components provided the best fit with the lowest overall Akaike's information criterion values. SCC displayed non-normality and LSM and SEM were log transformed for analysis and then back-transformed for presentation. Main effects were declared significant at $P \leq 0.05$ and tendencies at $0.05 < P \leq 0.10$. All data were expressed as LSM and SEM unless otherwise specified.

CHAPTER 4: RESULTS

Production

Overall, BYP decreased DMI and total milk yield by 0.8 and 2.2 kg/d, respectively (both $P < 0.01$), compared to CON. Although ECM yield decreased, fat content increased by 0.13% with the BYP diet when compared to CON (all $P < 0.01$). BYP also decreased protein content and yields ($P \leq 0.01$), as well as decreased lactose content and yields ($P < 0.01$). SCC increased with BYP ($P < 0.01$). ECM/DMI had numerically decreased with BYP ($P = 0.12$), indicating that cows fed BYP tended to be less efficient at converting feed into ECM. There was no difference in BW, BCS, or BCS change when comparing the two diets. However, cows fed BYP gained less BW per day than cows fed CON ($P = 0.03$).

Net Food Production

Atwater values were used to determine net food production on a human nutrition scale, as these are the same values that are used to determine calories on human nutrition labels. Compared to CON, cows fed BYP in our study were 14% more efficient at converting feed energy into milk energy when using Atwater energy values ($P < 0.01$) but slightly less efficient at converting feed protein into milk protein ($P < 0.01$). When we put these efficiency values on a human-edible basis, cows on BYP had energy efficiency that was 3.17 times that of cows fed CON and were able to produce 71% more human-edible energy in their milk than they consumed in their feed ($P < 0.01$). For human-edible protein, cows fed BYP had 2.81 times the efficiency of those fed CON and produced 102% more human-edible protein than they consumed ($P <$ 0.01).

Milk Fatty Acid Content

Milk FA are derived from two sources: shorter than 16 carbon FA are almost entirely from synthesis in the mammary gland and are termed "de novo" and longer than 16 carbon FA are extracted from plasma or mobilized from body tissue and are termed "preformed". FA of 16 carbons are sourced from both mammary gland de novo synthesis and plasma extraction and are termed "mixed". In this study, BYP decreased both the yield and content of C4 to C14 FA and C16 FA (all $P < 0.01$). However, BYP increased the yield and content of C18 FA by 36 g/d and 3.0 g/100g, respectively (all $P < 0.01$).

Regarding selected individual FA, BYP increased yields of C18:0 (P <0.01), *trans*-6 to-8 C18:1 ($P = 0.03$), and *cis*-9 C18:1 ($P < 0.01$) but decreased yields of C8:0 ($P < 0.01$), C10:0 ($P < 0.01$), C12:0 ($P < 0.01$), C14:0 ($P < 0.01$), C16:0 ($P < 0.01$), *cis*-9 C16:1 ($P = 0.04$), and *cis*-9, *cis*-12, *cis*-15 C18:3 ($P < 0.01$). Similar trends were reported on a concentration basis, with differences noted that BYP increased concentrations of C4:0 ($P = 0.01$) and *cis*-9, cis-12 C18:2 ($P = 0.03$).

Tables

Table 4.1. Effects of BYP diet on milk yield, milk composition, BW, BCS, and efficiency.

	Treatment[1]			*P*-Values
Variable	CON	BYP	SEM	CON vs BYP
DMI (kg)	30.9	30.1	0.473	<0.01
Milk (kg/d)	49.1	46.9	0.501	<0.01
ECM[2] (kg/d)	48.9	47.5	0.606	<0.01
Fat (%)	3.55	3.68	0.077	<0.01
Fat (kg/d)	1.70	1.69	0.037	0.75
Protein (%)	3.09	3.07	0.025	0.01
Protein (kg/d)	1.50	1.44	0.021	<0.01
Lactose (%)	4.95	4.91	0.016	<0.01
Lactose (kg/d)	2.43	2.30	0.032	<0.01
SCC[3] (x1,000 cells/ml)	11.52	14.08	1.21	<0.01
ECM/DMI	1.58	1.56	0.020	0.12
BW (kg)	738	736	1.34	0.18
BW Change (kg/d)	0.17	0.07	0.08	0.03
BCS	3.25	3.26	0.026	0.73
BCS Change (unit/28d)	0.017	0.027	0.029	0.73

[1] Treatments were 1) control (CON); 2) by-product diet (BYP)
[2] Energy-corrected milk; ECM = [(0.324 × kg milk) + (12.95 × kg milk fat) + (7.20 × kg milk protein)].
[3] Due to non-normality, SCC was log transformed for analysis. Means and SEM were back transformed for reporting.

Table 4.2. Effect of BYP diet on net food production for humans.

	Treatment[1]			*P*-Values
Variable (Mcal product / Mcal food)	CON	BYP	SEM	CON vs BYP
Net Food Production				
Atwater Energy	0.36	0.41	0.005	<0.01
Protein	0.29	0.28	0.005	<0.01
Human-Edible Net Food Production				
Atwater Energy	0.54	1.71	0.013	<0.01
Protein	0.72	2.02	0.023	<0.01

[1] Treatments were 1) control (CON); 2) by-product diet (BYP)

Table 4.3. Effect of BYP diet on milk fatty acid yield.

Variable	Treatment[1] CON	BYP	SEM	P-Values CON vs BYP
Summation by source, g/d				
De Novo only	399	367	13.7	<0.01
Mixed (C16)	529	495	16.5	<0.01
Preformed only	685	721	16.1	<0.01
Selected individual fatty acids, g/d				
C4:0	46.2	47.4	1.60	0.22
C6:0	31.8	31.1	1.23	0.29
C8:0	18.9	17.5	0.79	<0.01
C10:0	49.0	43.5	2.23	<0.01
C12:0	56.2	48.9	2.39	<0.01
C13:0, iso	0.34	0.32	0.02	0.43
C13:0, aiso	0.98	0.82	0.04	<0.01
C13:0	1.89	1.54	0.08	<0.01
C14:0, iso	0.91	0.99	0.04	0.03
C14:0	185	168	6.10	<0.01
cis-9 C14:1	11.8	10.2	0.34	<0.01
C15:0, iso	2.47	2.55	0.08	0.19
C15:0, aiso	4.96	6.57	0.15	<0.01
C15:0	14.5	12.9	0.47	<0.01
C16:0	512	478	16.3	<0.01
cis-9 C16:1	17.6	16.8	0.48	0.04
C17:0	6.53	6.12	0.18	<0.01
C18:0	190	217	7.50	<0.01
trans-4 C18:1	0.42	0.49	0.03	0.09
trans-5 C18:1	0.37	0.40	0.03	0.48
trans-6 to-8 C18:1	6.06	6.42	0.28	0.03
trans-9 C18:1	4.31	4.22	0.13	0.51
trans-10 C18:1	13.6	13.4	2.13	0.38
trans-11 C18:1	24.2	23.5	1.60	0.42
trans-12 C18:1	10.9	9.65	0.37	<0.01
cis-9 C18:1	291	314	7.15	<0.01
cis-11 C18:1	10.9	8.80	0.29	<0.01
cis-12 C18:1	14.9	10.1	0.62	<0.01
cis-13 C18:1	1.92	1.76	0.09	0.05
cis-14 to *trans*-16 C18:1	7.49	6.85	0.24	<0.01

Table 4.3. (cont'd).

cis-9, *cis*-12 C18:2	47.4	47.9	1.27	0.45
cis-9, *trans*-11 C18:2	8.77	8.34	0.51	0.17
cis-9, *cis*-12, *cis*-15 C18:3	5.63	3.22	0.13	<0.01
Unknown	13.8	12.7	0.36	<0.01

[1] Treatments were 1) control (CON); 2) by-product diet (BYP)

Table 4.4. Effect of BYP diet on milk fatty acid concentration.

