PHYSIOCHEMICAL AND NUTRIENT PROPERTIES AND TRUE NUTRIENT SUPPLY OF WHOLE OAT GRAINS IN RUMINANT SYSTEMS: EFFECT OF OAT VARIETIES AND TYPES (FEED TYPE VS. MILLING TYPE)

A Thesis Submitted to the
College of Graduate and Postdoctoral Studies
In Partial Fulfillment of the Requirements
For the Degree of Master of Science
In the Department of Animal and Poultry Science
University of Saskatchewan
Saskatoon

By

Ganqi Deng

PERMISSION TO USE

In presenting this dissertation in partial fulfillment of the requirements for a Postgraduate degree from the University of Saskatchewan, I agree that the Libraries of this University may make it freely available for inspection. I further agree that permission for copying of this dissertation in any manner, in whole or in part, for scholarly purposes may be granted by the professor or professors who supervised my dissertation work or, in their absence, by the Head of the Department or the Dean of the College in which my thesis work was done. It is understood that any copying or publication or use of this dissertation or parts thereof for financial gain shall not be allowed without my written permission. It is also understood that due recognition shall be given to me and to the University of Saskatchewan in any scholarly use which may be made of any material in my dissertation.

Requests for permission to copy or to make other uses of materials in this dissertation in whole or part should be addressed to:

Dean
College of Graduate and Postdoctoral Studies
University of Saskatchewan
116 Thorvaldson Building, 110 Science Place
Saskatoon, Saskatchewan S7N 5C9, Canada

Head
Department of Animal and Poultry Science
University of Saskatchewan
2D30 Agriculture Building, 51 Campus Drive
Saskatoon, Saskatchewan S7N 5A8, Canada

ABSTRACT

The general objectives of this study were to determine the effect of four varieties and two types of oats (feed type vs. milling type) on the physiological and nutrient properties and true nutrient supply in ruminant system as an alternative feed source for ruminants. This project was carried out in three major phases. In the first phase, results showed that CDC Nasser had highest EE, NPN and lowest ADL among four varieties ($P<0.05$). CDC Haymaker had highest CP content among four oat varieties ($P<0.05$), and the value of $iNDF_{120h}$ on CDC Haymaker were largest among four varieties. CDC Nasser had highest TDN and energy values among four varieties ($P<0.05$). Based on the CNCPS 6.5 model, the CC fraction of CDC Nasser was lowest among four varieties ($P<0.05$). In the second phase, results also showed that CDC Haymaker and Arborg had higher Kd of DM, CP, and starch than that of CDC Nasser ($P<0.05$), and these Kd values of CDC Nasser were much smaller than other oat varieties. The EDDM, EDCP, and EDST of CDC Nasser were smallest among varieties as well ($P<0.05$). Oat varieties also had significant impact on N/OM and ED_N/ED_OM, and CDC Arborg was closest to the optimal ratio of ED_N/ED_OM (25 g/kg). In the third phase, results revealed that CDC Nasser had lowest MREE, DVME, DVE and FMV based on the Dutch DVE/OEB system ($P<0.05$), and all the OEB values of oats were much larger than zero indicating had potential N losses in the rumen. As for the oat types, significant impact was observed on EE, CP, NPN, ADL, TDN, Kd of DM, starch and CP, BDM, EDDM, BST, EDST, TDDM, TDST, DVE, OEB and FMV between feed and milling type ($P<0.05$). Milling oats had higher non-fiber carbohydrate values, while feed oats had higher structure carbohydrate values and FMV comparing to milling oats. In conclusion, all the oat varieties could be a good feed source for the dairy cows. CDC Nasser had largest TDN and energy values on dairy cows. CDC Nasser was the optimal variety to replace the barley grains of rations of dairy cattle based on this study.

ACKNOWLEDGEMENTS

Firstly, I would like to thank my supervisor Dr. Peiqiang Yu for giving me the opportunity and valuable learning experience working in his team. Thank you very much for your patient guidance and help, valuable suggestions, support and encouragement during the study. I want to sincerely thank Zhiyuan Niu for his laboratory and skills training, unconditional support and kind assistance during the research and daily life. I would also like to acknowledge my advisory committee members, Dr. David Christensen, Dr. Herbert (Bart) Lardner and research chair Ryan Brook for all the academic suggestions, professional comments and guidance throughout the whole study. I also want to thank my work team fellows and all the friends for your help and life companion all the time. I really appreciate my families for your unconditional love and support no matter what I want to do and what choices I make. I would like to acknowledge the Government of Saskatchewan, the Prairie Oat Growers Association, the Ministry of Agriculture Strategic Research Chair in Feed R&D program, the Natural Sciences and Engineering Research Council, SaskMilk, Alberta Oat Growers, SaskOat, Manitoba Oat Growers, the University of Saskatchewan, and the Rayner Dairy Teaching and Research Facility for providing the funding and resources to develop this research.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ADF	Acid detergent fiber
ADICP	Acid detergent insoluble crude protein
ADL	Acid detergent lignin
AECP	Truly absorbed rumen endogenous protein in the small intestine
AMCP	Truly absorbed microbial protein in the small intestine
ARUP	Truly absorbed rumen undegraded protein in the small intestine (NRC dairy model)
BCP	Rumen bypass feed crude protein (DVE/OEB system)
BDM	Rumen bypass dry matter
BDNDF	Rumen bypass feed neutral detergent fiber
BST	Rumen bypass starch
CA4	Sugar (rapidly degradable carbohydrate fraction)
CB1	Starch (intermediately degradable carbohydrate fraction)
CB2	Soluble fiber (intermediately degradable carbohydrate fraction)
CB3	Digestible fiber (available neutral detergent fiber or slowly degradable carbohydrate fraction)
CC	Indigestible fiber (unavailable neutral detergent fiber)
CHO	Carbohydrate
CP	Crude protein
D	Degradable fraction
dBCP	Intestinal digestibility of rumen bypass protein
dBDM	Intestinal digestibility of rumen bypass dry matter
dBNDF	Intestinal digestibility of rumen bypass fiber

dBST	Intestinal digestibility of rumen bypass starch
DE_{p3x}	Digestible energy at a production level (3 × maintenance)
dIDP/dBCP	Intestinal digestibility of rumen bypass protein
DM	Dry matter
DPB	Degraded protein balance
DVEB	Truly absorbed bypass feed protein in the small intestine
DVE	Total truly digested protein in the small intestine (DVE/OEB system)
DVME	Truly absorbed rumen synthesized microbial protein in the small intestine
ECP	Rumen endogenous protein
ED_CHO	Effectively degraded carbohydrate
ED_N	Effectively degraded nitrogen
ED_OM	Effectively degraded organic matter
EDCP	Effective degraded crude protein
EDDM	Effective degraded dry matter
EDNDF	Effective degraded neutral detergent fiber
EDST	Effective degraded starch
EE	Ether extracts (crude fat)
FMV	Feed milk value
IADP/IDBCP	Intestinal digestible rumen bypass protein
IDBCP	Intestinal digestible rumen bypass protein
IDBDM	Intestinal digestible rumen bypass dry matter
IDBNDF	Intestinal digestible rumen bypass neutral detergent fiber
IDST	Intestinal digestible rumen bypass starch

$iNDF_{120h}$	undigestible neutral detergent fiber
IVDMD	In vitro dry matter disappearance
Kd	Degradation rate of degradable fraction
Kp	Passage rate
MCP_{RDP}	Microbial protein synthesized in the rumen based on rumen degraded protein
MCP_{TDN}	Microbial protein synthesized in the rumen based on available energy (total digestible nutrients at a protein level)
ME	Metabolizable energy
$ME_{p3\times}$	Metabolizable energy at a production level (3 × maintenance)
MP	Metabolizable energy (NRC Dairy model)
MREE	Microbial protein synthesized in the rumen based on available energy
MREN	Microbial protein synthesized in the rumen based on rumen degraded feed crude protein
NDF	Neutral detergent fiber
NDICP	Neutral detergent insoluble crude protein
NE_g	Net energy for gain
$NEL_{p3\times}$	Net energy for lactation at a production level (3 × maintenance)
NE_m	Net energy for maintenance
NFC	Non-fiber carbohydrate
N/OM	the ratio of nitrogen to organic matter
NPN	Non-protein nitrogen
OEB	Degraded protein balance (DVE/OEB system)
PA2	Soluble true protein (rapidly degradable true protein)

PB1	Insoluble true protein (moderately degradable true protein)
PB2	Fiber bound protein (slowly degradable true protein)
PC	Indigestible protein
RDNDF	Rumen degradable fiber
RDP	Rumen degradable protein
RUDM	Rumen undegradable dry matter
RUNDF	Rumen undegradable neutral detergent fiber
RUP	Rumen undegradable protein
T0	Lag time
tdCP	Truly digestible crude protein
TDDM	Total digestible dry matter
tdFA	Truly digestible fatty acid
$TDN_{1\times}$	Total digestible nutrients at a maintenance level
TDNDF	Total digestible fiber
tdNDF	Truly digestible neutral detergent fiber
tdNFC	Truly digestible non-fiber carbohydrate
TDP	Total digestible crude protein
TDST	Total digestible starch
U	Rumen undegradable fraction

1. GENERAL INTRODUCTION

In Canada, barley is the main cereal grain for cattle rations, and oat grains have not been used widely in cattle diets. Compared to barley grains, oat grains have higher percentage of hull ranged from 20 to 30% (Crosbie et al., 1985). Therefore, oat grains have higher indigestible lignin contents. However, this situation was changed from the early 21st century because the Crop Development Center of University of Saskatchewan bred a new type of oat variety named LLH-HOG oat with low lignin content and high oil content. Since then, the oat production has gradually increased and maintained in a steady state in recently years. Nasser oat used in this study is pretty similar with LLH-HOG oat variety, and it also has low lignin and high oil contents comparing to other oat varieties. In addition, oat grains also have higher lipid content than other cereal grains. It can provide more energy per unit than that of carbohydrates or protein, which could be better supported and satisfied with lactating dairy cows that needs substantial energy contents to keep a high level of productivity.

Canada is one of the largest producers of oat, and Canada's oat production was ranked second in the world in 2022, after EU-27. The prairies of Western Canada produce more than 90% of the country's oat, so development of domestic and international market for oat producers and oat related industries is a key to maintain and increase business, maximize profit, and provide economic return and benefit to prairie oat producers. The cost of grains has more than doubled in the past few years, posing a serious threat to the economic competitiveness. Therefore, it is necessary to use a systematic approach to find the best oat cereal varieties that have the highest milk value (FMV) and highest nutrient supply for high producing dairy cows, and that can improve digestive behaviors or FMV. Additionally, it is also important to develop alternative strategies to efficiently utilize oat grains and find a maximum replacement level to common barley or corn with oat grain because of the increasing price of barley. Any level of replacement could maximize economic return and benefit prairie oat growers while simultaneously supporting market development of oat grain nationally and internationally. Beyond this, it has been found that replacing barley grains with oat grains in dairy cow diets can keep the milk production at the same level (McKay et al., 2019) or even increase milk production based on previous production studies (Ekern et al., 2003; Fuhr, 2006; Martin & Thomas, 1988; Vanhatalo et al., 2008), although the milk fat and protein concentrations may be reduced. According to an in vitro study by Fan et al. (2020), they found that oat diets had 8.9% lower CH_4 emissions comparing to barley-based diets. Ramin et al. (2021) also reported that replacing barley with oat in the diet of dairy cow could mitigate the methane production, which didn't have any negative effects on the productivity at the same time. Studies to reduce methane enteric methane emissions from cattle have been increasing recently. Reports showed that there was 16% of global methane emissions coming from ruminant animals, and 73% of the methane emissions was from the livestock, represented by beef cattle (35%), dairy cows (30%), pigs and birds (20%), and small ruminants and buffalos (15%) (Islam & Lee, 2019; Opio et al., 2013). As the world's population increases along with an increasing demand for milk and meat products, the amount of methane production is still increasing. Dairy Farmers of Canada also set a goal to reach net-zero greenhouse gas (GHG) emissions from dairy production by 2050. Finding optimal oat variety to replace barley in the diets of dairy cow or beef cattle without negative impacts on production could help Canada achieve this goal, and this also contributes to look for new strategies to mitigate methane emissions.

To select optimum oat variety, the chemical composition and nutrition value of different oat varieties need to be accessed. The in situ and in vitro procedure are used for evaluating the rumen degradation kinetics and intestinal digestibility of primary nutrients. The newly revised DVE/OEB system, National Research Council (NRC)-2001 and Cornell Net Carbohydrate and Protein System (CNCPS) can be applied for obtaining metabolic information and truly digestible nutrient supply to dairy cows that provides more references for formulating balanced diets for ruminants.

The objectives of this study were to mainly compare different oat varieties and types on physiochemical and nutrient properties and true digestible nutrient supply, and select an optimal oat variety applying to ruminant systems. This project was carried out in three major phases. In the first phase, the effects of oat varieties and types on physiochemical and nutrient profiles were investigated. In the second phase, the effects of oat varieties and types on N to energy synchronization, rumen degradation kinetics and intestinal digestibility of primary nutrients like dry matter (DM), crude protein (CP), neutral detergent fiber (NDF), and starch were determined. In the third phase, the effects of oat varieties and types on metabolic characteristics and truly digestible nutrient supply to dairy cows were evaluated. It was hypothesized that different oat varieties and types would have significantly different physiochemical and nutritional characterization and have great impact on the nutrient utilization and availability to dairy cows with expecting that feed types would have higher TDN, FMV and metabolizable protein (MP) than milling type.

2. LITERATURE REVIEW

2.1 Production of Oat in Western Canada and All Around the World

Over the last decade, the production of oat has been approximately 23-25 million tons per year. In 2022, the world production of oat was 25.05 million tons and EU-27, Canada, and Russia were the top three with 7.6, 4.6 and 3.8 million tons, respectively (Index Mundi, 2023). The global production of oat as a cereal grain ranked sixth in 2022, after corn, wheat, rice (milled), barley and sorghum (FAO & US Department of Agriculture., 2023). Compared to other cereal grains (such as maize, rice, barley and so on), its global production is much lower, it accounts for 1% of the worldwide cereal production (Stewart & McDougall, 2014). But it is one of the most economically important cereal grains. Actually, there are many factors affecting the yields of oat, such as climate, cultivars, and advancements of agriculture in different regions (Singh & Upadhyaya, 2015). In Canada, the production of oat was 4.654 million tons in 2022, and from that 4.333 million tons was just from Western Canada. Saskatchewan's oat production reached 2.378 million tons in 2022, accounting for more than half of western Canada's production. The oat production of Western Canada has been on the rise since 2015 but with a huge drop in 2021 because of drought (Figure 2.1).

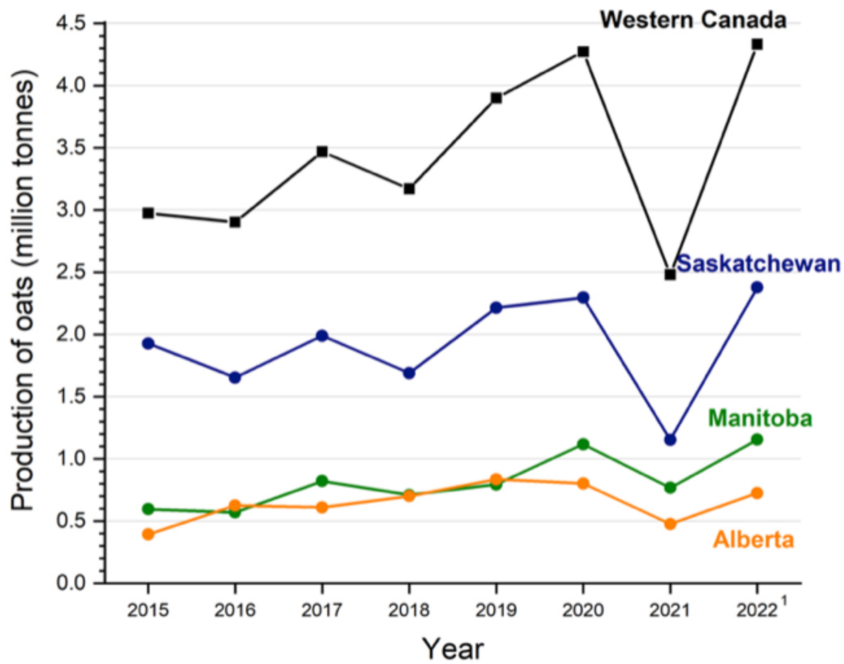

Figure 2.1. Yearly comparison of total oat production in Western Canada, SK: Saskatchewan, MB: Manitoba, AB: Alberta, BC: British Columbia (Canadian Grain Commission, 2022).

2.2 General Information of Oat

2.2.1 Background and history of oat

Oat (*Avena sativa L.*) is a cereal grain crop that originated in the Mediterranean area and Europe. According to archaeological discoveries, the earliest domestication of oat was in central Europe which dates back to the beginning of the modern era (Zohary et al., 2012). At the same time, they also appeared in China (Bernard Rene, 1997). In the sixteenth to seventeenth centuries, they were introduced to South America, North America, and Austria by the Spaniards and the English (Murphy & Hoffman, 1992). When oat was introduced to Canada, it was primarily used for feeding horses and other livestock, but also for human consumption. Studies have shown that eating oat has various health benefits, including prevention of cardiovascular diseases (Ho et al., 2016; Thies et al., 2014; Whitehead et al., 2014) and even cancer (Boffetta et al., 2014; Shen et al., 2016). However, the oat acreage declined steadily as mechanization in agriculture increased and reliance on horses decreased in the 1970s (Small, 1999). At one time, the planting area was occupying up to 6.8 million hectares but now it is just 1 million hectares. In addition, oat also has an advantage over wheat, barley or other cereals because they are better adapted to the acidic soil, cool and humid climates while they are very sensitive to heat and lack of water during seed germination and maturation (Murphy & Hoffman, 1992). The oat plant was usually 1-1.5 m and requires 90-115 days to mature. On the other hand, oat has a higher concentration of phytochemical and certain nutrients (e.g., fatty acids, beta-glucan, phenolic compounds) when compared to other cereal grains (Givens et al., 2004). Oat, wheat, and barley have the same origin, but the domestication of oat occurred much later than barley and wheat.

2.2.2 Oat structure and composition

Oat grain has a complicated matrix that contains the hull and groat (caryopsis) (Figure 2.2). The groat consists of a bran, germ, and endosperm (Figure 2.3). Oat is a good source of energy with a high level of lipids relative to other cereal grains, and is rich in mineral elements and vitamins such as potassium, calcium, phosphorus, and Vitamin E (Welch, 1995). The endosperm accounts for 70-80% of kernel weight, while the bran and germ consist of the other 20-30% of the kernel weight depending on the environment and varieties (White, 1995). The outermost layer is the coarse bran or hull, which is rich in cellulose, hemicellulose, lignin and other cell wall components like minerals, and β-glucan (Welch, 1995). Hemicellulose, cellulose, and lignin are insoluble in water, and they are structural carbohydrates belonging to polysaccharides group. Frolich and Nyman (1988) also observed some monosaccharides such as glucose and xylose, arabinose and so on. In a study by Thompson et al. (2000), they reported that ash, neutral detergent fiber (NDF), acid detergent fiber (ADF), lignin, crude protein (CP) from 10 different oat varieties ranged from 47-73, 799-882, 425-496, 13-77, and 23-45 g/kg DM, respectively. They also observed an inverse relationship between lignin content and in vitro dry matter disappearance (IVDMD). AC Assiniboia oat hull with lowest lignin content of 13 g/kg DM had highest IVDMD of 682 g/kg DM while Triple Crown oat hull had highest lignin content of 77 g/kg DM but with lowest IVDMD of 331 g/kg DM. Jung et al. (1997) also found there was a negative relationship between the digestibility of forage DM and NDF and lignin content, and digestibility of feed decreased with increasing lignin content. These same relationships were also reported in other studies (Crosbie et al., 1985; Garleb et al., 1991).

Under the hull, there are pericarp, seed coat, aleurone, and sub-aleurone layers. The cells in the aleurone and sub-aleurone are wrapped by the cell walls and are difficult to digest, the cell wall of endosperm cells is thin but rich in β-glucans (Grundy et al., 2018).

Further down is the endosperm, which is connected to sub-aleurone layers. There are two kinds of starch in the endosperm, which are single and compound starch granule, respectively (Webster & Wood, 2011). The protein and lipid content of oat increases from the center of endosperm to the periphery of oat, while the starch content gradually increases from the sub-aleurone to the center of endosperm (Webster & Wood, 2011). Usually, the structure with hull removed is called groat, and the carbohydrates in the groat are non-structural carbohydrates and water soluble, mainly starch and sugars. According to the study by Mustafa et al. (1998), they observed the soluble fractions (DM) of hull-less oat had highest soluble fractions (464 g/kg DM) and effective degradability (868 g/kg) comparing to hulled oat and barley. But when feeding hull-less oat to the ruminants, the dry matter intake also decreased at the same time, because less fiber in the diet can result in decreased the fiber digestion because of decreased rumen pH which may cause the risk of rumen acidosis. Therefore, oat groat is ideal to feed monogastric animals such as pig and chicken, or for human consumption.

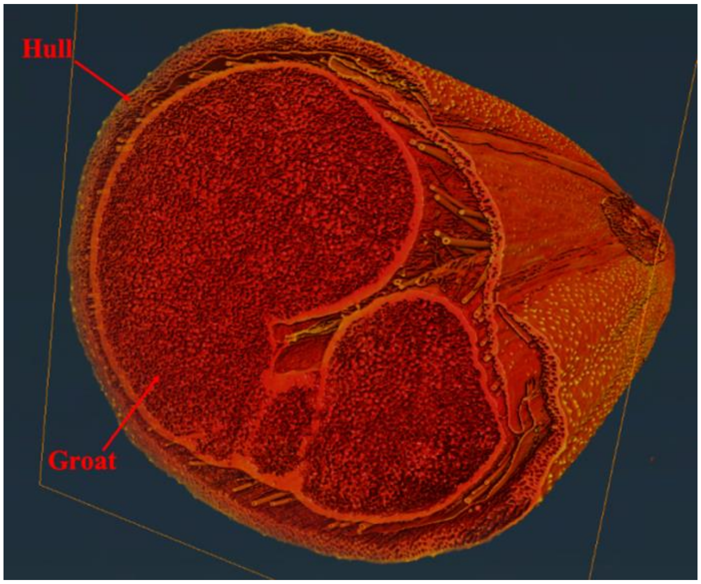

Figure 2.2. The cross section of Nasser oat taken from synchrotron μCT at BMIT beamline in Canadian Light Source (unpublished).

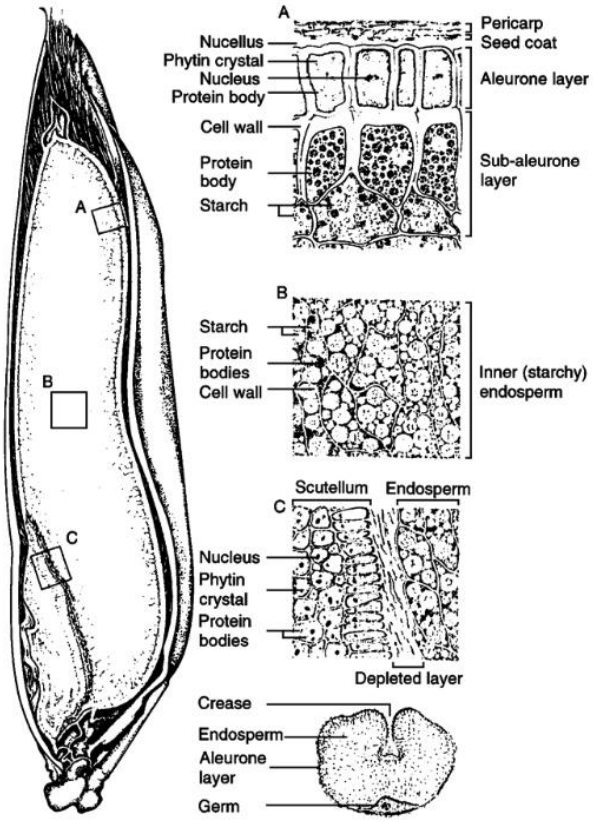

Figure 2.3. Inner structure of oat grain. On the left, it presents the longitudinal section of oat. Zoom in boxes A, B, C in the oat grain, which correspond to parts A (bran), B (endosperm), C (germ) on the right. It shows the cross section of oat grain on the lower right (modified from White, 1995).

2.2.3 Oat β-glucan

The most common consumption form of oat for humans are oat flakes, flour, and purified β-glucan. In addition, oat are a major source of soluble fiber since they are high in β-glucans in comparison to other cereal grains (Stewart & McDougall, 2014). In Cornell Net Carbohydrate and Protein System, the feed is divided into eight parts. β-glucan is soluble fiber which included in CB2 fraction. Oat β-glucan is a complex non-starch polysaccharide composed of β-D-glucopyranosyl units, which are connected by β-(1→4) and β-(1→3) linkages (Sun et al., 2020). β-glucan can be extracted from yeast, bacteria, fungi, and from cereal grains such as oat, barley and rye (GÁLFI, 2012). Oat β-glucan is mainly located in the endosperm cell wall (Bai et al., 2019). According to previous studies, consuming oat regularly could reduce blood cholesterol levels and coronary heart disease (CHD) incidence, it has been shown that this is due to the presence of β-glucans (Brown et al., 1999; Othman et al., 2011; Tiwari & Cummins, 2011). It has been reported that oat β-glucan can weaken the blood glucose and insulin response in the blood after a meal, lowering the total cholesterol and low density of lipoprotein (LDL) cholesterol in the blood, which improves the levels of high-density lipoprotein (HDL) cholesterol and blood lipids (Daou & Zhang, 2012). When oat β-glucan is stimulated macrophages can increase the number of immunoglobulins, NK, killer T cells etc., and increase immune function, thus improving resistance to cancer and other infectious disease (Daou & Zhang, 2012). Food and Drug Administration of the USA and Joint Health Claims Initiative of UK have approved health claims which they state that intake of 3g of soluble oat β-glucan per day is associated with reduced blood cholesterol levels and CHD incidence (Food and Drug Administration, HHS., 2008; Joint Health Claims Initiative, 2004). Ferreira et al. (2018) concluded that feeding oat β-glucan extract with a dietary supplement of 10g/kg for dogs can effectively reduce the total blood cholesterol concentration, LDL-c, VLDL-c and improve the overall total tract apparent macronutrient digestibility. A study by Błaszczyk et al. (2015) showed that feeding a certain amount of oat β-glucan to rats suffering from inflammation can reduce the lipid peroxide, 7-ketocholesterol concentration, and GSSG activity in the spleen, which also indicates that oat β-glucan has antioxidant properties. In general, supplementation of oat β-glucan can improve the oxidative stress parameters in the spleen of rats. ElSawy et al. (2015) found that it could significantly improve the average weight gain (AWG) of broiler chicks treated with 25 μg yeast β-glucan/ml (YBG/ml, drinking water/day), and the length of intestinal villi became significant longer when compared to the control group. A study by Uchiyama et al. (2012) demonstrated that the solid non-fat content in the milk of Holstein cows increased with the addition of β-glucan (produced by Aureobasidium pullulans), and the calf's intestinal flora had obvious changes.

2.2.4 The main characteristics of oat in this study

There are mainly two oat types in Canada which are classified as either milling or feed type. Milling oat is mainly used for human consumption while feed type of oat is used as animal feed. That leads to two oat types having differences in desired chemical characteristics. For example, milling oat grains had higher β-glucan content (usually more than 4.5%) and protein percent but had lower oil percent than feed oat grains. This type of oat grains also has clear white color and low hull content, and they don't have bitter flavor. Feed oat grains usually had higher hull content than milling oat but with lower lignin content (Winfield et al., 2007). Oat grains are good source of supplemental feed for animals, and they have higher fiber contents compared to barley and wheat, which reduced the chances of rumen acidosis. However, they also have some similarities, and both have high grain plumpness, hectolitre weight and groat percent. Figure 2.4 displays the planting area of various oat types in western Canada from 2017 to 2022. Overall, milling oat accounted for the highest production, with an average of 84.2 million tons, and feed and forage oat accounted for an average of 6.6 million tons.

The main characteristics of four oat varieties are presented in Table 2.1. Summit is a high yielding white milling oat with the best multi-gene stem and crown rust resistance in these four varieties. It has high plump, low thins, low hull, higher β-glucan, and high protein levels. In addition, Summit has good resistance to smut (FPGenetics, 2014; SaskSeed Guide, 2023). These advantages make it a competitive genotype. The amount of Summit oat being planted has gradually increased since 2015 in Western Canada, which accounts for 18.12% of the total areas seeded with milling oat (Figure 2.5). CDC Arborg oat is an early maturing and high-yielding white milling oat. It also has good characteristics such as low thins, high β-glucan, good groat percentage, good lodging resistance and so on, giving it a promising market in the future (FPGenetics, 2020; SaskSeed Guide, 2023). CDC Arborg oat is one of the newest milling genotypes, and it has been widely planted since 2019. In 2020, the total area planted of CDC Arborg accounted for 4% of the total areas seeded with milling oat in Western Canada, and it reached 13.85% in 2022 (Figure 2.5). CDC Haymaker is a spring oat that has higher forage yield (an increase of 7%) and better forage quality (improved digestibility for animals) compared with its parentage (CDC Baler). It is a feed type, and it has large plump seed and tall stature with late maturity. However, the lodging tolerance of CDC Haymaker is fair and it can be susceptible to the smut (SaskSeed Guide, 2023; SeCan, 2016). CDC Haymaker oat was bred by Dr. Brian Rossnagel and Dr. Aaron Beattie from Crop Development Center, University of Saskatchewan. It is ideal for double cropping, swath grazing, bale grazing, silage and forage blends with peas, or other cover crops. As for CDC Nasser oat, it is a selection that cultivar without rough awns and it is a feed type. In the early 21st century, the Crop Development Center of University of Saskatchewan bred a variety named CDC SO-1 oat with low lignin and high oil content. CDC Nasser oat is similar to this variety, which also has high oil and low lignin with excellent digestibility for cattle. Usually, oat grains have higher indigestible lignin contents. CDC Nasser oats have a light amber color based on grandparent color from low lignin Assiniboia cultivar. Low lignin varieties traditionally have dark grains.

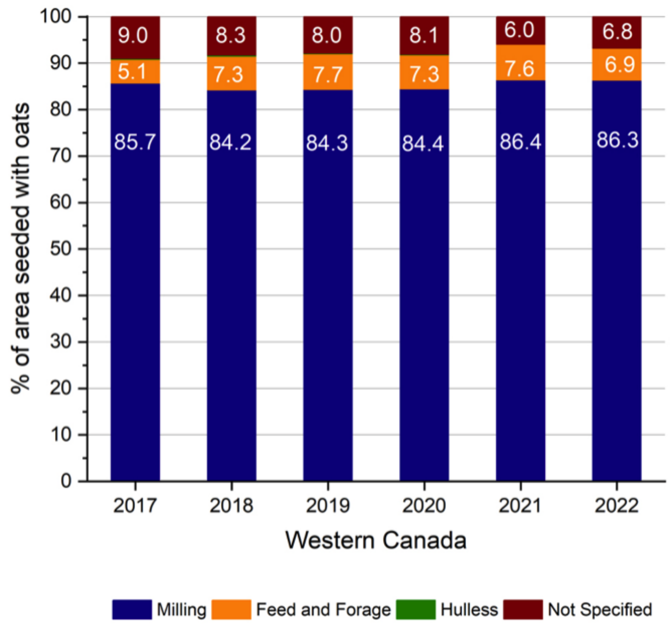

Figure 2.4. Distribution of oat type as percentage (%) of total area seeded with oat in Western Canada from 2017 to 2022 (Canadian Grain Commission, 2022).

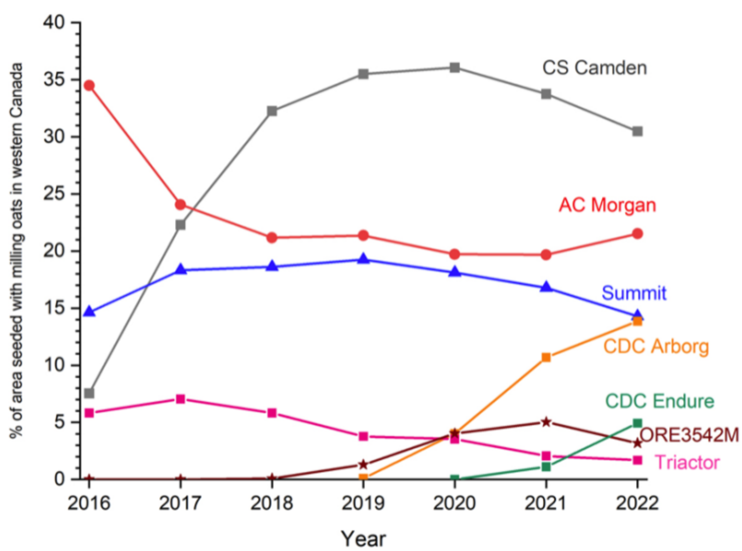

Figure 2.5. Planting area of varieties of milling oat in Western Canada (Canadian Grain Commission, 2022).

Table 2.1. The main characteristics of four oat varieties.

Variety	Test Weight (g/0.5L)	% Hull	Hull Color	% Plump	Height (cm)	Resistance To			
						Lodging[1]	Stem Rust[2]	Crown Rust	Smut
CDC Arborg	250	20.1	White	85	108	VG	S	I	R
Summit	256	21.6	White	81	94	G	I	I	R
CDC Haymaker	225	24.9	White	87	111	G	S	S	MR
CDC Nasser	233	21.8	White	79	106	G	MS	S	R

Adapted from SaskSeed Guide (2023).
[1]: VG = Very Good, G = Good, F = Fair, P = Poor, VP = Very Poor;
[2]: R = Resistant, MR = Moderately Resistant, I = Intermediate Resistance, MS = Moderately Susceptible, S = Susceptible.

2.3 Oat Grains as Feed in Ruminant Animals

In North American, feeding concentrate ingredients to cattle is a common practice, and barley and corn are the main cereal grains for the diet of cattle, especially lactating dairy cows, backgrounding and finishing cattle. These cattle need high requirement of energy for maintenance, milk production, fetal development, and growth. Barley grain will be mainly added into the diets of these cattle as concentrates to meet their energy needs in Canada. For example, the grain can achieve 85-90% DM basis in finishing stage of cattle, and the concentrate percentage in lactating dairy cows is around 50% DM basis. In the early twentieth century, oat was still the main cereal grain for dairy cows in Canada. But the oat production has been declining for decades until the early 21st century. During the last decade, the oat production has been gradually increasing while it is still much smaller than that of barley. So, there are limited studies conducted to evaluate the production performance of dairy cows with oat grain in the diet. Most studies have been conducted comparing oat to other cereal grains in complete rations (Fisher & Logan, 1969; Fuhr, 2006; Gozho & Mutsvangwa, 2008; Martin & Thomas, 1988; Moran, 1986; Ramin et al., 2021; Tommervik & Waldern, 1969; Yu et al., 2010), and some focused on dehulled oat (Fant et al., 2021; Fearon et al., 1996, 1998; Petit & Alary, 1999), and some focused on the protein or fat content (Ekern et al., 2003; Schingoethe et al., 1982).

In a recent study by Ramin et al. (2021), they assessed the effects of gradually replacing barley with oat grain on diet digestibility, milk production, enteric methane in lactating Nordic Red dairy cows that received a total mixed ration of forage (58%) to concentrate (42%) in Sweden. The grain supplements (30% of diet DM) were made up of 100% oat, 67% oat and 33% barley, 33% oat and 67% barley, and 100% barley, and the dairy cows were fed a grass silage-based diet. Their results found that gradually replacing barley with oat had no significant impact on the dry matter intake, body weight, milk yield, milk component yield, and energy-corrected milk (ECM) yield while the milk concentration of milk protein and milk fat were decreased linearly with increasing inclusion of oat. The lactose and feed efficiency (ECM/DMI) didn't differ between treatments. The digestibility of OM, NDF, and potentially digestible NDF were linearly decreased with increasing inclusion of oat. As for the methane emissions and methane intensity, they were linearly decreased from 467 to 445 g/d and 14.7 to 14 g/d, respectively, with increasing inclusion of oat. They concluded that replacing barley with oat in the diet of dairy cows based on a grass silage diet could mitigate the methane emissions without any adverse effects on productivity, but it will depend on the differences in the concentration of indigestible NDF and fat content between barley and oat.