	Treatment[1]			P-Values
Variable	CON	BYP	SEM	CON vs BYP
Summation by source, g/100g				
De Novo only	24.6	23.0	0.35	<0.01
Mixed (C16)	32.6	31.2	0.38	<0.01
Preformed only	42.8	45.8	0.64	<0.01
Selected individual fatty acids, g/100g				
C4:0	2.85	2.98	0.05	0.01
C6:0	1.96	1.95	0.04	0.75
C8:0	1.16	1.09	0.03	<0.01
C10:0	3.01	2.71	0.08	<0.01
C12:0	3.45	3.06	0.09	<0.01
C13:0, iso	0.02	0.02	0.001	0.57
C13:0, aiso	0.06	0.05	0.002	<0.01
C13:0	0.12	0.10	0.004	<0.01
C14:0, iso	0.05	0.06	0.002	<0.01
C14:0	11.4	10.6	0.17	<0.01
cis-9 C14:1	0.74	0.66	0.02	<0.01
C15:0, iso	0.15	0.16	0.002	<0.01
C15:0, aiso	0.31	0.42	0.01	<0.01
C15:0	0.89	0.81	0.02	<0.01
C16:0	31.5	30.1	0.39	<0.01
cis-9 C16:1	1.09	1.08	0.03	0.43
C17:0	0.40	0.38	0.01	<0.01
C18:0	11.8	13.7	0.28	<0.01
trans-4 C18:1	0.03	0.03	0.002	0.04
trans-5 C18:1	0.02	0.03	0.002	0.33
trans-6 to-8 C18:1	0.38	0.40	0.02	0.02
trans-9 C18:1	0.27	0.27	0.01	0.80
trans-10 C18:1	0.91	0.91	0.17	0.85
trans-11 C18:1	1.52	1.48	0.09	0.57
trans-12 C18:1	0.68	0.62	0.02	<0.01
cis-9 C18:1	18.2	20.0	0.38	<0.01
cis-11 C18:1	0.69	0.56	0.02	<0.01
cis-12 C18:1	0.94	0.64	0.04	<0.01
cis-13 C18:1	0.12	0.11	0.01	0.11

Table 4.4. (cont'd).

cis-14 to *trans*-16 C18:1	0.46	0.43	0.01	<0.01
cis-9, *cis*-12 C18:2	2.97	3.05	0.07	0.03
cis-9, *trans*-11 C18:2	0.55	0.54	0.04	0.27
cis-9, *cis*-12, *cis*-15 C18:3	0.35	0.20	0.01	<0.01
Unknown	0.86	0.81	0.01	<0.01

[1] Treatments were 1) control (CON); 2) by-product diet (BYP)

CHAPTER 5: DISCUSSION

Our study evaluated a specific blend of by-products that are commonly available in Michigan on high-producing dairy cattle. Because most published studies evaluating by-products tend to be dependent on the region where they are sourced, making a comparison to other studies is not simple. By-products are already commonly used in dairy cattle diets, but they tend to differ based on geographical region. For example, citrus pulp may be more common in the southeast United States while almond hulls are more typically fed in California and the Pacific Northwest. By increasing the amount of human inedible by-products that are used in dairy diets, nutritionists can effectively reduce the amount of ingredients that could be potentially eaten by humans. However, as each region differs from one another, finding a common by-product diet that sustains current milk production could prove to be challenging. The purpose of our study was to determine whether inclusion of by-products mostly from Michigan at 70% of the total diet could sustain high production levels in cows at peak lactation while also increasing net food production.

In our study, daily milk yields decreased by 4.5% when cows were fed the high by-product diet (49.1 kg/d vs 46.9 kg/d). Thus, our hypothesis was wrong but we did nonetheless sustain high levels of milk production with our by-product diet. In studies conducted by Takiya et al. (2019) and Erfani et al. (2024), similar results were observed where cows challenged with diets of 95% and 88% by-products, respectively, experienced a decline in milk yields (3.6 kg/d and 2.0 kg/d). There are also conflicting studies that provide evidence that cows fed similar diets experienced no change in daily milk yields (Ertl et al., 2015; Karlsson et al., 2018; Naderi et al., 2022), where human-inedible proportions ranged from 80-95% of diet DM. It is widely accepted that dietary starch concentrations of nearly 30% maximize milk production in high-producing dairy cattle. With this in mind, a possible explanation for the decrease in milk yield observed in our study is that the starch concentration in the BYP diet was too low (20% vs 30% in CON). Similarly, this can be hypothesized for the Takiya et al. (2019) and Erfani et al. (2024) studies as well, where starch concentration in treatment diets was also decreased by 7-10%. However, it must be noted that cows in these studies faced other challenges as well. In the Takiya et al. (2019) study, cows were both late lactation (154 ± 20 DIM) and producing less milk than cows in our study. In the Erfani et al. (2024) study, cows were fed diets under heat-stressed conditions.

We can also hypothesize that milk production decreased in our study simply because cows fed BYP ate less than cows fed CON, though this significant difference is only a decrease of 0.7 kg/d. Results from Erfani and colleagues (2024) found that cows fed a diet consisting of a blend of various cereal grain by-products ate less and produced less milk than cows fed a control diet. Our data does differ from what most studies have found when feeding high by-product diets (Ertl et al., 2015; Ertl et al., 2016; Karlsson et al., 2018; Takiya et al., 2019; Naderi et al., 2022), leading me to hypothesize that the cause perhaps lies somewhere in our diet ingredients. High concentrations of peNDF can decrease DMI (NRC, 2021). We included wheat straw at a higher rate than in Erfani and colleagues (2024) but lower than in Takiya et al. (2019). At a 7.5% inclusion rate, perhaps the wheat straw combined with wet beet pulp and whole cottonseeds resulted in too much physical fill of the rumen and thus limited DMI.

Cows fed BYP had a greater milk fat concentration than those fed CON. Similar results for increases in milk fat with high by-product diets were reported by Karlsson et al. (2018), Naderi et al. (2022), and Erfani et al. (2024). Perhaps this difference in milk fat concentrations was a result of the decreased starch concentration in BYP, as high starch concentrations cause milk fat depression (Palmquist et al., 1993; Bauman et al., 2011). Substitution of corn grain or other high energy ingredients for by-products can cause this shift towards higher milk fat production. In our study, we completely substituted ground corn with bakery waste and fibrous by-products and thus increased the fiber content and reduced the starch content of the diet. Similarly, other studies conducted by Zang et al. (2021) and Malekkhahi et al. (2023) observed such increases in milk fat concentrations when adding by-products to their diets in place of corn. Zang et al (2021) replaced corn grain with soyhulls and beet pulp and reported a 0.41% unit increase in milk fat concentration. Malekkhahi et al. (2023) reported an increase in milk fat concentration when substituting corn silage for beet pulp, thus reducing the starch concentration of the diet. Therefore, it is likely that the reduced starch concentration of the BYP diet contributed to the increased milk fat concentration. However, this increase did not compensate for the reduction in milk in yield of BYP cows so that ECM yield of cows fed BYP was decreased 1.4 kg/d.

Evaluating the efficiency of dairy cattle to convert feed energy and protein into human-edible nutrients is imperative to determining if dairy animals serve a purpose in a sustainable future. By increasing the proportion of by-products in the diets of dairy cattle, we are reducing the amount of human-edible food eaten by cows. For example, corn grain and soybean meal are integral ingredients on many dairy farms but they are 100% human-edible, creating direct competition with humans for food sources. As the global human population continues to grow, so will the need for more food to sustain more people. Feeding by-products to dairy cattle in place of these human-edible ingredients decreases the competition for food, making more available for humans while simultaneously providing milk for consumption—it increases net food production! It also reduces land-use competition, as 70% of the world’s agricultural land is used to produce feed for livestock consumption (FAO, 2009). By-products are sourced from the same land that humans grow crops from rather than strictly using land to produce commodities such as corn or alfalfa for feeding livestock, reducing this competition as well.

In our study, we calculated energy on an Atwater basis to provide values that were on a human nutrition scale. Atwater's equation is utilized to estimate calories on nutritional labels on food packaging, thus giving context for how much energy is available for humans. Results from our study showed that when evaluating Atwater energy and protein strictly on an input-to-output ratio, cows fed BYP were more efficient at producing energy than protein when compared to cows fed CON. The efficiencies for Atwater energy are 41% and 36% (BYP and CON) and protein are 28% and 29% (BYP and CON). Essentially, dairy cows are only able to return less than half of the energy and protein that they consume. However, when we only consider the human-edible portions of the ingredients, we observed that cows fed BYP were much more efficient at producing Atwater energy and protein than cows fed CON. These differences were evaluated at 171% and 54% for energy (BYP and CON) and 202% and 72% for protein (BYP and CON). Thus, cows fed BYP were able to produce more energy and protein in their milk than the human-edible inputs consumed in their feed because they consumed fewer human-edible nutrients ingredients and more by-products that are human-inedible.