In a study conducted by Yu et al. (2010) in Canada, they evaluated the effects of partially replacing barley and corn with CDC SO-1 oat on performance of lactating dairy cows. The CDC SO-1 oat was bred by Crop Development Center of University of Saskatchewan, which had low lignin and high oil content. Eight lactating multiparous Holstein cows were randomly assigned four diet treatments based on TMR with forage to concentrate ratio of 50 to 50 in a double 4 × 4 Latin Square design. Four diets were as follows: T1, 100% barley; T2, 42% raw CDC SO-1 oat and 58% barley; T3, 42% micronized CDC SO-1 oat and 58% barley; T4, raw CDC SO-1 oat and corn blend replacing 100% barley. Their results revealed that the dietary treatments had no significant impact on DMI, body weight, total milk yield, fat corrected milk (FCM), energy corrected milk (ECM), the protein and lactose of total milk yield and feed efficiency (ratio of DM intake to FCM yield). Dairy cows fed the T3 diet had higher fat content of total milk yield than cows fed T1 diet, and dairy cows fed T2 diet had higher fat content value of total milk yield than that of T1 diet, although there was no significant difference between them. There was also no significant difference on all the milk composition such as fat, protein, lactose, milk urea nitrogen (MUN) among dietary treatments. The author concluded that it increased the yield of milk fat and FCM when replaced 42% barley as a concentrate supplement in a TMR diet.

In another Canadian study conducted by Fuhr (2006), they compared the performance of Holstein lactating dairy cows fed 50:50 forage to concentrate (DM basis) TMR with grain sources of LLH-HOG oat, Derby oat, and CDC Dolly barley. LLH-HOG oat had low lignin and high oil content and Derby oat was a common variety. They determined the chemical composition of the TMR samples from three diet treatments, and they were similar in most of aspects such as CP and gross energy. Oat TMR diets provided more NDF and ADF contents than that of the barley TMR diet. Performance results showed that dietary treatments had no significant impact on the total DMI, body weight change, milk yield, milk fat, 3.5% FCM and lactose. The dairy cows fed oat grains source diets had longer eating time per day, however, dietary treatments had no significant impact on the ruminating time, laying time, and chewing time per day. Moreover, there were significant differences on milk protein and milk urea among dietary treatments. They came the conclusions that cows fed a TMR with LLH-HOG oat grain source was more satisfactory for milk production compared to conventional oat variety (Derby oat). As well, LLH-HOG oat would be an excellent cereal grain to replace barley for feeding lactating dairy cows in Western Canada.

Gozho and Mutsvangwa (2008) assessed the production performance of dairy cows fed barley, oat, corn or wheat grains as the main source of dietary carbohydrates on a TMR basis, and results showed that the four dietary treatments had no significant impact on the DMI and milk yield. Dairy cows fed barley and oat TMR diets had similar percentage of fat and protein, and fat corrected milk. Ekern et al. (2003) reported that dairy cows fed an oat TMR diet produced significantly higher milk than cows fed a barley TMR diet, while the milk fat and protein concentrations were lower in dairy cows fed oat TMR diet. So, most of these studies showed that replacing barley with oat grain in the diets of dairy cow diets had no impact on the milk production or even increase the milk production, although the milk fat or protein may be reduced.

2.4 Feed Evaluation Methods

2.4.1 Chemical evaluation of feed ingredients

Understanding the nutritional value of feeds is very important, especially for high-producing cows that require specific nutrient and energy levels for milk production, tissue maintenance, and optimal fetal development (NRC, 2001). When the chemical composition of the feedstuffs is known, this can help us formulate the diets for animals more accurately, and predict the production and performance of livestock. That will conserve the nutrients and save lots of money. The most common chemical analysis of feeds is proximate analysis, which was devised in 1860s by German scientists Hunneberg and Stohman. This analysis method involves a series of analytical procedures that partition the feed into 6 fractions with water (moisture), ash (minerals), crude protein (CP), crude fat (ether extract, EE), crude fiber, and nitrogen-free extract (NFE) (Van Soest & Robertson, 1979). Moisture is determined by placing samples in the drying oven (either 105-135℃ for 2 hours or 55℃ for 48 hours) to thoroughly remove all moisture from the test feed sample. Dry matter percentage is calculated by dividing the weight of dry test feed by the weight of wet feed. Ash is determined by putting the samples in a muffle furnace (500-600℃) for five hours. Crude protein is determined by using the Kjeldahl method, and then total nitrogen is multiplied by a protein factor of 6.25. Crude fat is determined by acid hydrolysis method, extracting test feed with diethyl ether in a Soxhlet extractor for several hours. Crude fiber is evaluated by the detergent fiber system, and nitrogen-free extract will be equal to 100 minus the amount of the above five composition values. The details and references would be reviewed in the Chapter 3.5.2.

2.4.2 Energy evaluation of feeds

Energy is critical for tissue maintenance and growth, milk synthesis, gestation and meat production in dairy and beef cattle. So, quantifying the energy value of feeds offered to cattle is important in determining the amount of feed needed per day as energy utilization is affected by activity and stressors. On the other hand, different feeds have different physical and chemical compositions that affects the dry matter intake and digestibility of animals thereby affecting the actual energy available in the feed. The dynamic NRC Dairy model (2001) covers animal and feed factors and provides equations to predict energy values of feeds for dairy cows (Eastridge, 2002). In this model, the energy values are expressed by using total digestible nutrient (TDN) on the basis of actual feed composition data, and TDN at maintenance is obtained from values of digestible protein (tdCP), digestible non-fiber carbohydrate (tdNFC), digestible neutral detergent fiber (tdNDF), and digestible fat (tdFA) (NRC, 2001).

For the high producing dairy cows or high milking cows, their dry matter intake will be increased to three or four-fold of maintenance intake while their feed digestibility is reduced, leading to decreases in the energy values of the diet. So, the NRC model will discount the digestibility when calculating the digestible energy at production level of intake (DE_p). Net energy values of lactation (NE_L) are obtained from the actual DMI and whole diet digestibility, and metabolizable energy (ME_p) at production levels of intake is calculated on the basis of DE_p basis. The Beef NRC model (1996) is used for determining the net energy for gain (NE_g) and net energy of maintenance (NE_m).

2.4.3 Application of Cornell Net Carbohydrate and Protein System V6.5 in feed evaluation

Cornell Net Carbohydrate and Protein System (CNCPS) is a mathematical model using animal, feed composition, and environmental information to precisely evaluate cattle nutrient requirements and supply, growth, pregnancy, and lactation, which is also a very useful model for diet formulation, evaluation, and adjustment (Fox et al., 2004; Van Amburgh et al., 2010; 2013). The first version was published in a series of papers describing the CNCPS with a kinetics submodel to quantitatively predict degree of rumen degradation, total metabolizable energy and protein supply, microbial protein synthesis, and intestinal absorption from 1992 to 1993 (Fox et al., 1992; O'Connor et al., 1993; Russell et al., 1992; Sniffen et al., 1992). Before CNCPS model, the NRC guidelines were commonly used by researchers, nutritional consultants, and producers. However, this model had some limitations at that time: 1) such as microbial growth in the rumen was mainly associated with TDN instead of available carbohydrate; 2) model underestimated microbial protein production at a low TDN intake; 3) the growth of rumen microbes was constant; 4) carbohydrate fermentation rates were not considered in conjunction with protein degradation rates; 5) model failed to classify rumen microbial populations according to the fermentation characteristics (Russell et al., 1992). Then the CNCPS model was developed because it considered these factors and quantified the rumen fermentation and nutrient availability, and this model has been improved and refined over the 30 years. The current version of CNCPS 6.5 had been available since 2015 (Higgs et al., 2015; Van Amburgh et al., 2015), and it was reported that it will be updated to version 7 in the next few years. The feed library and prediction equations were refined in the CPCPS 6.5 for more precise analysis. This model was extensively used in the ruminant industries to evaluate and formulate diets. The CNCPS model more accurately refines the prediction of nutrient supply and animal requirements, not only for research purpose, but also to directly impact farm production and save more resources (Higgs et al., 2015; Lanzas et al., 2007; Tylutki et al., 2008; Van Amburgh et al., 2015).

2.4.4 Using In Situ Technique to assess rumen degradation kinetics of feed ingredients

It is important to determine the rate and extent of degradation of feed for evaluating the nutritional value and quality of the feed. To determine the rate and extent of degradation of feeds, 2 methods can be adopted: 1) measuring the amount of certain nutrients that enters the abomasum; 2) incubating artificial-fiber bag with feeds in the rumen for a fixed time period using cannulated cattle (Ørskov & McDonald, 1979). The nylon bag technique proposed by Orskov and McDonald (1979) and modified by Tamminga et al. (1994) is a very valuable and convenient method to determine the rate and extent of degradation of main components such as DM, CP, starch in the rumen. This information is very critical to help understand the feed degradation in the rumen, and predict the rumen bypass of nutrients. For example, feeds have a rapid rumen degradation rate that probably induce digestive disorders and then can lead to rumen fermentation problems (Humer & Zebeli, 2017).

2.4.5 Evaluating intestinal digestibility of feed industry by Three-Step In Vitro Technique

It is important to know protein digestion in the small intestine as there is an increase of undegraded intake protein in the diet. Protein absorption in the small intestine depends on the amount of microbial protein and dietary nitrogen reaching the duodenum and its intestinal digestibility, and different feed ingredients has different intestinal digestibility of rumen bypass protein (Calsamiglia & Stern, 1995; Stern et al., 1985; Waltz et al., 1989). It is very expensive and labor intensive to determine the intestinal digestion of rumen undegradable protein (RUP) using in vivo methods, and it also requires lots of canulated animals. So, Calsamiglia and Stern (1995) proposed an in vitro method to analyze the intestinal digestibility of RUP, and it was modified by Gargallo et al. (2006) and adapted it to the Daisy^{II} incubator in 2006. This method was also adopted as a reference method in the NRC (2001) publication. In conclusion, this in vitro technique is considered to be a reliable method and can be implemented in the laboratory with a significant reduction in labor and cost. Moreover, it can also be used as a feed quality control method and could determine the value of ruminant feed protein and protein supplements in the ruminant diets (Calsamiglia & Stern, 1995).

2.4.6 Prediction of truly digestible protein supply to small intestine in dairy cattle

2.4.6.1 DVE/OEB system

In 1991, a new protein evaluation system, DVE/OEB system, was proposed by Tamminga et al. (1994) in the Netherlands to replace the digestible crude protein system (DCP), which was designed to help farmers feed dairy cows more accurately to their protein needs, thereby preventing avoidable nitrogen losses, as well as more accurately predicting milk protein yields. In the DVE/OEB system, each feed has a DVE value and OEB value, standing for truly absorbed protein in the small intestine and degraded protein balance, respectively. DVE is composed of three parts including feed protein escaping from rumen and is truly digested and absorbed in the small intestine (DVEB), microbial protein from rumen digested and absorbed in the small intestine (DVME), and endogenous protein lost during the digestion process (ENDP). So, the equation is DVE = DVEB + DVME – ENDP. OEB is the difference between potential microbial protein synthesis on the base of available rumen degradable protein (MREN) and on the base of available rumen degradable energy extracted from fermentation (MREE), and the equation is OEB = MREN – MREE. The positive OEB value indicates the potential loss of N from the rumen while the negative OEB value indicates N shortage in the rumen and it would impair the microbial protein synthesis (Tamminga et al., 1994; Yu, 2005). In general, DVE and OEB values are mainly used to assess the protein requirements at different physiological stages and to formulate dairy feeds accordingly (Yu, et al., 2003).

2.4.6.2 NRC-2001 model

NRC-2001 model is the seventh version of Nutrient Requirements for Dairy Cattle and was updated in 2001 (NRC, 2001). In this model, there are also two parameters to predict the truly absorbed protein in the small intestine, which are metabolizable protein (MP) and rumen degraded protein balance (DPB), respectively. It is very similar with the DVE/OEB system but has different concepts and factors used in the equations. Specifically. MP is mainly composed of truly absorbed microbial protein in the small intestine (AMCP), truly absorbed rumen undegradable protein in the small intestine (ARUP), and truly absorbed endogenous protein in the small intestine (AECP). So, the equation is MP = AMCP + ARUP + AECP. As for the DPB, it is primarily calculated on the basis of rumen degraded feed protein and microbial protein synthesized in the rumen. The equation is DPB (g/kg of DM) = RDP – 1.18 (MCP_{TDN}) (Ban, 2016; Maria, 2018; NRC, 2001; Ying, 2015; Yu, et al., 2003).

2.4.7 Feed Milk Value determination in dairy cattle

Feed efficiency is known as the ability of cows converting the feed nutrients into milk, which represents kilograms of milk produced per kilogram of dry matter consumed (Heinrichs et al., 2018). Feed milk value (FMV) can be evaluated based on metabolic characteristics from NRC-2001 and DVE/OEB system. Feed milk value (kg milk/kg DM) = 0.67 × MP (g/kg DM) / 33, where MP is metabolizable protein in NRC system and it equals to DVE value in the DVE/OEB system; 0.67 is the assuming a metabolizable protein efficiency during lactation, and 1 kg of milk contains 33 g of protein (Guevara, 2020; NRC, 2001).

2.5 Research Objectives and Hypotheses

2.5.1 Research Objective

Long term:

- To assist developing alternative or low-cost feeding strategies for high-producing dairy cow systems by utilizing alternative feed resources (recently developed cool-season oat grain varieties).
- To assist exploring the optimal variety of oat grain which may replace barley grain in the diet.

Short term:

- To study physiochemical and nutrient profiles: Compare oat varieties (CDC Arborg, CDC Haymaker, CDC Nasser, Summit) and types (feed type vs. milling type).
- To determine rumen degradation kinetics and intestinal digestibility of nutrients: Compare oat varieties (CDC Arborg, CDC Haymaker, CDC Nasser, Summit) and types (feed type vs. milling type).
- To investigate the difference of oat varieties (CDC Arborg, CDC Haymaker, CDC Nasser, Summit) and types (feed type vs. milling type) in metabolic characteristics and truly digestible nutrient supply, and feed milk value (FMV) based on DVE/OEB and NRC-2001 systems.

2.5.2 Research Hypothesis

In general:

- Different oat varieties (CDC Arborg, CDC Haymaker, CDC Nasser, Summit) and types (feed type vs. milling type) would impact the physiochemical and nutrient characteristics of oat grain grown in Western Canada with expecting that feed types (CDC Haymaker and CDC Nasser) would have higher nutritive value than milling type.

In details:

- Different oat varieties and types would result in differences of the rumen degradation kinetics, intestinal digestion of nutrients, hourly effective degradability of N to organic matter, and CDC Nasser oat would have higher effective degradability of nutrients than other oat varieties.
- Feed types (CDC Haymaker and CDC Nasser) would have higher total digestible nutrients (TDN), Feed milk value, metabolizable protein (MP), and truly digestible nutrient supply than milling type (CDC Arborg and Summit).

3. PHYSIOCHEMICAL AND NUTRIENT PROFILE STUDY: EFFECT OF OAT VARIETIES AND TYPES (FEED TYPE VS. MILLING TYPE)

3.1 Abstract

The objective of this project was to assess the impact of four oat varieties and types (feed type vs. milling type) on their physiochemical and nutrient profiles. Four oat varieties (CDC Haymaker, CDC Nasser, CDC Arborg, and Summit) from 3 consecutive years (2018, 2019, 2020) were used for chemical analysis, energy profiles and protein and carbohydrate subfractions evaluations following the AOAC standard methods, NRC-2001 model, and CNCPS 6.5 model, respectively. The experiment design was an RCBD design with oat varieties as a fixed effect and harvested year as a random block effect. The MIXED model of SAS 9.4 was used for statistical analysis with significant level declared at $P < 0.05$ and trends at $0.05 \leq P < 0.1$, and SAS contrasts were used for comparing oat types (feed type vs. milling type). Results showed that CDC Nasser oat had the highest ether extract (EE), and non-protein nitrogen (NPN) value of the four varieties (4.05, and 3.74 %DM, P<0.01) while the value of crude protein (CP) of CDC Nasser oat was smallest but had a similar CP content with CDC Arborg and Summit oat (14.69, 15.78, and 15.40 %DM). CDC Haymaker oat had the highest CP content among the four varieties (17.57 %DM, P<0.05). CDC Arborg, Summit and CDC Haymaker oat had similar acid detergent lignin (ADL) in the four oat varieties (3.60, 3.29, and 4.19 %DM), yet had higher ADL content compared to CDC Nasser oat (1.63 %DM, P<0.01). More importantly, CDC Haymaker oat had higher indigestible neutral detergent fiber at 120 h ($iNDF_{120h}$, %DM) compared to Summit oat (P<0.05), and had similar $iNDF_{120h}$ content with CDC Arborg and CDC Nasser oat. There was a significant difference in EE, CP, NPN, total CHO, and ADL values between feed type and milling type (P<0.05). CDC Haymaker oat had the highest truly digestible crude protein (tdCP) among the four oat varieties

(17.42 %DM, P<0.05). CDC Nasser oat also had the highest total digestible nutrients (TDN) and all energy values compared to other three oat varieties (P<0.05), while CDC Arborg and Summit oat had similar tdCP, TDNs and energy values. In addition, CDC Haymaker oat had higher PA2 (6.62 vs. 5.37 %DM) and PB1 (10.18 vs. 8.72 %DM) than that of CDC Nasser (P<0.05) although they were the same oat types, and the indigestible fiber fractions (CC) of CDC Nasser oat was lowest among these four varieties (5.04 %CHO or 3.93 %DM, P<0.05). CDC Haymaker also had higher RDPA2, RDPB1, total RDP, RUPA2, RUPB1, total RUP fractions than that of CDC Nasser oat (P<0.05). Milling type had relatively higher CP and total CHO contents than milling oat but feed oat had higher energy values. In conclusion, CDC Nasser oat could be an important source of grain to replace barley in the ration of dairy cattle.

3.2 Introduction

Canada is the leader in global oat market and oat production. The oat production was 4.6 million tons in Canada ranked second after EU-27 in 2022, which has grown gently in the last decade (Statistics Canada, 2023). In Western Canada alone, oat production reached 4.3 million tons, and Saskatchewan's oat production reached 2.4 million tons that was more than 50% of Canadian oat making Saskatchewan the largest oat producing area in the world (Canadian Grain Commission, 2022). Oat was introduced to Canada in the early 17th century by European settlers, and it was the main feed crop for horses at that time. These horses were the main power for farming and transportation work until the spread of mechanization changed this situation. Oat can also be adapted to acidic soil, cool and humid climate easier compared to wheat, barley, and other cereal grains. The oat plant is usually 1-1.5 meters tall and requires 90-115 days to mature (Givens et al., 2004). Oat is also used for human consumption. Oat has higher phytochemical and certain nutrients like fatty acids, beta-glucan, phenolic compounds when compared to other cereal grains. Studies reported that eating oat had many health benefits, such as prevention of cardiovascular disease (Ho et al., 2016; Thies et al., 2014; Whitehead et al., 2014), cancer prevention (Boffetta et al., 2014; Shen et al., 2016), reducing blood cholesterol and coronary heart disease (CHD) incidence (Brown et al., 1999; Othman et al., 2011; Tiwari & Cummins, 2011). The concentration of β-glucan in oat is also higher than other cereal grains, and it is mainly located in the cell wall of endosperm (Bai et al., 2019). These health benefits may be due to the higher concentration of β-glucan in the oat. The US Food and Drug Administration and UK Joint Health Claims Initiative have also approved these health claims that β-glucan could reduce the blood cholesterol levels and CHD incidence if an individual takes 3g of soluble oat β-glucan per day (Food and Drug Administration, HHS., 2008; Joint Health Claims Initiative, 2004).