The results that we observed on net food production align with results from multiple studies (Ertl et al., 2015; Ertl et al., 2016; Karlsson et al., 2018; Takiya et al., 2019; Naderi et al., 2022; Erfani et al., 2024). Each study reported considerable improvements in efficiency of protein and energy recoveries when evaluating on a scale of human-edible feed conversion. However, differences can be seen depending on the equations and methods use to obtain these values, and there are discrepancies between all aforementioned studies on the best method for evaluating net food production. Most agree with an efficiency of output/input but disagree with calculations to obtain input and/or output values. Nonetheless, all studies illustrate the fact that dairy cattle can be sustainable producers of milk when by-products are substituted for grain and other human-edible ingredients within the diet.

Although net food production was substantially improved when cows were fed a high by-product diet, other factors must also be considered when determining if high by-product diets are environmentally sustainable. Enteric methane (CH4) produced in the rumen and eructated by dairy cattle has a global warming potential that is 28x more potent than carbon dioxide (Knapp et al., 2014; EPA, 2023). Based on equations from the NASEM (2021), we expect that cows fed BYP produced more methane than cows fed CON (12.9 vs 12.2 g/kg milk). Fermentation of fiber produces more acetate and hydrogen, and consequently more enteric methane than starch (Bannink et al., 2008; Janssen 2010), so the increased methane was likely due to the higher NDF content of the BYP diet (37% vs 30% for CON). A study conducted by Hammond et al. (2016) supports this idea, as they reported that adding barley straw and soyhulls to increase the NDF content of diets increased methane emissions when expressed per unit of milk. Increasing the starch content and lowering the fiber content of diets is recommended as one strategy for the mitigation of enteric methane production (Beauchemin et al., 2008). Therefore, feeding more fibrous by-products to increase net food production presents tradeoffs for dairy farmers. Feeding by-products means less land is needed to produce milk, but it will likely cause an increase in enteric methane production. These tradeoffs must be considered when deciding how to feed dairy cattle for a sustainable future.

In this study, we observed that cows fed BYP had decreased concentrations of C4 to C16 FA when compared to CON, but elevated concentrations of C18 FA. The C4 to C14 FA and half the C16 FA are synthesized de novo in mammary alveolar cells and the C18 FA are blood FA used by mammary cells in making milk fat. The FA from blood are called preformed FA and also include about half the C16 FA; they originate from body tissue mobilization or absorbed dietary fats (Palmquist et al., 1993). Our finding of decreased de novo FA but more C18 FA with the BYP diet is similar to results of Naderi et al (2022), who found that increasing concentrations of by-products within a grain mix at 26%, 60%, and 95% DM decreased the de novo and C16 FA but increased the C18 FA, and diets also had increased fat with increasing concentration by-products. Our finding of more preformed FA with inclusion of bakery waste was reported by Khiaosa-ard, et al. (2022), who observed an increase in preformed FA of C18:1 origin when they fed 15 and 30% bakery waste in place of cereal grains; however, they observed no significant change in de novo FA synthesis. It is possible a shift in FA composition was observed in cows fed BYP, where more preformed FA (especially of C18 origin) were being allocated towards the milk rather than FA formed de novo in the mammary gland. In our study, the fat content of our diets was similar (4.0% for CON and 4.6% for BYP), and the slightly higher fat in BYP seems insufficient to cause the elevated concentration of preformed FA in cows fed BYP. However, the BYP diet also had less starch than CON (20 vs 30 %) and resulted in less BW gain (0.07 kg/d vs. 0.17 kg/d for CON). We suspect that the combination of less starch, less energy, and more fat in the BYP diet led to less storage of nutrients in adipose tissue and more longer chain FA directed towards milk production. Because our BYP diet had more fiber, and likely more digestible fiber, that CON, we expected that it might increase de novo FA synthesis so we cannot explain the decrease in de novo FA with feeding BYP. Future work should examine fiber digestibility to better understand effects of this type of high by-product diet on milk fat composition.

In summary, our study found that cows fed BYP had reduced daily milk yield yet produced milk with a higher concentration of milk fat with the extra fat coming from preformed

FA. This change in milk production is likely from the reduction of starch content, increase in fiber content, and slight increase in fat content of the BYP diet, which resulted in slightly less DMI and likely less glucose available for making lactose. Thus, we did not achieve our goal of maintaining milk production at the same level when feeding a diet high in leftovers compared to a conventional Michigan diet, but we were close. Cows fed BYP produced 97% as much energy-corrected milk as those fed CON, and these were high-producing cows averaging 47.5 kg of ECM/day. Despite this decline in milk yield when compared to cows fed CON, cows fed BYP were considerably more efficient in using human-edible nutrients to make milk due to the low level of human-edible nutrients in their diets. Out study clearly demonstrates that dairy cows can be part of a sustainable food production system, but shifting towards sustainable feeding may present tradeoffs such as limitations on milk production. More research should be conducted to assess the economic and environmental tradeoffs associated with sustainable feeding practices of dairy cattle.

Tables

Table 5.1. Comparison of Previous By-product Research Designs.

Study	Number of Cows	Breed	Parity	Stage of Lactation	Milk Production Level	By-products Used & Percent of Diet	Study Design	Days on Trial
Ertl et al., 2015	18	Holstein	Mutliparous (n = 13) and primiparous (n = 5)	108 ± 90 DIM	27.5 ± 5.1 kg/d	Corn middlings, beet pulp, rapeseed cake, soy cake, molasses (50% of diet)	Crossover	14 weeks
Ertl et al., 2016	20	Holstein	Mutliparous (n = 13) and primiparous (n = 7)	117 ± 113 DIM	26.2 ± 6.0 kg/d	Wheat bran and beet pulp (25% of diet)	Crossover	14 weeks
Karlsson et al., 2018	24	Swedish Holstein (n = 8) and Swedish Red (n = 16)	Mutliparous (n = 12) and primiparous (n = 12)	85 ± 13 DIM	38.6 ± 8.5 kg/d	Beet pulp, rapeseed meal, dried distiller's grain, wheat bran (45%,)	Crossover	12 weeks
Takiya et al., 2019	12	Holstein	Multiparous (n = 6) and primiparous (n = 6)	154 ± 20 DIM	42.6 ± 5.4 kg/d	Corn gluten feed, wheat straw, wheat middlings, hominy feed, molasses, porcine blood meal, post-extraction algae residue (95% of diet)	Crossover	40 days
Naderi et al., 2022	12	Holstein	Multiparous	112 ± 8 DIM	48 ± 2.3 kg/d	Corn gluten meal, cotton seed, corn bran, corn germ meal, corn grain screens, rice bran, barley malt sprouts, blood meal (26%, 65%, and 95% of diet)	3x3 Latin square	12 weeks
Erfani et al., 2024	12	Holstein	Multiparous	116 ± 12 DIM	42.7 ± 5.1 kg/d	Diet 1: rice bran, corn germ meal, wheat bran, barley sprout, broken corn (51% of diet) Diet 2: beet pulp, dried citrus pulp, canola meal, molasses (51% of diet)	3x3 Latin square	12 weeks
Current Study	31	Holstein	Multiparous	90 ± 23 DIM	50.1 ± 8.5 kg/d	Wheat straw, bakery waste, wet beet pulp, corn gluten feed, whole cottonseeds (~70% of diet)	Crossover	8 weeks

Table 5.2. Comparison of Previous By-product Research Results.