There are four oat varieties that were used in the current study. CDC Nasser oat is a newest variety with low lignin and high oil content than other normal oat varieties, which is similar with the CDC SO-1 oat variety. Both can provide higher digestible energy for cattle. CDC Haymaker oat has higher forage yield with an increase of 7%, better forage quality, and large plump seed but it is also susceptible to the smut (SeCan, 2016). Summit oat is a popular and milling oat with best multi-gene crown rust resistance. The oat has high plump, low hull, higher β-glucan, and high protein content making it a competitive genotype (FPGenetics, 2014). CDC Arborg oat is a new milling variety and widely planted since 2019. Its planted area already reached 13.85% of area seeded with milling oat in 2022 in Western Canada almost to the acreage of the Summit oat although it is a new variety (Canadian Grain Commission, 2022). It is characterized by high-yielding, high β-glucan content, good groat percentage, and good lodging resistance (FPGenetics, 2020).

In this phase, the chemical composition profiles of the oat varieties were determined, and then the energy values and protein and carbohydrate fractions based on CNCPS system were evaluated to compare the differences among oat varieties and types.

3.3 Study Objectives

To determine the effect of oat variety and type (feed type vs. milling type) on chemical characteristics, nutrients profile, total digestive nutrients, metabolic energy profiles, protein and carbohydrate subfractions.

3.4 Study Hypothesis

Chemical profiles, metabolic and net energy profiles, protein and carbohydrate subfractions would differ among oat varieties and between feed type and milling type with CDC Nasser having highest nutrient content (TDN) and highest energy values.

3.5 Materials and Methods

The University of Saskatchewan Animal Care Committee approved the animal study under the Animal Use Protocol No. 19910012 and animals were cared for and handled in accordance with the Canadian Council of Animal Care regulations (CCAC, 1993).

3.5.1 Sample Treatments and Preparation

Three different varieties of oat grain (CDC Haymaker, CDC Nasser, and CDC Arborg) were supplied by Dr. Aaron Beattie from the Crop Development Center (CDC), University of Saskatchewan, Canada. One variety (Summit) was developed by Agriculture and Agri-Food Canada, Cereal Research Center (AAFC-CRC), Winnipeg, MB. CDC Haymaker is a feed type with an average 24.9% of hull structure. Summit oat already is a popular milling type while CDC Arborg is newer milling type, with average 21.6% and 20.1% of hull, respectively. CDC Nasser oat has 21.8% of hull, which is a feed type (SaskSeed Guide, 2023). These four varieties of oats were grown in the same Crop Development Center research fields and harvested from three consecutive years (2018, 2019, 2020), 12 samples in total, were used in this study. The growth and management practices are in the reference (SaskSeed Guide, 2023).

Before chemical analysis all these samples were ground to pass through a 1 mm screen using a Retsch ZM 200 (Retsch Inc, Haan, Germany).

3.5.2 Chemical Analysis

The ground samples were used for chemical analysis. These parameters were determined, which included DM (AOAC official method 930.15), OM, CP (AOAC official method 984.13), sugars (AOAC official method 974.06), EE (AOAC official method 920.39), Ash (AOAC official method 942.05). The acid detergent fiber (ADF), neutral detergent fiber (NDF), and acid detergent lignin (ADL) were analyzed using ANKOM F57 filter bags (ANKOM Technology Corp., Fairport, NY) following the procedure of Van Soest et al. (1991). Cellulose (Cellulose = ADF – ADL) and Hemicellulose (Hemicellulose = NDF – ADF) were estimated according to NRC (2001). The neutral detergent insoluble crude protein (NDICP) and acid detergent insoluble crude protein (ADICP) were determined using the NDF (without sodium sulfide) and ADF residues following the methods of Licitra et al. (1996). Soluble crude protein (SCP) was analyzed by the incubating samples at 39 ℃ with borate-phosphate buffer and then filtering through Whatman filter paper (#54) according to Roe et al. (1990). Non-protein nitrogen (NPN) was determined by using the method in Litcitra et al. (1996). Starch was analyzed by a Megazyme Total Starch Kit (Megazyme International Ltd., Wicklow, Ireland), following the α-amylase/amyloglucosidase method (AOAC 996.11, AACC 76.13, ICC standard method No. 168). Total carbohydrate (CHO) was calculated as CHO = 100 – EE – CP – ash (NRC, 2001), and Non-fiber carbohydrate was calculated as NFC = 100 – (NDF – NDIP) – EE – CP – ash (NRC, 2001). uNDF was analyzed according to the procedure of Lopes et al. (2015). Procedure details were as follows, around 1 g of previous ground samples through 1 mm screen were weighted in duplicate into 5 × 3.3 cm Ankom bags with 6 μm pore size (Sefar American Inc., Depew, NY), and they were sealed twice. Then they were put into the rumen for incubating 120 h. They were removed from rumen after 120 h of incubation and were washed in cold tap water 6 times and oven dried at 55℃ for 48 h. Bags were weighted to collect the residue values and used for NDF analysis (Van Soest et al., 1991).

3.5.3 Determination of energy values

Based on the chemical analysis results, the energy values were determined for both dairy and beef cattle by using the NRC summative approach (NRC, 1996, 2001). For dairy cattle, the following parameters were evaluated, including truly digestible non-fiber carbohydrates (tdNFC), truly digestible crude protein (tdCP), truly digestible neutral detergent fiber (tdNDF), total digestible nutrients at 1 × maintenance level ($TDN_{1\times}$), total digestible nutrients at 3 × maintenance level ($TDN_{3\times}$), and digestible energy at a maintenance level ($DE_{1\times}$), digestible energy of production at 3 × maintenance level ($DE_{p3\times}$), metabolizable energy of production at 3 × maintenance level ($ME_{p3\times}$), net energy of production at 3 × maintenance level ($NE_{Lp3\times}$). As for beef cattle, metabolizable energy (ME), net energy for maintenance (NE_m), and net energy for gain (NE_g) were determined according to NRC-Beef (1996).

3.5.4 Determination of protein and carbohydrate subfractions (CNCPS 6.5)

According to Higgs et al. (2015) and Van Amburgh et al. (2015), protein was partitioned five sub-fractions, which were ammonia (PA1) with a degradation rate (Kd) of 200 %/h, soluble true protein (PA2) with a Kd of 10-40 %/h, insoluble true protein (PB1) with a Kd of 3-20 %/h, fiber-bound protein (PB2) with a Kd of 1-18 %/h, and indigestible protein (PC), respectively. More specifically, the calculations were as follows: PA1 = ammonia × (SP/100) × (CP/100), PA2 = SP × CP/100 −

PA1, PB1 = CP − (PA1 − PA2 − PB2 − PC), PB2 = (NDICP − ADICP) × CP / 100, PC = ADICP × CP / 100. While carbohydrate was subdivided into volatile fatty acids (CA1) with a Kd of 0 %/h, lactic acid (CA2) with a Kd of 7 %/h, other organic acids (CA3) with a Kd of 5 %/h, sugars (CA4) with a Kd of 40-60 %/h, starch (CB1) with a Kd of 20-40 %/h, soluble fiber (CB2) with a Kd of 20-40 %/h, available neutral detergent fiber (CB3) with a Kd of 1-18 %/h, and indigestible fiber (CC).

3.5.5 Statistical analysis

In this project, the treatment design was a one-way structure. Experimental design was an RCBD design with varieties as a fixed effect, and years as a random block effect. Statistical analysis of chemical profiles, energy values, protein and carbohydrate fractions were performed using MIXED procedure of SAS version 9.4 (SAS Institute, Inc., Cary, NC, US). RCBD model was in use during analysis:

$$Y_{ij} = \mu + T_i + \beta_j + e_{ij},$$

where Y_{ij} was an observation of the dependent variable ij; μ was the population mean of variable; T_i was the effect of varieties as a fixed effect (i = 1 to 4); β_j was the block effect of year (j = 2018, 2019, 2020), and e_{ij} was the random error associated with the observation ij. Multi treatment comparison was carried out using Tukey's method and SAS orthogonal contrast was used for comparison between the feed type and milling type oat. Significance was declared at $P<0.05$ and tendency at $0.05 \leq P \leq 0.10$.

3.6 Results and Discussion

3.6.1 Effect of oat varieties and types (feed type vs. milling type) on chemical nutrient profiles

The effect of oat varieties and types (feed type vs. milling type) on chemical composition profiles is presented in Table 3.1. Results showed that CDC Nasser oat had a significant difference in ether extract (EE) in these four varieties (P<0.01), and CDC Nasser oat had higher EE contents compared to other varieties (4.05 %DM), which was similar with the results of Tosta et al. (2019). They also reported that CDC Nasser oat had the highest EE concentration compared to other oat varieties, even though the EE contents of CDC Nasser oat in our study was lower than theirs (Tosta et al., 2019). Besides, there was a significant difference in EE contents between the milling type (CDC Arborg and Summit oat) and feed type (CDC Nasser oat) (P<0.01), and that was also same with Tosta et al.'s result. As for the dry matter (DM), ash and organic matter (OM) contents, no differences were found among these four varieties and between milling and feed types.

In the protein profiles, oat varieties had significant impact on crude protein (CP) content, and CDC Haymaker oat had highest CP content among four varieties (17.57 %DM, P<0.05). CDC Arborg, Summit and CDC Nasser oat had similar CP content (15.78, 15.40 and 14.69 %DM). There was also significant difference in CP content between milling type and feed type. Tosta et al. (2019) also found oat types had significant impact on CP content between feed type and milling type. In addition, there was a significant difference in non-protein nitrogen (NPN) among varieties and between oat types (P<0.05), and CDC Nasser oat had highest NPN in these four varieties (3.74 %DM or 25.54 %CP). For other protein profile parameters including soluble crude protein (SCP, %CP), neutral detergent insoluble crude protein (NDICP, %CP) and acid detergent insoluble crude protein (ADICP, %CP), oat varieties and types had no significant impact on them. The values of SCP were similar with Prates & Yu (2017) and NRC (2021), but they were smaller than Tosta's (2019). The CP, NDICP and ADICP values from our study were also similar with Tosta (2019), while these values were larger compared with NRC (2021), especially the CP values.

For most of oat varieties, the percentage of hull in oat is more than 25% or even up to a third of the whole grain while it is around 12% in barley grain (Crosbie et al., 1985; Harris, 1949). There are mainly structure carbohydrates that are indigestible such as lignin in the hull. According to the study, the DMI and ADG of steers were still linearly decreased with increasing inclusion ration of low lignin hull and high oil groat (Arya, 2010). In order to minimize the limitations, the new variety of oat, CDC Nasser, was bred by Crop Development Center, University of Saskatchewan, Canada. CDC Nasser oat is feed type oat, which has higher fat content and lower lignin content comparing to other oat varieties (Prates & Yu, 2017). In our study, CDC Nasser oat had strong significant difference in acid detergent lignin (ADL) comparing to other varieties but with lowest ADL content among these four varieties (1.63 %DM or 5.77 %NDF, $P<0.05$). CDC Arborg, Summit and CDC Haymaker oat had similar ADL content (3.60, 3.29 and 4.19 %DM). There was also a significant difference in ADL content between milling type and feed type oat ($P<0.05$). Moreover, varieties affected the indigestible neutral detergent fiber at 120h significantly, more specifically, CDC Haymaker had higher iNDF (%DM) content than that of Summit oat (25.26 vs. 18.00 %DM, $P<0.05$), and CDC Haymaker had similar iNDF content with CDC Arborg and CDC Nasser oat (25.26, 19.75, and 18.21 %DM). No significant difference was found on iNDF content between milling type and feed type. Tosta (2019) observed that CDC Nasser oat had lowest uNDF (%DM) content comparing with CDC Arborg and CDC Ruffian oat ($P<0.05$) but the samples were incubated in situ about 288h, and the uNDF value of CDC Nasser oat was even lower than CDC Austenson barley although there was no significant difference between them. The uNDF values of the oat were relatively larger in our study, and probably attributing to different incubation time.

Oat varieties and types had no significant impact on the starch, sugar, neutral detergent fiber (NDF), acid detergent fiber (ADF), hemicellulose, cellulose, non-fiber carbohydrate (NFC) and non-structural carbohydrate. However, oat varieties and types had significant impact on the total carbohydrates (CHO) ($P<0.05$). CDC Arborg, CDC Haymaker and CDC Nasser oat had similar

CHO contents, and CDC Arborg and CDC Haymaker oat had higher CHO contents than CDC Haymaker ($P<0.05$). The study of Ramin et al. (2021) showed that dry matter intake, milk yield, body weight, and energy corrected milk yield were not affected by the gradual replacement with 100% barley, 67% barley and 33% oat, 33% barley and 67% oat, and 100% oat (grains supplements, 30% of diet DM). With increasing the ratio of oat in the diet, the CH_4 emissions and intensity decreased from 467 to 445 g/d, and 14.7 to 14.0 g/kg energy-corrected milk (ECM), respectively. The digestibility of organic matter and neutral detergent fiber, and metabolizable energy decreased linearly with increasing ratio of oat. It was probably that the higher ADL and content EE in oat decreased the digestibility of OM and NDF, which then decreased the methane emission.

Table 3.1. Effect of oat varieties and type (feed type vs. milling type) on chemical composition profiles.

Items	Oat variety: CDC Arborg (Milling)	Oat variety: Summit (Milling)	Oat variety: CDC Nasser (Feed)	Oat variety: CDC Haymaker (Forage)	SEM	P value	Contrast P value Milling Type vs Feed Type
Basic chemical							
DM (%)	90.93	90.84	91.20	91.00	0.274	0.587	0.211
Ash (%DM)	3.38	3.27	3.34	3.48	0.097	0.521	0.870
EE (%DM)	1.82^{b}	2.20^{b}	4.05^{a}	1.85^{b}	0.094	<0.01	<0.01
OM (%DM)	96.62	96.73	96.66	96.52	0.097	0.521	0.870
Protein profile							
CP (%DM)	15.78^{b}	15.40^{b}	14.69^{b}	17.57^{a}	0.293	0.002	0.035
SCP (%DM)	5.20^{ab}	5.74^{ab}	5.37^{b}	6.62^{a}	0.347	0.016	0.043
SCP (%CP)	39.17	37.20	36.70	37.66	2.121	0.591	0.380
NPN (%DM)	2.60^{b}	2.45^{b}	3.74^{a}	2.43^{b}	0.466	0.046	0.013
NPN (%CP)	16.37^{b}	15.89^{b}	25.54^{a}	13.83^{b}	2.865	0.015	0.005
NDICP (%DM)	0.89	0.73	0.60	0.78	0.074	0.072	0.030
NDICP (%CP)	5.67	4.73	4.09	4.42	0.450	0.116	0.061
ADICP (%DM)	0.34	0.37	0.26	0.39	0.054	0.395	0.195
ADICP (%CP)	2.16	2.37	1.77	2.22	0.304	0.577	0.228
Carbohydrate profile							
CHO (%DM)	79.02^{a}	79.14^{a}	77.92^{ab}	76.98^{b}	0.404	0.026	0.042
Starch (%DM)	46.85	47.89	47.60	42.84	2.354	0.452	0.938
Starch (%NFC)	95.61	88.68	97.09	95.57	6.726	0.791	0.544
Sugar (%DM)	2.53	2.40	2.33	2.43	0.273	0.895	0.572
Sugar (%NFC)	5.13	4.45	4.76	6.05	0.574	0.373	0.965
NFC (%DM)	49.22	54.02	49.22	44.93	2.066	0.104	0.348
NFC (%CHO)	62.29	68.25	63.15	58.38	2.545	0.153	0.494
NSC (%DM)	49.38	50.29	49.93	45.27	2.494	0.492	0.975
Fibre profile							
NDF (%DM)	30.69	25.84	29.30	30.74	2.041	0.348	0.691
ADF (%DM)	15.76	13.54	14.27	16.41	1.297	0.428	0.819
ADF (%NDF)	51.54	52.62	48.84	53.65	2.840	0.673	0.379
ADL (%DM)	3.60^{a}	3.29^{a}	1.63^{b}	4.19^{a}	0.228	<0.01	<0.01
ADL (%NDF)	12.18^{a}	13.11^{a}	5.77^{b}	14.17^{a}	1.039	0.002	0.001
Hemicellulose (%DM)	14.38	11.94	14.69	13.95	1.360	0.515	0.385
Cellulose (%DM)	11.82	9.89	12.38	11.83	1.248	0.544	0.349
$iNDF_{120h}$ (%DM)	19.75^{ab}	18.00^{b}	18.21^{ab}	25.26^{a}	1.616	0.038	0.722

SEM: standard error of mean; $^{a-b}$ Means with the different letters in the same row are significant different ($P < 0.05$); Multi-treatment comparison: Tukey method; DM: dry matter; EE: ether extract (crude fat); OM: organic matter; CP: crude protein; SCP: soluble crude protein; NPN: non-protein nitrogen; NDICP: neutral detergent insoluble crude protein; ADICP: acid detergent insoluble crude protein; ADF: acid detergent fiber; ADL: acid detergent lignin; NDF: neutral detergent fiber; NFC: non-fiber carbohydrate; CHO: carbohydrate; NSC: non-structural carbohydrate; $iNDF_{120h}$: indigestible neutral detergent fiber at 120 h.