Study	Milk Yield (kg/d)	ECM Yield (kg/d)	DMI (kg/d)	Milk Fat (%, unless otherwise noted)	Net Food Production, Energy	Net Food Production, Protein
Ertl et al., 2015	CON: 26 BP: 27.8 P = 0.35	CON: 26.9 BP: 27.7 P = 0.58	CON: 21.2 BP: 21.1 P = 0.83	CON: 4.38 BP: 4.27 P = 0.43	CON: 1.39 BP: 5.55 P < 0.01	CON: 1.60 BP: 4.27 P < 0.01
Ertl et al., 2016	N/A	CON: 22.5 WBBP: 22.7 P = 0.79	CON: 18.1 WBBP: 18.5 P = 0.49	CON: 4.29 WBBP: 4.23 P = 0.74	CON: 1.08 WBBP: 7.29 P < 0.01	CON: 1.53 WBBP: 8.05 P < 0.01
Karlsson et al., 2018	CON: 32.1 SBP-DDGS: 30.8 SBP-RSM: 32.0 SBP-RSM-DDGS: 31.9 P = 0.06	CON: 33.1 SBP-DDGS: 32.4 SBP-RSM: 33.7 SBP-RSM-DDGS: 33.3 P = 0.17	CON: 22.9 SBP-DDGS: 22.4 SBP-RSM: 22.7 SBP-RSM-DDGS: 23.5 P = 0.20	CON: 4.27[b] SBP-DDGS: 4.57[a] SBP-RSM: 4.47[ab] SBP-RSM-DDGS: 4.46[ab] P = 0.03	CON: 0.54[b] SBP-DDGS: 1.62[a] SBP-RSM: 1.67[a] SBP-RSM-DDGS: 1.66[a] P < 0.01	CON: 0.73[b] SBP-DDGS: 2.56[a] SBP-RSM: 2.63[a] SBP-RSM-DDGS: 2.68[a] P < 0.01
Takiya et al., 2019	CON: 42.3 ECO: 38.7 P = 0.04	N/A	CON: 29.7 ECO: 29.3 P = 0.94	CON: 1.58 kg/d ECO: 1.33 kg/d P < 0.01	CON: 0.94 ECO: 7.33 P < 0.01	CON: 0.82 ECO: 19.7 P < 0.01
Naderi et al., 2022	BP26: 43.1 BP60: 43.7 BP95: 43.9 P = 0.37	BP26: 39.4 BP60: 40.3 BP95: 41.2 P = 0.05	BP26: 21.8 BP60: 22.2 BP95:22.2 P = 0.37	BP26: 2.95 BP60: 2.99 BP95: 3.13 P < 0.01	BP26: 2.27 BP60: 3.62 BP95: 9.22 P < 0.01	BP26: 1.06 BP60: 1.66 BP95: 4.14 P < 0.01
Erfani et al., 2024	CON: 37.7[a] CG-BY: 35.7[b] S-BY-CM: 38.0[a] P < 0.01	CON: 35.0[ab] CG-BY: 34.3[b] S-BY-CM: 36.2[a] P = 0.01	CON: 27.7[a] CG-BY: 25.4[b] S-BY-CM: 28.3[a] P < 0.01	CON: 3.01[b] CG-BY: 3.30[a] S-BY-CM: 3.23[a] P < 0.01	CON: 0.61[b] CG-BY: 2.51[a] S-BY-CM: 2.77[a] P < 0.01	CON: 0.32[b] CG-BY: 1.19[a] S-BY-CM: 1.17[a] P < 0.01
Current Study	CON: 49.1 BYP: 46.9 P <0.01	CON: 48.9 BYP: 47.5 P <0.01	CON: 30.9 BYP: 30.1 P <0.01	CON: 3.55 BYP: 3.68 P <0.01	CON: 0.54 BYP: 1.71 P <0.01	CON: 0.72 BYP: 2.02 P <0.01

CHAPTER 6: OVERALL CONCLUSIONS

By-products are a common feed for dairy cattle because of their nutritional benefits and low costs. Utilizing such feeds at higher levels in diets can also improve the sustainability of milk production and provide alternate ingredients to decrease the competition for resources with humans. Few studies have investigated the impact of including by-products at greater than half of total DM for diets of peak lactation dairy cattle with a specific emphasis on net food production. The objective of this thesis was to evaluate a diet of approximately 70% by-products and its effect on milk and net food production. In this study, I examined the effects of feeding a 70% by-product diet containing corn silage, soybean meal, bakery waste, corn gluten feed, wheat straw, wet beet pulp, and cottonseeds on milk production and net food production.

In our research, challenging dairy cattle by feeding a high by-product diet negatively impacted milk production, but the decrease was only 4.9%, and the cows fed the high by-product diet were able to produce an average of 46.9 kg of milk per day. Cows fed BYP also ate less feed, which could contribute to their decrease in milk yield. Additionally, cows fed BYP gained less body weight per day. The BYP diet also decreased milk protein and lactose yields and concentrations but increased milk fat concentration, with no impact on milk fat yield. These production results are most similar to a study conducted by Erfani et al. (2024), where their cereal-grain based by-product diet decreased milk yields, milk protein and lactose concentrations, and DMI but increased milk fat concentration.

Feeding the BYP diet altered milk FA composition with more C18 and less C4 to C16 FA, indicating that cows fed BYP were synthesizing less FA within the mammary gland and using more preformed FA from blood to make milk fat. These results align with research conducted by Naderi et al. (2022), who found that increasing the amount of by-products linearly increased preformed FA and decreased de novo FA.

Results for net food production were calculated using Atwater energy values in an effort to put data on a human nutrition scale, as dairy cows produce milk for human consumption. Our research also showed that feeding by-products significantly increased net food production for humans when considered on a human-edible nutrient basis. Our results align with current literature that suggest that feeding by-products can increase net food production by decreasing the feed inputs that humans could consume directly, thus increasing the ratio of human-edible nutrient outputs per human-edible nutrient input (Ertl et al., 2015; Ertl et al., 2016; Karlsson et al., 2018; Takiya et al., 2019; Naderi et al., 2022; Erfani et al., 2024). These findings demonstrate the capability of dairy cattle to efficiently convert agricultural waste products into nutritious milk that can sustainably feed a growing human population.

In conclusion, whereas the most effective by-product inclusion level will depend on the unique by-products and base feeds available in each situation, our results indicate that feeding a diet composed of approximately 70% by-products along with 25% corn silage doubles overall net food production for humans while decreasing milk production only 5% in high producing dairy cows. Further research should determine how this type of diet alters greenhouse gas production, and especially methane production.

REFERENCES

AAFCO (Association of American Feed Control Officials). 2016. 2016 Official Publication: Association of American Feed Control Officials Incorporated. Oxford, UK: Association of American Feed Control.

Agle, M., A.N. Hristov, S. Zaman, C. Schneider, P.M. Ndegwa, and V.K. Vaddella. 2010. Effect of dietary concentrate on rumen fermentation, digestibility, and nitrogen losses in dairy cows. J. Dairy Sci. 93:4211–4222. doi:10.3168/jds.2009-2977.

Albarrán-Portillo, B., and G.E. Pollott. 2013. The relationship between fertility and lactation characteristics in Holstein cows on United Kingdom commercial dairy farms. J. Dairy Sci. 96:635–646. doi:10.3168/jds.2012-5632.

AOAC. (2000a). Ash of Animal Feed (942.05). *Official Methods of Analysis*.

AOAC. (2000b). Protein (Crude) in Animal Feed, Combustion Method (990.03). *Official Methods of Analysis of AOAC International*.

AOAC. (2006). Crude Fat in Feeds, Cereal Grains, and Forages (2003.05). *Official Methods of Analysis*.

Arieli, A. 1998. Whole cottonseed in dairy cattle feeding: a review. Anim. Feed Sci. Technol. 72:97–110. doi:10.1016/s0377-8401(97)00169-7.

Atwater, W. O., and Bryant, A. P. (1900). The Availability and Fuel Values of Food Materials. Connecticut (Storrs) Agricultural Experiment Station 12th Annual Report.

Bales, A.M., M.E. Cinzori, and A.L. Lock. 2023. Increasing palmitic acid and reducing stearic acid content of supplemental fatty acid blends improves production performance of mid-lactation dairy cows. J. Dairy Sci. 107:278–287. doi:10.3168/jds.2023-23874.

Bampidis, V. A., and P. H. Robinson. 2006. Citrus by-products as ruminant feeds: A review. Anim. Feed Sci. Technol. 128:175–217.

Batajoo, K.K., and R.D. Shaver. 1998. In situ dry matter, crude protein, and starch degradabilities of selected grains and by-product feeds. Anim. Feed Sci. Technol. 71:165–176. doi:10.1016/s0377-8401(97)00132-6.

Beauchemin, K.A., M. Kreuzer, F. O'Mara, and T.A. McAllister. 2008. Nutritional management for enteric methane abatement: a review. Anim. Prod. Sci. 48:21–27. doi:10.1071/ea07199.

Berckmans, D. 2017. General introduction to precision livestock farming. Anim. Front. 7:6–11. doi:10.2527/af.2017.0102.

Bernard, J.K., R.C. Delost, F.J. Mueller, J.K. Miller, and W.M. Miller. 1991. Effect of Wet or Dry Corn Gluten Feed on Nutrient Digestibility and Milk Yield and Composition. J. Dairy Sci. 74:3913–3919. doi:10.3168/jds.s0022-0302(91)78584-6.

Berry, D.P., N.C. Friggens, M. Lucy, and J.R. Roche. 2015. Milk Production and Fertility in Cattle. Annu. Rev. Anim. Biosci. 4:1–22. doi:10.1146/annurev-animal-021815-111406.

Bickhart, D.M., and P.J. Weimer. 2018. Symposium review: Host–rumen microbe interactions may be leveraged to improve the productivity of dairy cows. J. Dairy Sci. 101:7680–7689. doi:10.3168/jds.2017-13328.

Blauwiekel, R., S. Xu, J.H. Harrison, K.A. Loney, R.E. Riley, and M.C. Calhoun. 1997. Effect of Whole Cottonseed, Gossypol, and Ruminally Protected Lysine Supplementation on Milk Yield and Composition. J. Dairy Sci. 80:1358–1365. doi:10.3168/jds.s0022-0302(97)76064-8.

Boerman, J.P., S.B. Potts, M.J. VandeHaar, M.S. Allen, and A.L. Lock. 2015. Milk production responses to a change in dietary starch concentration vary by production level in dairy cattle. J. Dairy Sci. 98:4698–4706. doi:10.3168/jds.2014-8999.

Bradford, B.J., and M.S. Allen. 2004. Milk Fat Responses to a Change in Diet Fermentability Vary by Production Level in Dairy Cattle 1,2. J. Dairy Sci. 87:3800–3807. doi:10.3168/jds.s0022-0302(04)73519-5.

Brandao, V.L.N., and A.P. Faciola. 2019. Unveiling the relationships between diet composition and fermentation parameters response in dual-flow continuous culture system: a meta-analytical approach. Transl. Anim. Sci. 3:1064–1075. doi:10.1093/tas/txz019.

Broderick, G. A., T. M. Kerkman, H. M. Sullivan, M. K. Dowd, and P. A. Funk. 2013. Effect of replacing soybean meal protein with protein from upland cottonseed, Pima cottonseed, or extruded Pima cottonseed on production of lactating dairy cows. J. Dairy Sci. 96:2374–2386.

Caradonna, J. 2022. Sustainability: A History. Oxford University Press, New York, NY.

Case, L.P., L. Daristotle, M.G. Hayek, and M.F. Raasch. 2011. Canine and Feline Nutrition (Third Edition). Sect. 3: Pet Foods 141–162. doi:10.1016/b978-0-323-06619-8.10016-7.

CDC. 2024. Preventing High Cholesterol. Accessed Jul. 03, 2024. https://www.cdc.gov/cholesterol/prevention/index.html

Chalupa-Krebzdak, S., C.J. Long, and B.M. Bohrer. 2018. Nutrient density and nutritional value of milk and plant-based milk alternatives. Int. Dairy J. 87:84–92. doi:10.1016/j.idairyj.2018.07.018.

Clark, P.W., and L.E. Armentano. 1993. Effectiveness of Neutral Detergent Fiber in Whole Cottonseed and Dried Distillers Grains Compared with Alfalfa Haylage1. J. Dairy Sci. 76:2644–2650. doi:10.3168/jds.s0022-0302(93)77600-6.

Cochran, R. C., Adams, D. C., Wallace, J. D., & Galyean, M. L. (1986). Predicting digestibility of different diets with internal markers: Evaluation of four potential markers 1476-1483.

Coffey, D., K. Dawson, P. Ferket, and A. Connolly. 2016. Review of the feed industry from a historical perspective and implications for its future. J. Appl. Anim. Nutr. 4:e3. doi:10.1017/jan.2015.11.

Collard, K.M., and D.P. McCormick. 2021. A Nutritional Comparison of Cow's Milk and Alternative Milk Products. Acad. Pediatr. 21:1067–1069. doi:10.1016/j.acap.2020.12.007.

Coon, R.E., T.F. Duffield, and T.J. DeVries. 2018. Effect of straw particle size on the behavior, health, and production of early-lactation dairy cows. J. Dairy Sci. 101:6375–6387. doi:10.3168/jds.2017-13920.

Coppock, C.E., J.K. Lanham, and J.L. Horner. 1987. A review of the nutritive value and utilization of whole cottonseed, cottonseed meal and associated by-products by dairy cattle. Anim. Feed Sci. Technol. 18:89–129. doi:10.1016/0377-8401(87)90041-1.

de Souza, R, R. J. Tempelman, M. S. Allen, W. Weiss, J. Bernard, and M. J. VandeHaar. 2018. Predicting nutrient digestibility in high-producing lactating dairy cow. J. Dairy Sci. 101:1123–1135.

DePeters, E.J., S.J. Taylor, A.A. Franke, and A. Aguirre. 1985. Effects of Feeding Whole Cottonseed on Composition of Milk. J. Dairy Sci. 68:897–902. doi:10.3168/jds.s0022-0302(85)80907-3.

Drackley, J. K., ed. 2000. Soy in Animal Nutrition. Savoy, IL: Federation of Animal Science Societies.

Eastridge, M. 2007. Soybean Meal- They're Not All the Same. Accessed Jul. 03, 2024. https://dairy.osu.edu/newsletter/buckeye-dairy-news/volume-9-issue-4/soybean-meal-theyre-not-all-same

EPA. 2004. National Emission Inventory—Ammonia Emissions from Animal Husbandry Operations US EPA, Washington, DC.

EPA. 2024. Importance of Methane. Accessed Jul. 3, 2024. https://www.epa.gov/gmi/importance-methane#:~:text=Methane%20is%20more%20than%2028,due%20to%20human%2Drelated%20activities.

EPA. 2024. Composting. Accessed Jul. 3, 2024. https://www.epa.gov/sustainable-management-food/composting

EPA. 2024. The Effects: Dead Zones and Harmful Algal Blooms. Accessed Jul. 3, 2024. https://www.epa.gov/nutrientpollution/effects-dead-zones-and-harmful-algal-blooms

Erfani, H., G.R. Ghorbani, F. Hashemzadeh, E. Ghasemi, A.R. Khademi, N. Naderi, and J.K. Drackley. 2024. Effects of complete substitution of dietary grain and protein sources with by-products on the production performance of mid-lactation dairy cows fed diets based on barley silage under heat stress conditions. J. Dairy Sci. 107:1993–2010. doi:10.3168/jds.2022-23179.

Ertl, P., Q. Zebeli, W. Zollitsch, and W. Knaus. 2015. Feeding of by-products completely replaced cereals and pulses in dairy cows and enhanced edible feed conversion ratio. J. Dairy Sci. 98:1225–1233. doi:10.3168/jds.2014-8810.

Ertl, P., Q. Zebeli, W. Zollitsch, and W. Knaus. 2016. Feeding of wheat bran and sugar beet pulp as sole supplements in high-forage diets emphasizes the potential of dairy cattle for human food supply. J. Dairy Sci. 99:1228–1236. doi:10.3168/jds.2015-10285.

FAO. 2024. Sustainable Food and Agriculture. Accessed Jul. 26, 2024. https://www.fao.org/sustainability/en/

Ferraretto, L. F., P. M. Crump, and R. D. Shaver. 2013. Effect of cereal grain type and corn grain harvesting and processing methods on intake, digestion, and milk production by dairy cows through a meta-analysis. J. Dairy Sci. 96:533–550.

Firkins, J. L. 1997. Effects of nonforage fiber sources on site of fiber digestion. J. Dairy Sci. 80:1426–1437.

Firkins, J. L., M. L. Eastridge, N. R. St.-Pierre, and S. M. Noftsger. 2001. Effects of grain variability and processing on starch utilization by lactating dairy cattle. J. Anim. Sci. 79(E. Suppl.):E218–E238.