3.6.2 Effect of oat varieties and types (feed type vs. milling type) on energy values

As we know, digestible energy (DE) equals gross energy minus energy lost in feces (fecal energy), and metabolizable energy equals digestible energy minus urinary energy, and gaseous energy losses (National Academies of Sciences, Engineering, and Medicine., 2016). Total digestible energy (TDN) is similar with digestible energy, which is to express the energy requirement of animals. Starch is the major energy component in the grain and is placed in endosperm. Microbes in the rumen can penetrate the grains and digest them to produce volatile fatty acids (Ørskov, 1986). The effect of different oat varieties and types (feed type vs. milling type) on truly digestible nutrients, total digestible nutrients (TDN) and energy profiles is showed in Table 3.2. According to the results, there was a significant difference in truly digestible crude protein (tdCP) among oat varieties ($P<0.05$), and CDC Haymaker had highest tdCP content in these four varieties (17.42 %DM, $P<0.05$). CDC Arborg, Summit and CDC Nasser oat had similar tdCP content (15.65, 15.25, and 14.58 %DM). Significant difference was also found on tdCP content between milling type and feed type of oat. In addition, these oat varieties had similar truly digestible non-fibre carbohydrate (tdNFC) contents and truly digestible neutral detergent fibre (tdNDF) contents. There was significant difference in the total digestible nutrient at one time maintenance and at three times maintenance ($TDN_{1\times}$ and $TDN_{3\times}$) among these oat varieties and between milling type and feed type oat ($P<0.05$). More specifically, CDC Nasser oat had the highest $TDN_{1\times}$ (81.91 %DM, $P<0.05$) and $TDN_{3\times}$ (75.22 %DM, $P<0.05$). Summit oat had higher $TDN_{1\times}$ (78.16 vs. 73.18 %DM) and $TDN_{3\times}$ (71.78 vs. 67.21 %DM) than CDC Haymaker oat ($P<0.05$), but had similar $TDN_{1\times}$ (75.52 %DM) and $TDN_{3\times}$ (69.35 %DM) with CDC Arborg oat.

As mentioned before, CDC Nasser oat is bred to get lower lignin in the hull and higher fat content to expect having a higher energy value comparing to other oat varieties. In our study, there was significant difference in digestible energy at one time maintenance ($DE_{1\times}$) on dairy, digestible energy at production level of intake (3×) ($DE_{p3\times}$) on dairy, metabolizable energy at production level of intake (3×) ($ME_{p3\times}$) on dairy, net energy for lactation at production level of intake (3×) ($NE_{pL3\times}$) on dairy, metabolizable energy (ME) on beef, net energy for maintenance (NE_m) and net energy for growth (NE_g) on beef among four oat varieties ($P<0.05$), and CDC Nasser oat had highest energy values comparing to other varieties ($P<0.05$). CDC Arborg and CDC Haymaker oat had similar energy values although they were from different oat types. The energy values of CDC Haymaker oat were smallest among four oat varieties. These energy values in our study were pretty similar with the results of Niu et al. (2007) and Tosta et al. (2019) though these varieties were totally different. Oat types had no significant impact on all the energy characteristics between feed type and milling oat, and the energy values of feed oat was relatively higher than the energy values of milling oat. These results are in line with the expectations. CDC Nasser oat had highest energy values compared to other varieties. It can be the higher fat content and lower content of lignin in Nasser oat, and can provide more energy for cattle.

Table 3.2. Effect of oat varieties and types (feed type vs. milling type) on TDN and energy profiles.

Items	Oat variety				SEM	P value	Contrast P value
	CDC Arborg (Milling)	Summit (Milling)	CDC Nasser (Feed)	CDC Haymaker (Forage)			Milling Type vs Feed Type
Truly digestible nutrient (%DM)							
tdNFC	50.16	55.06	50.17	45.80	1.863	0.104	0.349
tdCP	15.65[b]	15.25[b]	14.58[b]	17.42[a]	0.281	0.001	0.036
tdNDF	14.87	12.15	17.31	14.16	1.377	0.145	0.054
Total digestible nutrients (%DM)							
TDN_{1x}	75.52[bc]	78.16[b]	81.91[a]	73.18[c]	0.621	<0.01	<0.01
TDN_{3x}	69.35[bc]	71.78[b]	75.22[a]	67.21[c]	0.573	<0.01	<0.01
Energy value (Mcal/kg)							
DE_{1x}, NRC-2001 dairy	3.38[bc]	3.49[b]	3.64[a]	3.31[c]	0.025	<0.01	<0.01
DE_{p3x}, NRC-2001 dairy	3.11[bc]	3.21[b]	3.34[a]	3.04[c]	0.023	<0.01	<0.01
ME_{p3x}, NRC-2001 dairy	2.69[bc]	2.79[b]	2.93[a]	2.62[c]	0.023	<0.01	<0.01
NE_{Lp3x}, NRC-2001 dairy	1.70[c]	1.77[b]	1.88[a]	1.65[c]	0.015	<0.01	<0.01
ME, NRC-1996 beef	2.78[bc]	2.86[b]	2.98[a]	2.72[c]	0.020	<0.01	<0.01
NE_m, NRC-1996 beef	1.85[bc]	1.92[b]	2.02[a]	1.79[c]	0.016	<0.01	<0.01
NE_g, NRC-1996 beef	1.21[c]	1.28[b]	1.36[a]	1.17[c]	0.015	<0.01	<0.01

SEM: standard error of mean; a-b: Means with different letters in the same row are significantly different ($P < 0.05$); Multi-treatment comparison: Tukey method; tdCP: truly digestible crude protein; tdNDF: truly digestible neutral detergent fiber; tdNFC: truly digestible non-fiber carbohydrate; TDN_{1x}: total digestible nutrient at one time maintenance; DE_{1x}: digestible energy at one time maintenance; DE_{p3x}: digestible energy at a production level (3 × maintenance); ME_{p3x}: metabolizable energy at a production level (3 × maintenance); NE_{Lp3x}: net energy for lactation at a production level (3 × maintenance); ME: metabolizable energy; NE_m: net energy for maintenance; NE_g: net energy for gain.

3.6.3 Effect of oat varieties and types (feed type vs. milling type) on protein and carbohydrate subfractions

According to the Cornell Net Carbohydrate and Protein System (CNCPS 6.5), protein is partitioned PA1, PA2, PB1, PB2 and PC. They are ammonia, soluble true protein (rapidly degradable true protein), insoluble true protein (moderately degradable true protein), fiber-bound protein (slowly degradable true protein), indigestible protein, respectively. Carbohydrate is sorted into CA1, CA2, CA3, CA4, CB1, CB2, CB3, and CC. They stand for volatile fatty acids, lactate, other organic acids like fumarate, sugars, starch, soluble fiber, digestible fiber and indigestible fiber, respectively. β-glucan is soluble fiber, which is included in the CB2 fraction. The effect of oat varieties and types (milling type vs. feed type) on protein and carbohydrate fractions, rumen degradable and undegradable fractions of protein and carbohydrate is presented on Table 3.3 and 3.4. Results showed that oat varieties had significant impact on the PA2 and PB1 fraction (%DM) ($P<0.05$), and CDC Haymaker had higher PA2 fraction than that of CDC Nasser oat (6.62 vs. 5.37 %DM, $P<0.05$), and had similar PA2 fraction with CDC Arborg and Summit oat (6.19 and 5.73 %DM). CDC Haymaker oat had higher PB1 fraction than CDC Arborg and CDC Nasser oat (8.72 vs. 8.70, 8.94 %DM, $P<0.05$), but had similar PB1 fraction with Summit oat (8.94 %DM). However, there was no significant difference in PB1 (%DM) fraction between milling type and feed type oat. Based on the protein (CP%), no significant differences were found on the protein fractions among these four varieties and between feed type and milling type of oat. Oat varieties had significant impact on the RDPA2, RDPB1, total RDP, RUPA2, RUPB1 and total RUP ($P<0.05$). CDC Haymaker had higher RDPA2 (5.91 vs. 4.79 %DM) and RUPA2 (0.71 vs. 0.58 %DM) than CDC Nasser oat ($P<0.05$), and had similar RDPA2 (5.53 and 5.12 %DM) and RUPA2 (0.67 and 0.62 %DM) with CDC Arborg and Summit oat. CDC Haymaker had higher RDPB1 (4.96 vs. 4.24

and 4.25 %DM, P<0.05) and RUPB1 (5.22 vs. 4.46 and 4.58 %DM, P<0.05) than CDC Arborg and CDC Nasser oat, and had similar RDPB1 (4.35 %DM) and RUPB1 (4.58 %DM) with Summit oat. CDC Haymaker oat also had highest total RDP (11.06 %DM) and total RUP (6.52 %DM) fractions among four oat verities (P<0.05). CDC Arborg and Summit oat had similar total RDP and total RUP fractions. There were significant differences on RDPA2, RUPA2 and total RDP between feed and milling types (P<0.05). As for other fractions, no significant differences were found on the rumen degradable protein fractions and rumen undegradable protein fractions between feed type and milling type. Compared to other studies, the value of PB1 fraction was much bigger. For example, the value of PB1 fraction of CDC Nasser oat was 29.56 %CP in the study of Tosta et al. (2019) while it was 59.21 %CP in our study. On the contrary, the values of PA2, PB2, and PC fractions in our study were smaller than theirs. In their study, oat varieties and types also had no significant impact on all the protein subfractions (P<0.05).

With regard to the carbohydrate fraction, there was significant difference in CC (%CHO or %DM) fraction (P<0.05). CDC Nasser oat had lowest CC fraction in these four varieties (5.04 %CHO or 3.93 %DM, P<0.05), and CDC Arborg, CDC Haymaker and Summit had similar CC fractions (10.92, 9.98 and 13.02 %CHO or 8.63, 7.90 and 10.05 %DM). There was also significant difference in CC fraction content based on DM basis between milling and feed type. For the CA4, CB1, CB2 and CB3 fraction contents, there were no significant differences among these four varieties, and between feed type and milling type. However, the values of CC fractions in milling oat were much higher than that of feed oat (P<0.05). The values of CB2 fraction of milling oat (CDC Arborg and Summit) were also much larger than feed oat (CDC Nasser) although they don’t have significant differences. It was in line with the previous review that milling oat had higher β-glucan than feed oat. The value of CB3 (digestible fiber) such as cellulose and hemicellulose in

CDC Nasser oat was largest, and it could explain that the percentage of hull in CDC Nasser oat was highest among these four varieties. In addition, there were no significant differences in all rumen degradable carbohydrate fraction characteristics. However, the RUCC fraction of CDC Nasser oat was lowest in these four varieties (3.93 %DM, $P<0.05$), and CDC Arborg, CDC Haymaker, and Summit oat had similar RUCC fractions (8.63, 7.90, and 10.05 %DM). As for the oat types, significant difference in RUCC fraction was also found between feed type and milling type oat ($P<0.05$). The results have similarities with the study of Niu et al. (2007). Specifically, the CDC SO-1 oat (low lignin hull and high fat content) like CDC Nasser oat had lowest CC fractions compared to other oat varieties ($P<0.05$). It was in line with that CDC Nasser oat had less lignin (indigestible fiber) in the hull again. As is known that microorganisms can't digest the lignin in the plants, and lignin can block the microbes access to cellulose and hemicellulose, the digestible fiber fractions. Compared to barley, Tosta (2019) found the value of CC fractions in CDC Nasser oat was remained higher even though no significant difference between them, and Barley also had higher CA4 and CB1 fractions than oat. That is probably why replacing barley with oat in dairy cows decreased the metabolizable energy and organic matter digestibility, although it didn't affect the milk yield (Ramin et al., 2021).

In Study Phase I, the impact on different oat varieties and types (milling type vs. feed type) was investigated, and CDC Nasser oat had highest TDN contents and energy values compared to other oat varieties. However, we don't know the effect of different oat varieties and types on the rumen degradation kinetics, intestinal digestion characteristics, and N to OM synchronization. Therefore, we would determine them in the next phase.

Table 3.3. Effect of oat varieties and types (feed type vs. milling type) on CNCPS 6.5 of protein and carbohydrate fractions.

Items	Oat variety				SEM	P value	Contrast P value Milling Type vs Feed Type
	CDC Arborg (Milling)	Summit (Milling)	CDC Nasser (Feed)	CDC Haymaker (Forage)			
Protein subfractions							
PA1 (%CP)	-	-	-	-	-	-	-
PA2 (%CP)	39.17	37.20	36.70	37.66	2.121	0.591	0.380
PB1 (%CP)	55.16	58.07	59.21	57.92	1.895	0.242	0.146
PB2 (%CP)	3.51	2.36	2.33	2.20	0.417	0.178	0.266
PC (%CP)	2.16	2.37	1.77	2.22	0.304	0.577	0.228
PA2 (%DM)	6.19^{ab}	5.73^{ab}	5.37^{b}	6.62^{a}	0.347	0.014	0.042
PB1 (%DM)	8.70^{b}	8.94^{ab}	8.72^{b}	10.18^{a}	0.347	0.035	0.799
PB2 (%DM)	0.55	0.36	0.34	0.38	0.060	0.138	0.159
PC (%DM)	0.34	0.37	0.26	0.39	0.054	0.395	0.195
Carbohydrate subfractions							
CA4 (%CHO)	3.19	3.03	2.99	3.15	0.351	0.920	0.695
CB1 (%CHO)	59.27	60.51	61.12	55.47	2.968	0.562	0.743
CB2 (%CHO)	4.68	8.03	3.26	5.83	3.071	0.744	0.481
CB3 (%CHO)	26.79	21.77	31.81	25.78	2.646	0.140	0.049
CC (%CHO)	10.92^{a}	9.98^{a}	5.04^{b}	13.02^{a}	0.728	< 0.01	<0.01
CA4 (%DM)	2.53	2.40	2.33	2.43	0.273	0.895	0.572
CB1 (%DM)	46.85	47.89	47.60	42.84	2.354	0.452	0.938
CB2 (%DM)	3.68	6.36	2.56	4.53	2.353	0.738	0.474
CB3 (%DM)	21.17	17.22	24.78	19.91	2.039	0.146	0.056
CC (%DM)	8.63^{a}	7.90^{a}	3.93^{b}	10.05^{a}	0.545	<0.01	<0.01

SEM: standard error of mean; $^{a-b}$ Means with the different letters in the same row are significant different ($P < 0.05$); Multi-treatment comparison: Tukey method; PA1: ammonia; PA2: soluble true protein (rapidly degradable true protein); PB1: insoluble true protein (moderately degradable true protein); PB2: fiber-bound protein (slowly degradable true protein); PC: indigestible protein; CHO: carbohydrate; DM: dry matter; CA4: water soluble carbohydrates (rapidly degradable carbohydrate fraction); CB1: starch (intermediately degradable carbohydrate fraction); CB2: soluble fiber (intermediately degradable carbohydrate fraction); CB3: digestible fiber (available neutral detergent fiber or slowly degradable carbohydrate fraction); CC: indigestible fiber (unavailable neutral detergent fiber).

Table 3.4. Effect of oat varieties and types (feed type vs milling type) on rumen degradable and undegradable subfractions of protein and carbohydrate of oat.

Items	Oat variety				SEM	P value	Contrast P value Milling Type vs Feed Type
	CDC Arborg (Milling)	Summit (Milling)	CDC Nasser (Feed)	CDC Haymaker (Forage)			
Rumen degradable protein fractions							
RDPA1 (%DM)	-	-	-	-	-	-	-
RDPA2 (%DM)	5.53^{ab}	5.12^{ab}	4.79^{b}	5.91^{a}	0.308	0.014	0.039
RDPB1 (%DM)	4.24^{b}	4.35^{ab}	4.25^{b}	4.96^{a}	0.169	0.035	0.801
RDPB2 (%DM)	0.27	0.18	0.16	0.19	0.030	0.147	0.135
Total RDP (%DM)	10.04^{b}	9.65^{bc}	9.21^{c}	11.06^{a}	0.220	<0.01	0.016
Rumen undegradable protein fractions							
RUPA1 (%DM)	-	-	-	-	-	-	-
RUPA2 (%DM)	0.67^{ab}	0.62^{ab}	0.58^{b}	0.71^{a}	0.037	0.013	0.036
RUPB1 (%DM)	4.46^{b}	4.58^{ab}	4.47^{b}	5.22^{a}	0.178	0.035	0.797
RUPB2 (%DM)	0.28	0.19	0.17	0.20	0.031	0.133	0.130
RUPC (%DM)	0.34	0.37	0.26	0.39	0.054	0.395	0.195
Total RUP (%DM)	5.75^{b}	5.75^{b}	5.48^{b}	6.52^{a}	0.185	0.014	0.204
Rumen degradable carbohydrate fractions							
RDCA4 (%DM)	2.11	2.00	1.94	2.03	0.228	0.894	0.573
RDCB1 (%DM)	36.04	36.84	36.62	32.95	1.812	0.452	0.938
RDCB2 (%DM)	2.83	4.89	1.97	3.49	1.846	0.739	0.475
RDCB3 (%DM)	8.47	6.89	9.91	7.96	0.815	0.146	0.056
Total RDC (%DM)	46.49	48.60	47.92	44.49	0.946	0.063	0.757
Rumen undegradable carbohydrate fractions							
RUCA4 (%DM)	0.42	0.40	0.39	0.41	0.045	0.913	0.576
RUCB1 (%DM)	10.81	11.05	10.99	9.88	0.544	0.450	0.936
RUCB2 (%DM)	0.85	1.47	0.59	1.05	0.555	0.740	0.476
RUCB3 (%DM)	12.70	10.33	14.87	11.95	1.223	0.147	0.056
RUCC (%DM)	8.63^{a}	7.90^{a}	3.93^{b}	10.05^{a}	0.545	<0.01	<0.01
Total RUCC (%DM)	32.53	30.54	30.00	32.75	0.763	0.078	0.139

SEM: standard error of mean; $^{a-b}$ Means with the different letters in the same row are significant different ($P < 0.05$); Multi-treatment comparison: Tukey method; DM: dry matter; RDP: rumen degradable protein; RUP: rumen undegradable protein; CA4: water soluble carbohydrate, sugar; CB1: starch; CB2: soluble fiber; CB3: digestible fiber; CC: indigestible fiber; PA1: ammonia; PA2: soluble true protein; PB1: insoluble true protein; PB2: fiber bound protein;

3.7 Chapter Summary and Conclusions

Physiochemical profiles were different among these four varieties, and thereby leading to differences in energy values, total digestible nutrients, and protein and carbohydrate fractions. Specifically, CDC Nasser oat had highest ether extracts in these four varieties (4.05 %DM), which also had lowest lignin among varieties (1.63 %DM). The value of protein in CDC Nasser oat was smallest (14.69 %DM) while CDC Nasser oat had highest NPN contents (3.74 %DM). The CP value of CDC Haymaker oat was largest (17.57 %DM) but CDC Haymaker oat also had smallest total CHO value among varieties. Oat varieties had significant impact on iNDF based on 120 h incubation (%DM) but no differences between feed type and milling type. The value of $iNDF_{120h}$ of CDC Haymaker oat was largest and Summit's $iNDF_{120h}$ value was smallest. In addition, the CDC Nasser oat had highest TDN contents, and energy values among four oat varieties. CDC Nasser oat also had lowest indigestible fiber (CC) and RUCC among varieties, and the CC fraction of CDC Arborg, CDC Haymaker, and Summit oat was more than twice as high as CDC Nasser's. The values of RDPA1, RDPB1, total RDP, RUPA1, RUPB1, and total RUP on CDC Haymaker oat were biggest among varieties because of the highest CP contents. Oat types (feed type vs. milling type) had significant impact on the EE (%DM), CP (%DM), NPN (%DM), total CHO (%DM) and ADL (%DM). Milling type had relative higher CP content and total CHO content than milling type. Feed type also had relatively higher energy values and indigestible carbohydrates than milling type. These results indicate that CDC Nasser oat can provide higher energy for the cattle because they have less indigestible fiber like lignin. Higher lignin can block microbes in the rumen to penetrate the plants and digest the cellulose and hemicellulose. Therefore, CDC Nasser oat could be an important source of grain to replace barley in cattle.