Giallongo, F., J. Oh, T. Frederick, B. Isenberg, D.M. Kniffen, R.A. Fabin, and A.N. Hristov. 2015. Extruded soybean meal increased feed intake and milk production in dairy cows. J. Dairy Sci. 98:6471–6485. doi:10.3168/jds.2015-9786.

Gross, J.J. 2023. Dairy cow physiology and production limits. Anim. Front.: Rev. Mag. Anim. Agric. 13:44–50. doi:10.1093/af/vfad014.

Haddad, S.G., R.J. Grant, and S.D. Kachman. 1998. Effect of Wheat Straw Treated with Alkali on Ruminal Function and Lactational Performance of Dairy Cows1. J. Dairy Sci. 81:1956–1965. doi:10.3168/jds.s0022-0302(98)75769-8.

Hall, M. B. (2009). Determination of starch, including maltooligosaccharides, in animal feeds: Comparison of methods and a method recommended for AOAC collaborative study. *Journal of AOAC International*, *92*(1), 42-49.

Hammond, K.J., A.K. Jones, D.J. Humphries, L.A. Crompton, and C.K. Reynolds. 2016. Effects of diet forage source and neutral detergent fiber content on milk production of dairy cattle and methane emissions determined using GreenFeed and respiration chamber techniques. J. Dairy Sci. 99:7904–7917. doi:10.3168/jds.2015-10759.

Humer, E., S. Aditya, A. Kaltenegger, F. Klevenhusen, R.M. Petri, and Q. Zebeli. 2018. Graded substitution of grains with bakery by-products modulates ruminal fermentation, nutrient degradation, and microbial community composition in vitro. J. Dairy Sci. 101:3085–3098. doi:10.3168/jds.2017-14051.

Hungate, R.E. 1966. The rumen and its microbes. Academic Press Inc. New York, NY.

Ipharraguerre, I. R., R. R. Ipharraguerre, and J. H. Clark. 2002. Performance of lactating dairy cows fed varying amounts of soyhulls as a replacement for corn grain. J. Dairy Sci. 85:2905–2912.

Ipharraguerre, I. R., and J. H. Clark. 2003. Soyhulls as an alternative feed for lactating dairy cows: A review. J. Dairy Sci. 86:1052–1073.

Janssen, P.H. 2010. Influence of hydrogen on rumen methane formation and fermentation balances through microbial growth kinetics and fermentation thermodynamics. Anim. Feed Sci. Technol. 160:1–22. doi:10.1016/j.anifeedsci.2010.07.002.

Kaltenegger, A., E. Humer, A. Stauder, and Q. Zebeli. 2020. Feeding of bakery by-products in the replacement of grains enhanced milk performance, modulated blood metabolic profile, and lowered the risk of rumen acidosis in dairy cows. J. Dairy Sci. 103:10122–10135. doi:10.3168/jds.2020-18425.

Kammes, K. L., and M. S. Allen. 2012. Nutrient demand interacts with legume maturity to affect rumen pool sizes in dairy cows. J. Dairy Sci. 95:2632–2647.

Karakas, P., H.A.J. Versteegh, Y. van der Honing, J. Kogut, and A.W. Jongbloed. 2001. Nutritive Value of the Meat and Bone Meals from Cattle or Pigs in Broiler Diets. Poult. Sci. 80:1180–1189. doi:10.1093/ps/80.8.1180.

Karlsson, J., R. Spörndly, M. Lindberg, and K. Holtenius. 2018. Replacing human-edible feed ingredients with by-products increases net food production efficiency in dairy cows. J. Dairy Sci. 101:7146–7155. doi:10.3168/jds.2017-14209.

Karr-Lilienthal, L. K., L. L. Bauer, P. L. Utterback, K. E. Zinn, R. L. Frazier, C. M. Parsons, and G. C. Fahey. 2006. Chemical composition and nutritional quality of soybean meals prepared by extruder/expeller processing for use in poultry diets. J. Agric. Food Chem. 54:8108–8114.

Khiaosa-ard, R., A. Kaltenegger, E. Humer, and Q. Zebeli. 2022. Effect of inclusion of bakery by-products in the dairy cow's diet on milk fatty acid composition. J. Dairy Res. 89:236–242. doi:10.1017/s0022029922000619.

Knapp, J.R., G.L. Laur, P.A. Vadas, W.P. Weiss, and J.M. Tricarico. 2014. Invited review: Enteric methane in dairy cattle production: Quantifying the opportunities and impact of reducing emissions. J. Dairy Sci. 97:3231–3261. doi:10.3168/jds.2013-7234.

Koba, K., and T. Yanagita. 2014. Health benefits of conjugated linoleic acid (CLA). Obes. Res. Clin. Pr. 8:e525–e532. doi:10.1016/j.orcp.2013.10.001.

Kuhlman, T., and J. Farrington. 2010. What is Sustainability?. Sustainability 2:3436–3448. doi:10.3390/su2113436.

Lee, C., A. N. Hristov, K. S. Heyler, T. W. Cassidy, M. Long, B. A. Corl, and S. K. R. Karnati. 2011. Effects of dietary protein concentration and coconut oil supplementation on nitrogen utilization and production in dairy cows. J. Dairy Sci. 94:5544–5557.

Lee, C., A. N. Hristov, T. W. Cassidy, K. S. Heyler, H. Lapierre, G. A. Varga, M. J. de Veth, and R. A. Patton. 2012. Rumen-protected lysine, methionine, and histidine increase milk protein yield in dairy cows fed a metabolizable protein-deficient diet. J. Dairy Sci. 95:6042–6056.

Leonardi, C., and L.E. Armentano. 2003. Effect of Quantity, Quality, and Length of Alfalfa Hay on Selective Consumption by Dairy Cows. J. Dairy Sci. 86:557–564. doi:10.3168/jds.s0022-0302(03)73634-0.

Lock, A.L., C.L. Preseault, J.E. Rico, K.E. DeLand, and M.S. Allen. 2013. Feeding a C16:0-enriched fat supplement increased the yield of milk fat and improved conversion of feed to milk. J. Dairy Sci. 96:6650–6659. doi:10.3168/jds.2013-6892.

Lock, A. L. and de Souza, J. 2016. Fatty Acid Digestibility and Impacts on Responses of Dairy Cows. Pages 78-90 in Florida Ruminant Nutrition Symposium Vol 27, University of Florida, Gainesville, FL.

Lovarelli, D., J. Bacenetti, and M. Guarino. 2020. A review on dairy cattle farming: Is precision livestock farming the compromise for an environmental, economic and social sustainable production?. J. Clean. Prod. 262:121409. doi:10.1016/j.jclepro.2020.121409.

Maia, M.R.G., L.C. Chaudhary, L. Figueres, and R.J. Wallace. 2007. Metabolism of polyunsaturated FA and their toxicity to the microflora of the rumen. Antonie Van Leeuwenhoek. 91:303–314.

Maijala, K. 2000. Cow milk and human development and well-being. Livest. Prod. Sci. 65:1–18. doi:10.1016/s0301-6226(00)00194-9.

McCarthy, K.S., M. Parker, A. Ameerally, S.L. Drake, and M.A. Drake. 2017. Drivers of choice for fluid milk versus plant-based alternatives: What are consumer perceptions of fluid milk?. J. Dairy Sci. 100:6125–6138. doi:10.3168/jds.2016-12519.

Moharrery, A., M. Larsen, and M.R. Weisbjerg. 2014. Starch digestion in the rumen, small intestine, and hind gut of dairy cows – A meta-analysis. Anim. Feed Sci. Technol. 192:1–14. doi:10.1016/j.anifeedsci.2014.03.001.

Morgavi, D.P., E. Forano, C. Martin, and C.J. Newbold. 2010. Microbial ecosystem and methanogenesis in ruminants. Animal 4:1024–1036. doi:10.1017/s1751731110000546.

Naderi, N., G.R. Ghorbani, H. Erfani, and L.F. Ferraretto. 2022. Feeding Byproduct-Based Concentrates Instead of Human-Edible Feed Ingredients Increases Net Food Production and Improves Performance of High-Producing Holstein Cows. Animals 12:2977. doi:10.3390/ani12212977.

National Research Council. 2021. Nutrient Requirements of Dairy Cattle. 8th revised edition. National Academy Press, Washington, DC.

Oba, M., and M. S. Allen. 1999. Effects of brown midrib 3 mutation in corn silage on dry matter intake and productivity of high yielding dairy cows. J. Dairy Sci. 82:135–142.

Oba, M., and M.S. Allen. 2003. Effects of Diet Fermentability on Efficiency of Microbial Nitrogen Production in Lactating Dairy Cows. J. Dairy Sci. 86:195–207. doi:10.3168/jds.s0022-0302(03)73600-5.

Oltenacu, P., and D. Broom. 2010. The impact of genetic selection for increased milk yield on the welfare of dairy cows. Anim. Welf. 19:39–49. doi:10.1017/s0962728600002220.

Owens, F. N., R. A. Zinn, and Y. K. Kim. 1986. Limits to starch digestion in the ruminant small intestine. J. Anim. Sci. 63:1634–1348.

Owens, F.N., and M. Basalan. 2016. Rumenology 63–102. doi:10.1007/978-3-319-30533-2_3.

Palmquist, D.L., A.D. Beaulieu, and D.M. Barbano. 1993. Feed and Animal Factors Influencing Milk Fat Composition1. J. Dairy Sci. 76:1753–1771. doi:10.3168/jds.s0022-0302(93)77508-6.

Palmquist, D.L., A.L. Lock, K.J. Shingfield, and D.E. Bauman. 2005. Biosynthesis of conjugated linoleic acid in ruminants and humans. Pages 179-217. In: Advances in Food and Nutrition Research. Vol. 50. S.L. Taylor, (ed.). Elsevier Inc., San Diego, CA.

Pereira, P.C. 2014. Milk nutritional composition and its role in human health. Nutrition 30:619–627. doi:10.1016/j.nut.2013.10.011.

Peters, C.J., J. Picardy, A.F. Darrouzet-Nardi, J.L. Wilkins, T.S. Griffin, and G.W. Fick. 2016. Carrying capacity of U.S. agricultural land: Ten diet scenarios. Elementa 4:000116. doi:10.12952/journal.elementa.000116.

Piantoni, P., A.L. Lock, and M.S. Allen. 2013. Palmitic acid increased yields of milk and milk fat and nutrient digestibility across production level of lactating cows. J. Dairy Sci. 96:7143–7154. doi:10.3168/jds.2013-6680.

Pillai, O., and R. Panchagnula. 2001. Insulin therapies – past, present and future. Drug Discov. Today 6:1056–1061. doi:10.1016/s1359-6446(01)01962-6.

Plaizier, J.C., D.O. Krause, G.N. Gozho, and B.W. McBride. 2008. Subacute ruminal acidosis in dairy cows: The physiological causes, incidence and consequences. Vet. J. 176:21–31. doi:10.1016/j.tvjl.2007.12.016.

Poppi, D. P., D. J. Minson, and J. H. Ternouth. 1981. Studies of cattle and sheep eating leaf and stem fractions of grasses: III. The retention time in the rumen of large feed particles. Aust. J. Agric. Res. 32:123.

Rainer, L., and C.J. Heiss. 2004. Conjugated linoleic acid: health implications and effects on body composition. J. Am. Diet. Assoc. 104:963–968. doi:10.1016/j.jada.2004.03.016.

Reynolds, C.K. 2006. Production and metabolic effects of site of starch digestion in dairy cattle. Anim. Feed Sci. Technol. 130:78–94. doi:10.1016/j.anifeedsci.2006.01.019.

Riewe, M. E., and H. Lippke. 1970. Considerations in determining the digestibility of harvested forages. Pp. F1–FI7 in Proceedings of the National Conference on Forage Quality Evaluation and Utilization. Lincoln: Nebraska Center for Continuing Education.

Rotz, A., and C.A. Rotz. 2020. Environmental Sustainability of Livestock Production. Meat Muscle Biol. 4. doi:10.22175/mmb.11103.

Sanchez-Sabate, R., and J. Sabaté. 2019. Consumer Attitudes Towards Environmental Concerns of Meat Consumption: A Systematic Review. Int. J. Environ. Res. Public Heal. 16:1220. doi:10.3390/ijerph16071220.

Schiano, A.N., W.S. Harwood, P.D. Gerard, and M.A. Drake. 2020. Consumer perception of the sustainability of dairy products and plant-based dairy alternatives. J. Dairy Sci. 103:11228–11243. doi:10.3168/jds.2020-18406.

Schroeder, J. W. 1997. Corn Gluten Feed Composition, Storage, Handling, Feeding and Value. Accessed Jul. 03, 2024. https://library.ndsu.edu/ir/bitstream/handle/10365/4796/as1127.pdf

Schwab, C.G., T.P. Tylutki, R.S. Ordway, C. Sheaffer, and M.D. Stern. 2003. Characterization of Proteins in Feeds*. J. Dairy Sci. 86:E88–E103. doi:10.3168/jds.s0022-0302(03)74042-9.

Schwab, C.G., and G.A. Broderick. 2017. A 100-Year Review: Protein and amino acid nutrition in dairy cows. J. Dairy Sci. 100:10094–10112. doi:10.3168/jds.2017-13320.

Slominski, B. A., D. Boros, L. D. Campbell, W. Guenter, and O. Jones. 2004. Wheat by-products in poultry nutrition: Part I. Chemical and nutritive composition of wheat screenings, bakery by-products and wheat mill run. Can. J. Anim. Sci. 84:421–428.

Staples, C.R., C.L. Davis, G.C. McCoy, and J.H. Clark. 1984. Feeding Value of Wet Corn Gluten Feed for Lactating Dairy Cows1. J. Dairy Sci. 67:1214–1220. doi:10.3168/jds.s0022-0302(84)81426-5.

Swain, S. M., and L. E. Armentano. 1994. Quantitative evaluation of fiber from nonforage sources used to replace alfalfa silage. J.Dairy Sci. 77:2318–2331.

Takiya, C.S., C.M. Ylioja, A. Bennett, M.J. Davidson, M. Sudbeck, T.A. Wickersham, M.J. VandeHaar, and B.J. Bradford. 2019. Feeding Dairy Cows With "Leftovers" and the Variation in Recovery of Human-Edible Nutrients in Milk. Front. Sustain. Food Syst. 3:114. doi:10.3389/fsufs.2019.00114.

Tamminga, S. 1992. Nutrition Management of Dairy Cows as a Contribution to Pollution Control. J. Dairy Sci. 75:345–357. doi:10.3168/jds.s0022-0302(92)77770-4.

Thompson, A. 2008. Ingredients: Where Pet Food Starts. Top. Companion Anim. Med. 23:127–132. doi:10.1053/j.tcam.2008.04.004.

Thorning, T.K., A. Raben, T. Tholstrup, S.S. Soedamah-Muthu, I. Givens, and A. Astrup. 2016. Milk and dairy products: good or bad for human health? An assessment of the totality of scientific evidence. Food Nutr. Res. 60:32527. doi:10.3402/fnr.v60.32527.

Tullo, E., A. Finzi, and M. Guarino. 2019. Review: Environmental impact of livestock farming and Precision Livestock Farming as a mitigation strategy. Sci. Total Environ. 650:2751–2760. doi:10.1016/j.scitotenv.2018.10.018.

UN. 2023. Reducing food loss and waste: Taking Action to Transform Food Systems. Accessed Jul. 03, 2024. https://www.un.org/en/observances/end-food-waste-day#:~:text=the%20consumption%20level.-,An%20estimated%2017%20percent%20of%20total%20global%20food%20production%20is,in%20the%20global%20food%20system

USDA. 2024. Organic Agriculture Overview. Accessed Jul. 03, 2024. https://www.ers.usda.gov/topics/natural-resources-environment/organic-agriculture/

USDA. n.d. Food Loss and Waste. Accessed Jul. 03, 2024. https://www.usda.gov/peoples-garden/food-access-food-waste/flw#:~:text=In%20the%20United%20States%2C%20between,need%20is%20sent%20to%20landfills.