4. RUMEN DEGRADATION, N-TO-ENERGY SYNCHRONIZATION, AND INTESTINAL DIGESTION STUDY IN DAIRY COWS: EFFECT OF OAT VARIETIES AND TYPES (FEED TYPE VS. MILLING TYPE)

4.1 Abstract

This phase aimed to determine the impact of four oat varieties and types (feed type vs. milling type) on the rumen degradation kinetics of nutrients, intestinal digestion of nutrients, and N to energy synchronization. Twelve samples [4 varieties (CDC Arborg, CDC Haymaker, CDC Nasser, Summit) × 3 harvested years (2018, 2019, 2020)] were used for in situ rumen incubation analysis, three-step in vitro analysis, and available N to energy synchronization evaluations. The experiment design was RCBD design (oat varieties as a fixed effect and harvested year as a random block effect). Statistical analysis was performed by MIXED procedure model of SAS 9.4, and significance was declared at $P<0.05$ and tendency at $0.05 \leq P<0.10$. Results showed that CDC Haymaker and CDC Arborg oat had higher rate of degradation of degradable fractions (Kd) of dry matter (DM), crude protein (CP), and starch than that of CDC Nasser oat ($P<0.05$). CDC Nasser oat had highest rumen bypass dry matter (BDM, g/kg DM), and rumen bypass feed starch (BST, g/kg DM) in these four varieties ($P<0.05$) while the effective degradability of dry matter (EDDM, g/kg DM), effective degradability of feed crude protein (EDCP, g/kg DM), and effective degradability of feed starch (EDST, g/kg DM) of CDC Nasser oat were lowest among varieties ($P<0.05$). There were significant differences in Kd (DM, CP, and starch), BDM, EDDM, EDCP, %BST, and EDST between milling oat and feed oat. For the intestinal nutrient digestibility, Summit oat had highest intestinal digestibility of rumen bypass dry matter (%dBDM) among four varieties ($P<0.05$), and the value of intestinal digestible rumen bypass dry matter (IDBDM, g/kg DM) of Summit was highest in these varieties, which has higher IDBDM (g/kg DM) content than

that of CDC Nasser oat ($P<0.05$). CDC Nasser oat also had lowest total digestible dry matter (TDDM, g/kg DM) in these varieties ($P<0.05$). Summit oat had similar intestinal digestibility of rumen bypass protein (%dBCP) with CDC Haymaker and CDC Nasser oat, but had higher %dBCP content than that of CDC Arborg oat ($P<0.05$). CDC Nasser oat had higher intestinal digestible rumen bypass protein (%IDBCP, % of CP) in these four varieties ($P<0.05$), while its value of total digestible protein (TDCP, g/kg DM) was the smallest and the TDCP content of CDC Nasser oat was lower than CDC Haymaker oat ($P<0.05$). Summit and CDC Arborg oat had higher total digestible feed starch (TDST) than that of CDC Nasser oat ($P<0.05$). Significant differences were found on %dBDM, IDBDM, IDBCP, TDDM, TDCP and TDST between the feed type and milling type oat ($P<0.05$). CDC Haymaker oat had similar ratio of N to organic matter (OM) of the oat (N/OM) with CDC Nasser oat, but had higher N/OM content than that of CDC Arborg and Summit oat ($P<0.05$).

4.2 Introduction

From the early to mid-twentieth century, oat is the main grain for livestock especially for horse in Canada, but it was also the foremost feed for dairy cows. With mechanization on the farm, the oat production was gradually declined because people no longer relied on horse. Then barley has gradually replaced oat as the main feed grain to livestock like dairy and beef cattle from that time. Although the price of oat were attractive for farmers, oat grain also had higher indigestible fiber (lignin) comparing to barley grain, which decreased the metabolizable energy content of dairy cow (Fuhr, 2006). However, this situation has been changed since the early of twenty-first century. The Crop Development Center (CDC) of University of Saskatchewan developed a variety with low lignin and high fat content named CDC SO-1. CDC Nasser oat in this study was similar with CDC SO-1 oat. Since then, the oat yields have been increased gradually. Oat grain was also included to the ration of dairy cows gradually, especially for lactating dairy cow as the higher fat content provide higher energy for them. Previous studies showed that replacing barley grains with oat grains in dairy cow diets could keep the milk production at the same level (McKay et al., 2019) or even increase the milk production (Ekern et al., 2003; Fuhr, 2006; Martin & Thomas, 1988; Vanhatalo et al., 2008; Yu et al., 2010), although the milk fat and protein concentrations may be reduced. Moreover, some proteins and starches escaped rumen fermentation and were digested in the small intestine, which also increased the utilization of the glucose in the oat for milk production (Noftsger & St-Pierre, 2003; Rigout et al., 2002). In an in vitro study by Fan et al. (2020), they also found the amount of methane based on oat diet was 8.9% lower than that of barley diet. Ramin et al. (2021) also reported that replacing barley with oat in the dairy ration could mitigate the methane emissions. There is very limited study to compare the degradation rate of basic nutrients on Canadian oat varieties. In this phase, the rumen degradation kinetics and intestinal of basic nutrients among Canadian oat varieties will be determined.

4.3 Study Objectives

To determine the impact of oat varieties and types (feed type vs. milling type) on the rumen degradation kinetics of primary nutrients, intestinal digestible nutrients and digestibility of nutrients, rumen available N to rumen available energy synchronization.

4.4 Study Hypothesis

There would be differences on the rumen degradation kinetics, intestinal digestion of nutrients, and hourly effective degradability of N to organic matter among the four oat varieties and types with CDC Nasser oat having higher effective degradability of nutrients than other oat varieties.

4.5 Materials and Methods

The University of Saskatchewan Animal Care Committee approved the animal study under the Animal Use Protocol No. 19910012 and animals were cared for and handled in accordance with the Canadian Council of Animal Care regulations (CCAC, 1993).

4.5.1 Sample treatments

Three varieties of oat grain (CDC Haymaker, CDC Nasser, and CDC Arborg) were obtained from Crop Development Center (CDC), University of Saskatchewan, Canada. One variety (Summit) was developed by Agriculture and Agri-Food Canada, Cereal Research Center (AAFC-CRC), Winnipeg, MB. Specifically, CDC Haymaker was a feed type with average 24.9% of hull. Summit already is a popular milling type while CDC Arborg is newer milling type, with average 21.6% and 20.1% of hull, respectively. CDC Nasser oat is a feed type with 21.8% of hull (SaskSeed Guide, 2023). These four varieties of oats were grown in the same Crop Development Center research fields and harvested from three consecutive years (2018, 2019, 2020), 12 samples in total, were used in this study.

4.5.2 Rumen in situ incubation procedure and degradation kinetics

Animal and sample preparation:

Four canulated Holstein Friesian dry cows were used in this study. They were kept in stall during the period of sampling with free access to water and fed two times daily with a total mixed ration (TMR). The details of TMR were as follows: barley silage (45.1%), straw (15.5%), dry rolled corn (13.2%), protein blend (14.5%), dry cow supplement (5.4%), SoyChlor (5.8%), and ReaShure Choline (0.3%). SoyChlor included canola meal, rice hull, soybean seeds meal, hydrochloric acid, calcium carbonate, and magnesium oxide. ReaShure included hydrogenated vegetable oil, choline chloride, and corn cobs (dehydrated and fine ground). The animal trail was carried out in the Rayner Dairy Research and Teaching Facility in Saskatoon, SK, Canada.

Samples were ground with Malt Muncher Grain Mill (3 roller Malt Mill, Toronto Brewing-Homebrew Supplies) with a roller gap of 1.0 mm. 7.5 g of sample were weighted into nylon bag (10 × 20 cm) with a pore size of 41 μm, and all samples were prepared for three runs.

Incubation procedure:

Samples were incubated in the rumen for 24 h, 12 h, 8 h, 4 h, 2 h, 0 h. Two bags were used at the time point of 8 h, 4 h, 2 h, 0 h. As for the 24 h and 12 h, four bags were used to collect more residues. These nylon bags were put into a polyester mesh lingerie bag with a weight to fully mix the rumen fluid, which was put into the rumen according to the incubation time. All nylon bags were removed at once at the last time point (gradually in/all out) (Yu et al., 2000).

After incubation, these nylon bags were removed from rumen and immediately washed 6 times with tap water to remove attached rumen contents and stop microbial degradation. Then all the nylon bags were put into a forced-air oven and dried at 55℃ for 48 h. The dried bags were taken out of the oven exposed to room temperature and reweighted. Residues were composited by incubation time point, treatments and run, and then ground through 1 mm screen (Retsch ZM 200, Retsch Inc, Haan, Germany). These ground samples were used for analysis of CP (CP LECO FP-528, AOAC 990.03), starch (AOAC 996.11, AACC 76.13, ICC standard method No. 168), and neutral detergent fiber (NDF) with Ankom A200 filter bag technique (Ankom Technology, Fairport, NY, USA).

Rumen degradation kinetics:

Based on the results of in situ incubation, degradation characteristics of DM, OM, CP and starch were determined by using first-order degradation kinetics model described by Ørskov and

McDonald (1979) and Tamminga et al. (1994). Specifically, DM, CP and NDF were calculated by $R(t) = U + D \times e^{-Kd \times (t - T0)}$, and starch was calculated by $R(t) = D \times e^{-Kd \times (t - T0)}$ where, R(t) was residue after t hours of incubation in the rumen; U was undegradable fraction (%); D stands for potentially degradable fraction (%); Kd stands for degradation rate (%/h); and T0 was lag time (h). The effective degradable fractions (ED) and rumen undegradable fractions (RU) of each nutrient were evaluated with the flowing equations from NRC (2001), %EDDM (EDOM, EDCP or EDST) $= S + D \times Kd / (Kp + Kd)$, $RU = U + D \times Kp / (Kp + Kd)$ where, S was the soluble fractions (%), Kp was the estimated rate of outflow from rumen (%/h), which was assumed to be 6 %/h (Tamminga et al., 1994).

4.5.3 Determination of intestinal digestibility of nutrients

A three-step in vitro technique was used for determining the intestinal digestibility of oat nutrients following the procedure of Calsamiglia and Stem (1995) and modified by Gargallo et al. (2006). More specifically, 0.3 – 0.4 g of residue samples from 12 hours ruminal incubation were taken and placed into a 50 ml centrifuge tube in duplicates with 10 ml of pepsin (Sigma P-7012) solution (0.1 mol/L HCL, pH = 1.9) for every tube. They were vortexed and incubated for 1 h in a shaking water bath (Precision, Serial Nº: 602071249, Thermo Scientific, USA) at 38 ℃. Then 0.5 ml 1 mol/L NaOH solution and 13.5 ml of pancreatin (Sigma P-7545, pH = 7.8) were added into every tube, which were vortexed and incubated for 24 h at 38 ℃. After incubation, 3 ml of TCA were added to stop the enzymatic hydrolysis, and then these tubes were vortexed and put at room temperature for 15 min. After that, they were centrifugated for 15 min at 5000 rpm. 5 ml of supernatant were used for analyzing soluble N by Kjeldahl method (AOAC 984.13). Intestinal digestion of protein was calculated through TCA soluble N divided by N present in the rumen residual samples.

4.5.4 Hourly effective rumen degradation ratios and potential N to energy synchronization

For efficient microbial growth, both energy sources and nitrogen (N) were available at same time throughout whole day, and it was called nutrient synchronization. Studies reported that providing matched diets (e.g. rapid carbohydrate fermentation together with rapid protein fermentation) to steers produced more microbial protein (Herrera-Saldana et al., 1990). If you provide more N, microbes also can't use those extra N and they will be excreted as urine (Tas et al., 2006). Studies also showed that it was optimal for microbial growth, which the values were around 32 g N/kg CHO or 25 g N/kg OM (Huang et al., 2015; Sinclair et al., 1993; Tamminga et al., 2007).

To maximize the microbial synthesis and decrease the N losses, effective rumen degradation of N and energy should be considered. The effective degradation of available N and available OM were calculated by following equation from Sinclair et al. (1993) : ED (g/kg DM) = $S + [(D \times K_d) / (K_p + K_d)] \times [1 - e^{-t \times (Kd + Kp)}]$. The hourly effective degradation ratios of N to OM were calculated by the following equations described by Nuez-Ortín and Yu (2010): Hourly ED $N/OM_t = (HEDN_t - HEDN_{t-1}) / (HEDOM_t - HEDOM_{t-1})$, where hourly ED N/OM_t stood for the ratio of N to OM at the time of t (g N/kg OM); $HEDN_t$ was hourly effective degradability of N at time t (g/kg DM); $HEDN_{t-1}$ stood for the hourly effective degradability of N 1h before the time t (g/kg DM); $HEDOM_t$ was the hourly effective degradability of organic matter at the time t (g/kg DM); $HEDOM_{t-1}$ was the hourly effective degradability of organic matter 1h before the time t (g/kg DM).

4.5.5 Statics analysis

The treatment design was a one-way structure. Experimental design was RCBD design with varieties as a fixed effect, and years as a random block effect. Statistical analysis of rumen degradation kinetics and intestinal digestion of primary nutrients, and hourly effective degradability of N to OM were performed using MIXED procedure of SAS version 9.4 (SAS Institute, Inc., Cary, NC, US). RCBD model was in use during analysis:

$$Y_{ij} = \mu + T_i + \beta_j + e_{ij},$$

where Y_{ij} was an observation of the dependent variable ij; μ was the population mean of variable; T_i was the effect of varieties as a fixed effect (i = 1 to 4); β_j was the block effect of year (j = 2018, 2019, 2020), and e_{ij} was the random error associated with the observation ij. Specially, PROC NLIN-Gauss-Newton procedure of SAS was used for fitting the rumen degradation data to the model. Multi treatment comparison was carried out using Tukey's method and SAS orthogonal contrast was used for comparison between the feed type and milling type oat. Significance was declared at $P<0.05$ and tendency at $0.05<P\leq0.10$.

4.6 Results and Discussion

4.6.1 Effect of oat varieties and types (feed type vs. milling type) on in situ degradation kinetics

In situ DM degradation kinetics:

The rumen fractions (S, D, U), rate of degradation (Kd), rumen undegradable dry matter (BDM), and effective degradability of dry matter (EDDM) of four oat varieties were presented in Table 4.1. Results revealed that lag time (T0) and soluble fraction (S) were not significantly affected by the oat varieties and types. However, the rate of degradation (Kd) of CDC Arborg and CDC Haymaker oat were higher than CDC Nasser oat (10.53 and 11.36 vs. 2.36 %/h, P<0.05) while CDC Nasser and Summit oat had similar Kd value (2.36 and 7.61 %/h). CDC Nasser oat had higher degradable fraction (D) comparing to CDC Haymaker oat (86.9% vs. 53.9%, P<0.05), but had similar D fraction with Summit and CDC Arborg oat (66.8% and 66.3%). Instead, CDC Haymaker oat had higher undegradable fraction (U) than that of CDC Nasser (41.2% vs. 9.2%, P<0.05), but had similar U fraction with CDC Arborg and Summit oat (28.1% and 28.7%). Between the milling type and feed type, there were significant differences that were found on Kd, D, U, BDM, and EDDM (g/kg DM). As for the rumen bypass dry matter (BDM), CDC Nasser was highest among four varieties ($P<0.05$). However, the effective degradability of dry matter (EDDM) of CDC Nasser was lowest comparing to CDC Arborg, CDC Haymaker and Summit oat ($P<0.05$). Likewise, there were both significant difference in BDM and EDDM between milling type and feed type oat ($P<0.05$). The values of BDM of feed type were higher while the EDDM values of milling type of oat was higher although there wasn't significant difference between CDC Haymaker and CDC Arborg, Summit oat. So, the effective degradability of dry matter on milling type of oat was higher than feed type. In the study by Tosta (2019), the author reported that no significant difference in dry matter Kd, BDM, and EDDM among varieties (CDC Nasser, CDC Arborg, and CDC Ruffian oat), and values were 41.97-53.28 %/h, 280-304 g/kg DM, and 696-720 g/kg DM, respectively. The value of Kd (DM) and EDDM of oat in their study was much larger than ours, and CDC Nasser oat had lowest Kd (DM) and EDDM content, highest BDM content in our study. The D and U fractions in both studies had relative similarity. The differences of DM of Kd, BDM, and EDDM between these two studies were attributed to difference of roller milling gap between these two studies. In Tosta's study, she used the roller miller with a roller gap of 0.508 mm, while our roller gap was 1.00 mm. That was causing big differences on the Kd, BDM, and EDDM. She had severe processing on the oat grains, which leads to bigger degradations and EDDM. In the study by Fuhr (2006), the author reported that the dry matter Kd of LLH-HOG (low lignin and high oil content) oat was 11.3 %/h, which was higher than CDC Nasser oat from our study. The Kd (DM) of CDC Derby oat was 14.9 %/h, and it was similar with CDC Arborg and CDC Haymaker oat from our study. But their EDDM contents of oat were still higher than ours, and they were around 68%.