USDA National Agricultural Statistics Service. 2023. Census of Agriculture: National Statistics for Milk. Accessed Jul. 03, 2024. https://www.nass.usda.gov/Statistics_by_Subject/result.php?3F21A7A4-BB7F-3071-85A6-E9E204B8061C&sector=ANIMALS%20%26%20PRODUCTS&group=DAIRY&comm=MILK

van Soest, P. J., Robertson, J. B., & Lewis, B. A. 1991. Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. *Journal of Dairy Science*, *74*(10), 3583–3597. doi:10.3168/jds.S0022-0302(91)78551-2

van Soest, P. J. 1994. Nutritional Ecology of the Ruminant. 2nd ed. Ithaca, NY: Comstock.

VandeHaar, M.J., L.E. Armentano, K. Weigel, D.M. Spurlock, R.J. Tempelman, and R. Veerkamp. 2016. Harnessing the genetics of the modern dairy cow to continue improvements in feed efficiency1. J. Dairy Sci. 99:4941–4954. doi:10.3168/jds.2015-10352.

VandeHaar, M.J., and N. St-Pierre. 2006. Major Advances in Nutrition: Relevance to the Sustainability of the Dairy Industry. J. Dairy Sci. 89:1280–1291. doi:10.3168/jds.s0022-0302(06)72196-8.

Voelker, J.A., and M.S. Allen. 2003a. Pelleted Beet Pulp Substituted for High-Moisture Corn: 1. Effects on Feed Intake, Chewing Behavior, and Milk Production of Lactating Dairy Cows. J. Dairy Sci. 86:3542–3552. doi:10.3168/jds.s0022-0302(03)73959-9.

Voelker, J.A., and M.S. Allen. 2003b. Pelleted Beet Pulp Substituted for High-Moisture Corn: 2. Effects on Digestion and Ruminal Digestion Kinetics in Lactating Dairy Cows. J. Dairy Sci. 86:3553–3561. doi:10.3168/jds.s0022-0302(03)73960-5.

Waldroup, P. W., D. L. Whelchel, and Z. B. Johnson. 1982. Variation in nutrient content of samples of dried bakery product. Anim. Feed Sci. Technol. 7:419–421.

Walsh, M.C., and C. Gunn. 2020. Milk and Dairy Foods 347–369. doi:10.1016/b978-0-12-815603-2.00013-9.

Wathes, C.M., H.H. Kristensen, J.-M. Aerts, and D. Berckmans. 2008. Is precision livestock farming an engineer’s daydream or nightmare, an animal’s friend or foe, and a farmer’s panacea or pitfall?. Comput. Electron. Agric. 64:2–10. doi:10.1016/j.compag.2008.05.005.

White, R.R., and C.B. Gleason. 2023. Global contributions of milk to nutrient supplies and greenhouse gas emissions. Journal of Dairy Science 0. doi:10.3168/jds.2022-22508.

White, R.R., and M.B. Hall. 2017. Nutritional and greenhouse gas impacts of removing animals from US agriculture. Proceedings of the National Academy of Sciences 114:E10301–E10308. doi:10.1073/pnas.1707322114.

Wilderer, P.A. 2007. Sustainable water resource management: the science behind the scene. Sustain. Sci. 2:1–4. doi:10.1007/s11625-007-0022-0.

Wolf, C.A., G.T. Tonsor, M.G.S. McKendree, D.U. Thomson, and J.C. Swanson. 2016. Public and farmer perceptions of dairy cattle welfare in the United States. J. Dairy Sci. 99:5892–5903. doi:10.3168/jds.2015-10619.

Wolin, M.J. 1979. Advances in Microbial Ecology, Volume 3. Adv. Microb. Ecol. 49–77. doi:10.1007/978-1-4615-8279-3_2.

Yang, W.Z., and K.A. Beauchemin. 2006. Effects of Physically Effective Fiber on Chewing Activity and Ruminal pH of Dairy Cows Fed Diets Based on Barley Silage 1. J. Dairy Sci. 89:217–228. doi:10.3168/jds.s0022-0302(06)72086-0.

Zebeli, Q., J.R. Aschenbach, M. Tafaj, J. Boguhn, B.N. Ametaj, and W. Drochner. 2012. Invited review: Role of physically effective fiber and estimation of dietary fiber adequacy in high-producing dairy cattle. J. Dairy Sci. 95:1041–1056. doi:10.3168/jds.2011-4421.

APPENDIX: DIGESTIBILITY

Table A.1. Effect of BYP diet on nutrient digestibility.

	Treatment[1]		SEM	*P*-Values
Variable	CON	BYP		CON vs BYP
DMI (kg)	30.9	30.1	0.473	<0.01
NDF Digestibility (%)	45.3	45.9	0.92	0.68
Starch Digestibility (%)	99.4	99.1	0.11	0.12
CP Digestibility (%)	71.5	64.8	0.82	<0.01
Fat Digestibility (%)	77.5	66.6	1.64	<0.01

[1] Treatments were 1) control (CON); 2) by-product diet (BYP)

Apparent total tract digestibility was determined for the study. Samples of all feed ingredients and orts from each cow were collected daily for 5 d at the end of period 2 in each study. Samples of feed ingredients were composited for the 5 d, and orts were composited by cow for the 5 d. Feces were collected from each cow through palpation of the rectum or during defecation every 15 h over the same 5 d, resulting in 8 samples/cow. Feces were stored at -20°C until they were dried and composited on an equal DM basis. Diet ingredients, orts, and feces were dried at 55ºC for 72 h in a forced-air oven to obtain DM. Dried samples were then ground with a Wiley mill (6-mm screen; Arthur H. Thomas, Philadelphia, PA). All samples were analyzed by Cumberland Valley Analytical Services (Waynesboro, PA) for CP (method 990.03; AOAC, 2000), starch (Hall, 2009), and fat (method 2003.05; AOAC, 2006). NDF and indigestible NDF were determined according to Van Soest et al. (1991) modified to use Whatman 934-AH glass microfiber filters with 1.5-µm particle retention (Cytiva, Marlborough, MA). Indigestible NDF, estimated as NDF residue after 240 h in vitro fermentation, was used as an internal marker to predict fecal output (Cochran et al., 1986).

Results showed that there was no significant difference in NDF or starch digestibility between treatments. However, cows fed BYP experienced decreased CP and fat digestibility by 9.4% and

14.1%, respectively (both $P < 0.01$). Results on NDF and starch digestibility do not agree with literature investigating effects of by-product diets, where NDF digestibility increases and starch digestibility decreases with by-products (Karlsson et al., 2018; Erfani et al., 2024).

Research has shown that microbial populations that aid in digesting protein in the rumen also need an adequate supply of carbohydrates to sustain growth (Agle et al., 2010; Brandao and Faciola, 2019). Therefore, we could assume that the lower starch content of BYP negatively impacted CP digestibility, as less energy was available to support microbial growth in the rumen. Additionally, it has been documented that feeds high in fat can have detrimental effects on rumen microbial populations (Palmquist et al., 2005; Maia et al., 2007; Lock and de Souza, 2016). Perhaps substituting corn grain for bakery waste, a feed that is high in fat, could have had a negative effect on bacteria populations within the rumen as well. A high fat feed coupled with lower starch within the treatment diet could have been harmful to ruminal microbes, negatively impacting protein digestion.

It is also possible that there was not an adequate amount of physically effective fiber in the BYP diet to slow down passage rate in the rumen. Although we did not measure fecal consistency, we observed that cows on the BYP diet had loose and bubbly feces when compared to cows fed CON. Thus, we suggest that some of the by-product fiber was moving quickly past the rumen and being digested in the hind gut. Therefore, this could have had additional negative effects on protein and fat digestion.

Decreased CP digestibility in cows fed BYP could present additional environmental challenges. When ruminal ammonia nitrogen is not utilized by rumen microbes for protein synthesis, it is excreted from the animal as urine (Tamminga, 1992). Ammonia in animal excrements have been noted to be a danger to the environment due to their contribution to eutrophication, the excessive richness of nutrients in bodies of water that contributes to a lack of oxygen and marine animal death, and soil acidification (EPA, 2004). Decreased CP digestibility has been noted in other studies using higher proportions of by-products in diets (Karlsson et al., 2018; Erfani et al., 2024). This poses yet another environmental tradeoff associated with feeding dairy cattle a sustainably sourced diet and continues the conversation of whether or not such diets have a place in the future of sustainable dairy cattle production.