In situ crude protein degradation kinetics:

The rumen degradation kinetics of crude protein of four oat varieties were presented in Table 4.2. Results demonstrated that CDC Haymaker had higher rate of degradation of crude protein (Kd) than that of CDC Nasser oat (13.33 vs. 2.64 %/h, $P<0.05$), but had similar Kd value with CDC Arborg and Summit oat (10.88 and 9.59 %/h). CDC Haymaker oat also had higher undegradable fraction (U) comparing to CDC Nasser oat (24.1% vs. 5%, $P<0.05$), but there was no significant difference in U fraction among CDC Haymaker, CDC Arborg and Summit. In addition, CDC Haymaker oat also had higher effective degradability of feed crude protein (EDCP) comparing to CDC Nasser oat (102 vs. 64 g/kg DM, $P<0.05$), which also had similar EDCP content with CDC Arborg and Summit oat (88 and 84 g/kg DM). As for %EDCP, CDC Nasser oat was lowest in these varieties (45.6%, $P<0.05$), but no significant difference was found on %EDCP values among oat varieties. Oat varieties also had no significant differences in degradable fraction (D) and rumen bypass or undegraded feed crude protein (%BCP or BCP or RUP). The %BCP, BCP values of CDC Nasser oat were largest among varieties because it had smallest EDCP value. Oat types (feed type vs. milling type) affected the Kd of CP, soluble fractions (S), and U (%) ($P<0.05$), and there was no significant impact on other characteristics of rumen degradation kinetics of crude protein. The BCP values of feed oat were larger than that of milling oat while it still has higher EDCP value like CDC Haymaker oat. The CDC Nasser oat in situ protein degradation kinetic characteristics had similar pattern with CDC Austenson barley in the study of Tosta (Tosta, 2019; Tosta et al., 2019) even though the values were smaller in our study. In their study, CDC Austenson barley also had lowest Kd, U, EDCP and highest D, BCP (DVE), and RUP (NRC) contents ($P<0.05$). However, these characteristics of CDC Nasser oat in their study were different with ours.

For example, CDC Nasser oat had no significant difference in Kd, D, U, BCP (DVE), RUP (NRC), and %EDCP among varieties.

In situ NDF degradation kinetics:

The NDF rumen degradation characteristics of four oat varieties are presented in Table 4.3. Results showed that oat varieties and types didn't affect any rumen degradation characteristics of NDF significantly, and there was just a trend on the rate of degradation of D fraction (Kd) between milling type and feed type (0.05<P<0.1). In the study by Thompson, they also observed that there was no significant difference in Kd (NDF) between Calibre oat and AC Assinboia oat, which differed in ADL content (5.4% and 1.3%) (Thompson, 2001). These two varieties had same Kd values, 1.30 %/h, and it was similar with ours, ranged from 1.06 to 1.55 %/h. However, Mustafa et al. (1998) reported that AC Mustang and Calibre oat had different Kd (NDF) values with similar ADL contents (7.7% and 7.6%), 4.3 and 11.2 %/h, respectively. Fuhr also found that LLH-HOG oat (low lignin and high oil content) had lower Kd value than that of Derby oat (Fuhr, 2006). From the current study, ADL content also had little effect on the Kd of NDF. CDC Nasser oat had lowest ADL content (P<0.05), but CDC Nasser oat had no significant difference in the Kd of NDF comparing to other varieties although the Kd value of oat was largest. ADL may alter the quantities of D and U fractions of oat thus indirectly affecting Kd, BNDF, and EDNDF values. The value of D fraction of CDC Nasser oat was largest, while the value of U fraction of CDC Nasser oat was smallest.

In situ starch degradation kinetics:

The starch rumen degradation characteristics of four oat varieties are presented in Table 4.4. Results demonstrated that oat varieties affected the rate of degradation of D fraction (Kd) significantly, and CDC Haymaker had the highest Kd value comparing to CDC Nasser and Summit oat (15.07 vs. 2.76 and 7.85 %/h, P<0.01), and CDC Haymaker oat had similar Kd fraction with CDC Arborg oat (11.84 %/h). These four varieties of oat also had similar soluble fraction (S) and degradable fraction (D), in other words, no significant differences were found among them. As for undegraded feed starch (BST) and effective degradability of feed starch (EDST), varieties affected them significantly, which CDC Nasser oat had highest BST or %BST fraction (325 g/kg DM or 68.0%, P<0.01) while CDC Nasser had lowest EDST or %EDST fraction (151 g/kg DM or 32.0%, P<0.01) in these four oat varieties. Furthermore, CDC Arborg, CDC Haymaker and Summit oat had similar BST or %BST content (157, 121 and 194 g/kg DM or 33.3%, 28.5% and 40.3%) and EDST or %EDST content (312, 307, and 285 g/kg DM or 66.7%, 71.5% and 59.7%). Oat types (feed type vs. milling type) had significant impact on the Kd of starch, BST, EDST (P<0.01) but no significant impact on the S and D. The lag time (T0) and undegradable fractions (U) of four varieties oat were all 0, so they weren't presented in the Table 4.4.

Damiran and Yu (2010) also found the starch Kd of SO-1 oat (with low lignin and high oil content) was smallest although no significant difference were found on Kd of starch among oat varieties. Mustafa et al. (1998) observed that the Kd value of AC Belmont oat (hull-less) was larger than that of AC Mustang oat (hulled). The values of starch Kd from different varieties in their study were larger than ours. These two studies and the current study indicated that the lower the content of ADL in the oat grains the lower Kd of starch. In the study by Tosta, they observed the value of starch Kd of CDC Nasser oat was largest among oat varieties, but there was no significant difference among them (Tosta, 2019). Compared to other cereal grains like barley, Tosta also revealed that the value of starch Kd of CDC Austenson barley was lowest than other three oat varieties (CDC Nasser, CDC Arborg, CDC Ruffian oat), and there was significant difference in starch Kd between CDC Nasser oat and CDC Austenson barley (P<0.05), which had similar ADL contents, with 1.55 and 0.80 %DM, respectively. Their nutrients degradations were all larger than ours because of severe processing method, and different processing index had largest influence on the CDC Nasser oat when compared to Tosta's study. Other studies also reported that barley has a lower starch Kd than that of oat, and oat had highest protein and starch Kd compared to wheat, sorghum, and corn (Herrera-Saldana et al., 1990; Pan et al., 2021; Prestløkken, 1999). The differences of protein and starch rumen degradation rate between barley and oat could be attributed to discrepancy in protein-starch matrix arrangement. McAllister et al. (1993) also reported that variations in protein-starch matrix maybe a major factor contributing to differences in rumen digestion of cereal grains. Typically, oat had spherical protein-starch bodies in a rather loose arrangement while the protein in barley formed a fairly hard matrix in which starch granules were embedded (Webster & Wood, 2011). In addition, there was big difference in composition of protein fractions between barley and oat. Barley mainly had globulins and insoluble prolamins but oat had more globulins and soluble albumins (El Halal et al., 2019; Hoseney, 1994). This may explain the differences of protein and starch degradation in the rumen between barley and oat. On one hand, CDC Nasser oat, with low lignin and high oil content, could have similar structure of protein-starch matrix as in barley because of low lignin content. If plants have lower lignin content, they probably form rigid protein-starch matrix to keep themselves hard. It probably has a lower starch and protein degradation in the rumen like barley. On the other hand, it's also possible that the oil in oat encapsulate the protein and starch matrix because of higher oil content thus reducing the protein and starch degradation rate in the rumen.

Table 4.1. Effect of oat varieties and types (feed type vs. milling type) on in situ DM degradation kinetics of oat.

Items	Oat variety				SEM	P value	Contrast P value Milling Type vs Feed Type
	CDC Arborg (Milling)	Summit (Milling)	CDC Nasser (Feed)	CDC Haymaker (Forage)			
In situ rumen DM degradation							
Kd (%/h)	10.53[a]	7.61[ab]	2.36[b]	11.36[a]	1.500	0.011	0.006
T0 (h)	1.22	0.05	0.55	0.29	0.367	0.207	0.855
S (%)	5.6	4.5	3.9	4.9	0.71	0.160	0.078
D (%)	66.3[ab]	66.8[ab]	86.9[a]	53.9[b]	5.31	0.015	0.014
U (%)	28.1[ab]	28.7[ab]	9.2[b]	41.2[a]	5.44	0.020	0.021
%BDM (=%RUDM)	53.7[b]	58.2[b]	72.6[a]	59.9[b]	2.87	0.003	0.001
BDM (=RUDM, g/kg DM)	537[b]	582[b]	726[a]	599[b]	28.70	0.003	0.001
%EDDM (=%RDDM)	46.3[a]	41.8[a]	27.4[b]	40.1[a]	2.87	0.003	0.001
EDDM (=RDDM, g/kg DM)	463[a]	418[a]	274[b]	401[a]	28.70	0.003	0.001

Kd: the rate of degradation of D fraction (%/h); U: undegradable fractions; D: degradable fractions; T0: lag time in h; S: soluble fraction in the in situ incubation; BDM or RUDM: rumen bypass dry matter; EDDM or RDDM: effective degradability of dry matter in the rumen; Kp: passage rate of 6%/h was adopted for concentrate (Tamminga et al., 1994). SEM: standard error of mean; [a-b] Means with the different letters in the same row are significant different ($P < 0.05$); Multi-treatment comparison: Tukey method;

Table 4.2. Effect of oat varieties and types (feed type vs. milling type) on in situ CP degradation kinetics of oat.

Items	Oat variety				SEM	P value	Contrast P value Milling Type vs Feed Type
	CDC Arborg (Milling)	Summit (Milling)	CDC Nasser (Feed)	CDC Haymaker (Forage)			
In situ rumen CP degradation							
Kd (%/h)	10.88[a]	9.59[ab]	2.64[b]	13.33[a]	1.569	0.017	0.009
T0 (h)	1.39	0.27	3.16	0	0.694	0.068	0.040
S (%)	10.2[b]	12.0[b]	26.7[a]	17.5[ab]	3.55	0.032	0.007
D (%)	73.1	69.0	69.8	58.4	3.60	0.060	0.776
U (%)	16.8[ab]	19.0[ab]	5.0[b]	24.1[a]	5.72	0.021	0.014
%BCP	44.6	45.8	54.4	42.2	4.73	0.167	0.072
BCP^{NRC} or RUP (g/kg DM)	78	78	87	82	8.4	0.684	0.289
BCP^{DVE} or RUP (g/kg DM)	70	70	78	74	7.5	0.684	0.289
%EDCP (=%RDP)	55.4	54.2	45.6	57.8	4.59	0.167	0.072
EDCP (=RDP, g/kg DM)	88[ab]	84[ab]	64[b]	102[a]	8.2	0.025	0.029

Kd: the rate of degradation of D fraction (%/h); U: undegradable fractions; D: degradable fractions; T0: lag time in h; S: soluble fraction in the in situ incubation; BCP or RUP: rumen bypass or undegraded feed crude protein; EDCP or RDP: effective degradability of feed crude protein in the rumen; Kp: passage rate of 6%/h was adopted for concentrate (Tamminga et al., 1994). SEM: standard error of mean; [a-b] Means with the different letters in the same row are significant different ($P < 0.05$); Multi-treatment comparison: Tukey method;

Table 4.3. Effect of oat varieties and types (feed type vs. milling type) on in situ NDF degradation kinetics of oat.

Items	Oat variety				SEM	P value	Contrast P value Milling Type vs Feed Type
	CDC Arborg (Milling)	Summit (Milling)	CDC Nasser (Feed)	CDC Haymaker (Forage)			
In situ rumen NDF degradation							
Kd (%/h)	1.18	1.06	1.55	1.37	0.187	0.303	0.092
T0 (h)	0.52	0.80	0	0.17	0.435	0.559	0.238
S (%)	12.6	2.8	0	0	3.98	0.157	0.153
D (%)	43.2	86.7	87.6	59.0	13.90	0.138	0.221
U (%)	44.1	10.6	12.4	41.0	11.82	0.152	0.333
%BNDF	79.9	84.4	81.9	89.5	3.42	0.289	0.959
BNDF (=RUNDF, g/kg DM)	244	218	239	274	13.0	0.085	0.611
%EDNDF (=%RDNDF)	20.1	15.7	18.1	10.5	3.42	0.289	0.959
EDNDF (=RDNDF g/kg DM)	63	41	54	33	12.6	0.393	0.905

Kd: the rate of degradation of D fraction (%/h); U: undegradable fractions; D: degradable fractions; T0: lag time in h; S: soluble fraction in the in situ incubation; BNDF or RUNDF: rumen bypass or undegraded feed neutral detergent fiber; EDNDF or RDNDF: effective degradability of feed neutral detergent fiber in the rumen; Kp: passage rate of 6%/h was adopted for concentrate (Tamminga et al., 1994). SEM: standard error of mean; [a-b] Means with the different letters in the same row are significant different ($P < 0.05$); Multi-treatment comparison: Tukey method;

Table 4.4. Effect of oat varieties and types (feed type vs. milling type) on in situ starch degradation kinetics of oat.

Items	Oat variety				SEM	P value	Contrast P value Milling Type vs Feed Type
	CDC Arborg (Milling)	Summit (Milling)	CDC Nasser (Feed)	CDC Haymaker (Forage)			
In situ rumen starch degradation							
Kd (%/h)	11.84^{ab}	7.85^{b}	2.76^{c}	15.07^{a}	1.039	<0.01	<0.01
S (%)	2.0	9.7	2.4	1.0	3.57	0.350	0.446
D (%)	98.0	90.3	97.7	99.0	3.57	0.350	0.446
%BST	33.3^{b}	40.3^{b}	68.0^{a}	28.5^{b}	3.41	<0.01	<0.01
BST (=RUST, g/kg DM)	157^{b}	194^{b}	325^{a}	121^{b}	24.3	0.002	0.001
%EDST (=%RDST)	66.7^{a}	59.7^{a}	32.0^{b}	71.5^{a}	3.41	<0.01	<0.01
EDST (=RDST g/kg DM)	312^{a}	285^{a}	151^{b}	307^{a}	16.4	<0.01	<0.01

Kd: the rate of degradation of D fraction (%/h); U: undegradable fractions; D: degradable fractions; T0: lag time in h; S: soluble fraction in the in situ incubation; BST or RUST: rumen bypass or undegraded feed starch; EDST or RDST: effective degradability of feed starch in the rumen; Kp: passage rate of 6%/h was adopted for concentrate (Tamminga et al., 1994). SEM: standard error of mean; $^{a-b}$ Means with the different letters in the same row are significant different ($P < 0.05$); Multi-treatment comparison: Tukey method;

4.6.2 Effect of oat varieties and types (feed type vs. milling type) on intestinal digestible nutrients

Intestinal digestibility on DM:

The effect of oat varieties of and types (feed type vs. milling type) on intestinal dry matter (DM) and total digestion of four oat varieties are presented in Table 4.5. Results showed that oat varieties and types had significant impact on all intestinal DM characteristics and total digestion DM ($P<0.05$). Detailly, CDC Arborg, Summit and CDC Haymaker oat had similar intestinal digestibility of rumen bypass dry matter (%dBDM) (30.1, 32.2, and 25.6 % of BDM) while CDC Arborg and CDC Haymaker oat had higher %dBDM contents than CDC Nasser oat (17.5 % of BDM) ($P<0.05$). Summit oat had higher intestinal digestible rumen bypass dry matter (IDBDM) content than that of CDC Nasser oat (186 vs. 126 g/kg DM, $P<0.01$), but had similar IDBDM content comparing to CDC Arborg and CDC Haymaker oat (161 and 151 g/kg DM). CDC Nasser oat also had lowest total digestible dry matter (TDDM) in these four varieties (401 g/kg DM, $P<0.01$), and there was no significant impact on TDDM content among CDC Arborg, CDC Haymaker and Summit oat (625, 552, and 605 g/kg DM). Oat types had significant impact on all the intestinal DM characteristics and TDDM content between feed type and milling type ($P<0.05$), and milling types of oat had larger %dBDM, IDBDM, and %TDDM than feed types.

Intestinal digestibility on CP:

The crude protein (CP) intestine and total digestion characteristics of four oat varieties are presented in Table 4.5. Results revealed that CDC Nasser oat had highest intestinal digestible rumen bypass protein (%IDBCP, % of CP) in these four varieties (45.0 % of CP, $P<0.01$) while CDC Arborg, Summit and CDC Haymaker oat had similar %IDBCP (29.5, 39.2 and 32.1 % of CP). However, varieties had no significant impact on the IDBCP (g/kg DM) content. Summit oat had higher intestinal digestibility of rumen bypass protein (%dBCP, % of BCP) than that of CDC

Arborg oat even though both were oat milling type (85.3 vs. 65.6 % of BCP, P<0.05), which had similar %dBCP fractions with CDC Haymaker and CDC Nasser oat (74.1 and 79.0 % of BCP). As for the total digestible protein (TDCP), CDC Haymaker oat was higher than CDC Nasser oat (158 vs. 129 g/kg DM, P<0.05) while had similar TDCP contents with Summit oat (144 g/kg DM). Summit oat had higher %TDCP fraction than that of CDC Arborg oat (93.4 vs. 84.9 % of CP, P<0.05), and had similar %TDCP with CDC Haymaker and CDC Nasser oat (89.9 and 88.0 % of CP). Oat types (feed type vs. milling type) had significant impact on the IDBCP (g/kg DM) and TDCP (g/kg DM) characteristics.

Zebrowska et al. (1997) observed that the intestinal digestibility of rumen undegraded protein on oat estimated by mobile bags method was 57.5 which was smallest comparing with barley, rye, wheat. Peng et al. (2014) reported that the value of intestinal digestibility of RUP (g/100g CP) in oat was lowest than that of barley, corn and wheat. Tosat (2019) found that the value of dBCP of barley was largest comparing with other three oat varieties (54 %RUP), and the value of dBCP of CDC Nasser oat was largest among oat varieties comparing to CDC Arborg and CDC Ruffian oat (52.0 vs. 44.6 and 39.9 %RUP). In contrast, the value of %dBCP of Summit oat was largest instead of CDC Nasser oat in our study. In their study, the TDCP value of CDC Nasser oat was smallest among varieties. This was in line with our results that CDC Nasser oat's TDCP was smallest comparing to other oat varieties.

Intestinal digestibility on NDF:

The neutral detergent fiber (NDF) intestine and total digestion characteristics of oat are presented in Table 4.6. Results showed that varieties had no significant impact to any NDF intestine and total digestion characteristics. In addition, oat types also had no significant impact on all the characteristics, and there was just a trend on the intestinal digestibility of rumen bypass NDF

(%dBNDF) and intestinal digestible rumen bypass NDF (%IDBNDF or IDBNDF) ($0.05<P<0.1$). The %dBNDF and IDBNDF values of feed oat were much larger than milling oat.

Intestinal digestibility on starch:

The effect of oat varieties and types (feed type vs. milling type) on intestine and total digestion of starch are presented in Table 4.6. Results indicated that CDC Nasser oat had lowest total digestible starch (TDST, % of starch) in these varieties (49.5 % of starch, $P<0.05$). The value of TDST content of CDC Nasser was smallest in these four varieties but had similar content with CDC Haymaker oat (233 and 332 g/kg DM), and both of them were lower than CDC Arborg and Summit oat (367 and 381 g/kg DM, $P<0.01$). CDC Arborg, CDC Haymaker and Summit oat had similar %TDST (78.6, 77.2 and 79.2 % of starch). Varieties had no significant impact on the intestinal digestibility of rumen bypass starch (%dBST), intestinal digestible rumen bypass starch (%IDBST or IDBST). Oat types just had significant impact on the TDST ($P<0.01$), and the TDST values of feed oat were much smaller than milling oat. Prates et al. (2023) observed that the dBST and TDST value of oat were 49.0 %BST and 308 g/kg DM, respectively, which was similar with ours. However, Tosta (2019) reported that the %dBST of oat ranged from 91.63 to 94.46 %BST, and it was around 2-3 times larger than ours. So, different roller milling gaps also had big influence on the intestinal digestion of nutrients in the small intestine.

Table 4.5. Effect of oat varieties and types (feed type vs. milling type) on intestine and total digestion of DM and CP of oat.

Items	Oat variety				SEM	P value	Contrast P value
	CDC Arborg (Milling)	Summit (Milling)	CDC Nasser (Feed)	CDC Haymaker (Forage)			Milling Type vs Feed Type
Intestinal digestion of dry matter							
%dBDM (% of BDM)	30.1^{a}	32.2^{a}	17.5^{b}	25.6^{ab}	2.30	0.005	0.001
%IDBDM (% of DM)	16.1^{ab}	18.6^{a}	12.6^{b}	15.1^{ab}	0.80	0.007	0.002
IDBDM (g/kg DM)	161^{ab}	186^{a}	126^{b}	151^{ab}	8.0	0.007	0.002
%TDDM (% of DM)	62.5^{a}	60.5^{a}	40.1^{b}	55.2^{a}	3.53	0.003	<0.01
TDDM (g/kg DM)	625^{a}	605^{a}	401^{b}	552^{a}	35.3	0.003	<0.01
Intestinal digestion of crude protein							
%dBCP (% of BCP)	65.6^{b}	85.3^{a}	79.0^{ab}	74.1^{ab}	4.66	0.033	0.431
%IDBCP (% of CP)	29.5^{b}	39.2^{ab}	45.0^{a}	32.1^{b}	5.39	0.013	0.010
IDBCP (g/kg DM)	46	60	67	56	9.3	0.078	0.048
%TDCP (% of CP)	84.9^{b}	93.4^{a}	88.0^{ab}	89.9^{ab}	1.74	0.048	0.614
TDCP (g/kg DM)	134^{b}	144^{ab}	129^{b}	158^{a}	3.8	0.002	0.041

Note: %dBDM: intestinal digestibility of rumen bypass dry matter (in %); %IDBDM: intestinal digestible rumen bypass dry matter (percentage of total BDM) (in % of DM); IDBDM: intestinal digestible rumen bypass dry matter (in g/kg DM); %TDDM: total digestible dry matter (in % of DM); TDDM: total digestible dry matter (in g/kg DM); %dBCP: intestinal digestibility of rumen bypass protein (in % of BCP); %IDBCP: intestinal digestible rumen bypass protein (in % of CP); IDBCP: intestinal digestible rumen bypass protein (in g/kg DM); %TDCP: total digestible protein (in % of CP); TDCP: total digestible protein (in g/kg DM); SEM: standard error of mean; $^{a-b}$ Means with the different letters in the same row are significant different (P < 0.05); Multi-treatment comparison: Tukey method;

Table 4.6. Effect of oat varieties and types (feed type vs. milling type) on intestine and total digestion of NDF and starch of oat.

Items	Oat variety: CDC Arborg (Milling)	Summit (Milling)	CDC Nasser (Feed)	CDC Haymaker (Forage)	SEM	P value	Contrast P value Milling Type vs Feed Type
Intestinal digestion of NDF							
%dBNDF (% of BNDF)	2.4	1.6	8.9	7.1	2.80	0.247	0.075
%IDBNDF (% of NDF)	1.9	1.3	7.3	6.2	2.45	0.265	0.085
IDBNDF (g/kg DM)	6	4	21	22	8.2	0.305	0.132
%TDNDF (% of NDF)	21.1	14.3	25.5	13.0	5.12	0.336	0.249
TDNDF (g/kg DM)	66	37	75	44	18.1	0.453	0.330
Intestinal digestion of starch							
%dBST (% of BST)	36.1	47.5	27.1	42.2	8.30	0.371	0.168
%IDBST (% of ST)	11.9	19.5	17.6	11.2	3.88	0.390	0.672
IDBST (g/kg DM)	55	96	82	48	19.7	0.332	0.762
%TDST (% of ST)	78.6^{a}	79.2^{a}	49.5^{b}	77.2^{a}	6.4	0.014	0.003
TDST (g/kg DM)	367^{a}	381^{a}	233^{b}	332^{ab}	33.9	0.015	0.003

Note: %dBNDF: intestinal digestibility of rumen bypass NDF (in % of BNDF); %IDBNDF: intestinal digestible rumen bypass NDF (in % of NDF); IDBNDF: intestinal digestible rumen bypass NDF (in g/kg DM); %TDNDF: total digestible neutral detergent fiber (in % of NDF); TDNDF: total digestible neutral detergent fiber (in g/kg DM); %dBST: intestinal digestibility of rumen bypass ST (in % of BST); %IDBST: intestinal digestible rumen bypass ST (in % of ST); IDBST: intestinal digestible rumen bypass ST (in g/kg DM); %TDST: total digestible starch (in % of starch); TDST: total digestible starch (in g/kg DM); SEM: standard error of mean; $^{a-b}$ Means with the different letters in the same row are significant different ($P < 0.05$); Multi-treatment comparison: Tukey method;

4.6.3 Effect of oat varieties and types (feed type vs. milling type) on hourly effective rumen degradation ratios and potential nitrogen to organic matter synchronization in the rumen

As is known, balancing the rate of supply of nitrogen and energy-producing substrates can lead to maximum capture of rumen degradable nitrogen by rumen microorganisms, thereby optimizing their growth rate and efficiency (Johnson, 1976; Sinclair et al., 1993). If cattle could capture rumen degradable nitrogen more efficiently, that would be able to reduce the need for expensive non-degradable protein sources and reduce the urinary nitrogen excretion. According to the study, Sinclair et al. (1993) observed that the optimal ratio between effectively degradability of available N to available organic matter (OM) was 25 g N/kg OM. Being at this rate could prevent nitrogen loss and maximize microbial synthesis. Below this optimum value indicates that there is not enough nitrogen to allow microbial growth, while above the optimal value implies potential nitrogen loss or insufficient energy to allow using nitrogen for microbial protein synthesis (Nuez-Ortín & Yu, 2010). The effect of oat varieties and types (feed type vs. milling type) on potential available nitrogen (N) to OM synchronization at different incubation time points is presented in Table 4.7, and the effect of oat varieties on hourly effective degradation ratios is shown in Figure 4.1. The details of the results demonstrated that oat varieties had significant effect on the ratio of N to OM of the oat, and CDC Haymaker oat had the highest ratio of N to OM among oat varieties (29 g/kg, $P<0.05$), and CDC Arborg, Summit, and CDC Nasser oat had similar ratio of N to OM (26, 25, and 24 g/kg). In addition, oat types also had significant impact on the ratio of N to OM of the oat. Oat varieties and types had significant impact on the ratio of effective degradability of N (ED_N) to effective degradability of OM (ED_OM) ($P<0.05$). CDC Haymaker oat had larger ratio of ED_N to ED_OM than CDC Arborg and Summit oat (38 vs. 29, 30 g/kg, $P<0.05$), but had similar ratio of ED_N to ED_OM with CDC Nasser oat (32 g/kg). According to the hourly effective degradability ratios, significant differences were found at all the time points (P<0.05). From 0-1 h of incubation, CDC Nasser and CDC Haymaker oat had a big drop on the effective degradability ratio and then had stable effective degradability ratios from 1-24 h of incubation. On the contrary, Summit and CDC Arborg oat had a big increase from 0-1 h, and CDC Arborg oat had effective degradability ratios from 1-24 h of incubation. While Summit oat gradually decreased from 1-24 h of incubation on the effective degradability ratios. As for the oat types, there were significant differences on the effective degradability ratios from 0-16 h of incubation, but there were no significant differences on the effective degradability ratios from 16-24 h of incubation. In conclusion, CDC Arborg oat was closest to the optimal ratio of ED_N to ED_OM (25 g/kg), but all of them had potential nitrogen loss or insufficient energy for microbial protein synthesis.

In Study Phase II, we did effect of oat varieties and types on rumen degradation kinetics, intestinal digestion characteristics, and N to OM synchronization. To better evaluate the nutrient contents of oat grains, the true nutrient supply of oat grains would be analyzed based on the DVE/OEB and NRC-2001 model.

Table 4.7. Effect of oat varieties and types (feed type vs. milling type) on potentially available N to OM synchronization in terms of hourly effective degradability ratios of oat.

Items	Oat variety				SEM	P value	Contrast P value Milling Type vs Feed Type
	CDC Arborg (Milling)	Summit (Milling)	CDC Nasser (Feed)	CDC Haymaker (Forage)			
Ratio of N to OM of the oat							
N/OM (g/kg)	26^{b}	25^{b}	24^{b}	29^{a}	0.5	0.002	0.039
Ratio of ED_N to ED_OM of the oat							
ED_N/ED_OM (g/kg)	29^{b}	30^{b}	32^{ab}	38^{a}	1.6	0.021	0.095
Hourly Effective Degradability Ratios							
0 h	26^{bc}	24^{c}	56^{a}	48^{ab}	3.9	0.008	0.003
1 h	33^{ab}	37^{a}	21^{b}	35^{a}	2.4	0.021	0.006
2 h	33^{a}	36^{a}	21^{b}	35^{a}	2.2	0.016	0.005
3 h	33^{a}	35^{a}	21^{b}	35^{a}	2.0	0.012	0.003
4 h	33^{a}	35^{a}	21^{b}	35^{a}	2.0	0.009	0.003
6 h	33^{a}	33^{a}	21^{b}	35^{a}	1.5	0.004	0.001
8 h	33^{a}	32^{a}	21^{b}	35^{a}	1.2	0.002	0.001
10 h	33^{a}	31^{a}	21^{b}	35^{a}	1.0	0.001	<0.01
12 h	33^{ab}	30^{b}	21^{c}	36^{a}	0.9	0.001	<0.01
16 h	33^{b}	28^{c}	22^{d}	37^{a}	1.0	<0.01	<0.01
20 h	33^{a}	26^{ab}	20^{b}	33^{a}	2.8	0.026	0.022
24 h	33^{a}	24^{b}	21^{b}	37^{a}	1.8	0.004	0.014

SEM: standard error of mean; $^{a\text{-}b}$ Means with the different letters in the same row are significant different ($P < 0.05$); Multi-treatment comparison: Tukey method; ED: effective degradability; OM: organic matters.

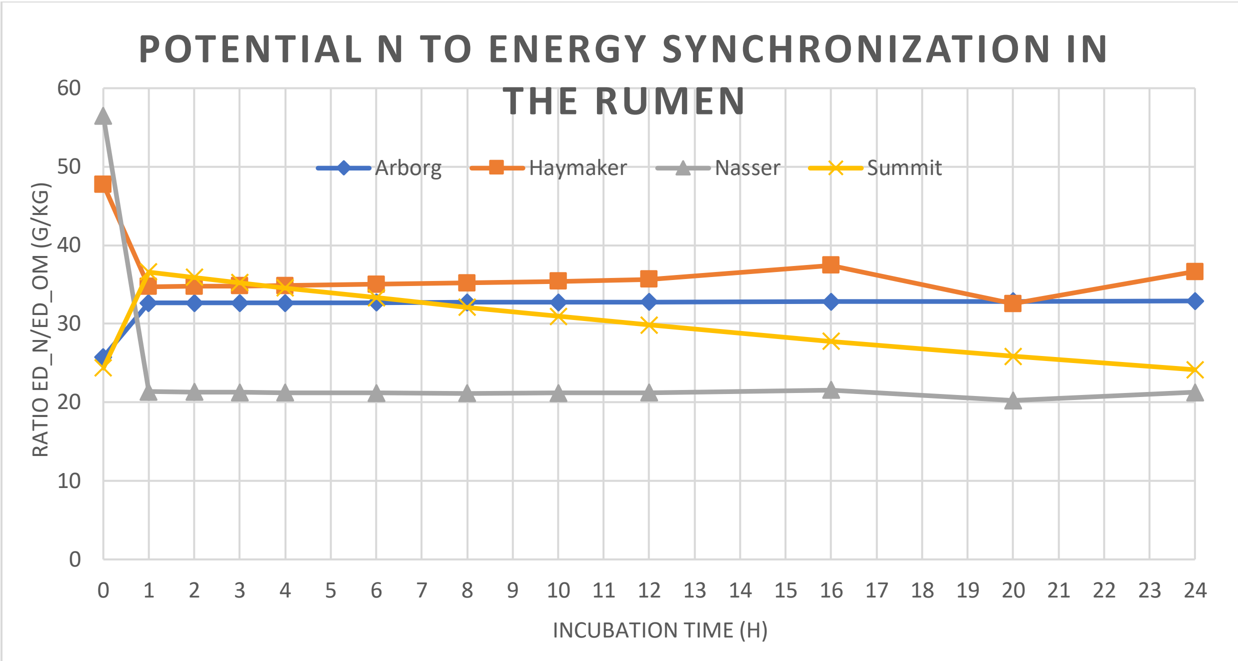

Figure 4.1. Hourly effective degradation ratios (ED_N/ED_OM) between available N and available OM of different varieties of oat.

4.7 Chapter Summary and Conclusions

Four oat varieties had differences on most characteristics of in situ DM, CP, and starch, such as DM, CP and starch Kd, BDM, EDDM, EDCP, BST, and EDST. There was no significant difference on in situ NDF characteristics. CDC Nasser oat, with lowest lignin and highest fat content, had lowest DM, CP and starch Kd, and lowest EDDM, EDCP and EDST among varieties, which might indicate that lignin content probably changes the inner structure and have a more rigid protein-starch matrix structure, which need to be revealed using synchrotron molecular spectroscopic technology. Comparing to other oat varieties, roller milling gap changes had bigger impact on the nutrient digestion of CDC Nasser oat. On the contrary, CDC Haymaker oat had largest values on these characteristics in these oat varieties. Feed oat had larger NDF Kd value than milling oat. Oat varieties and types also had significant impact on the intestinal digestion of nutrients including %dBDM, %IDBDM, %TDDM, %IDBCP, %TDCP, and %TDST. Milling oat had larger %dBDM, IDBDM, TDDM, and TDST values than feed oat. Moreover, oat varieties and types also had significant impact on the ratio of ED_N to ED_OM and all the hourly effective degradability ratios, and feed type of oat had larger ratio of ED_N to ED_OM of the oat than milling type. The results help us understand the DM, protein, NDF and starch degradability of different varieties and types of oat in the rumen. In conclusion, this study suggests that CDC Arborg oat can provide higher effective degradability of DM, CP, and starch in the rumen, and it could contribute to the maximum microbial protein while assuming minimal nitrogen loss. It also presents the reference for providing a combination of energy and protein supplements to potentially increase the efficiency of nutrient utilization which could improve animal performance in future animal production study.

5. METABOLIC CHARACTERISTICS AND TRULY DIGESTIBLE NUTRIENT SUPPLY TO DAIRY COWS: EFFECT OF OAT VARIETIES AND TYPES (FEED TYPE VS. MILLING TYPE)

5.1 Abstract

The objective of this study was to investigate effect of oat varieties and types (feed type vs. milling type) on metabolic characteristics, truly digestible nutrient supply, and feed milk value (FMV). Twelve samples [4 varieties (CDC Arborg, CDC Haymaker, CDC Nasser, Summit) × 3 harvested years (2018, 2019, 2020)] were used in this study. The DVE/OEB system and NRC-2001 system were applied to evaluate these parameters. The experiment design was RCBD design (oat varieties as a fixed effect and harvested year as a random block effect). MIXED procedure model of SAS 9.4 was used for statistical analysis, and significance was declared at $P<0.05$ and tendency at $0.05 \leq P<0.1$. Based on the DVE/OEB system, results showed that microbial protein synthesized in the rumen based on available nitrogen (MREN, g/kg DM), microbial protein synthesized in the rumen based on available energy (MREE, g/kg DM), truly absorbed microbial protein in the small intestine (DVME, g/kg DM), truly digested protein in the small intestine (DVE, g/kg DM) and feed milk value (FMV, kg milk /kg feed) of CDC Nasser oat were lowest in these four varieties although CDC Nasser oat had no significant differences on MREN content with CDC Arborg and Summit oat. CDC Nasser oat had highest endogenous protein loss (ENDP, g/kg DM) and undigested dry matter (UDM, g/kg DM) in these four oat varieties ($P<0.05$). CDC Nasser oat also had largest degraded protein balance (OEB, g/kg DM) value comparing to CDC Arborg, CDC Haymaker and Summit oat, and all the OEB values were positive indicating having potential N losses from rumen. There were significant differences in the MREN, MREE, DVME, ENDP, UDM, DVE, OEB and FMV between feed oat and milling oat ($P<0.05$), and feed oat had larger

OEB values than milling oat. Based on the NRC-2001 model, oat varieties had significant impact on microbial protein synthesized in the rumen based on available energy (MCP_{TDN}, g/kg DM), microbial protein synthesized in the rumen based on available protein (MCP_{RDP}^{NRC}, g/kg DM) and truly absorbed microbial protein in the small intestine (AMCP, g/kg DM) (P<0.05). CDC Haymaker oat had higher metabolizable protein (MP) and FMV than Summit oat (P<0.05), and had similar MP and FMV with CDC Arborg and CDC Nasser oat. As for the oat types, significant differences were found on MCP_{TDN}, MCP_{RDP}, AMCP, and DPB between feed type and milling type, and feed oat had better FMV compared to milling oat.

5.2 Introduction

Oat was introduced to Canada in the early 17th century by European settlers. Nowadays, it is a common cereal grain for livestock and human consumption in Canada. In Western Canada, barley grains are widely used in the diet of cattle. For example, lactating dairy cows need to consume a high-energy diet to maintain milk yield, and so farmers will add 40-55% concentrates to the diet to supply the starch as energy sources. As the price of barley increased, people began to look for other cereal grains like oat to replace barley grains and reduce the feed costs. Previous studies reported that there was no negative impact of replacing barley by oat grains in performance or even increasing milk production although the milk fat and protein could be reduced (Ekern et al., 2003; Fuhr, 2006; Martin & Thomas, 1988; Vanhatalo et al., 2008; Yu et al., 2010). Before doing animal experiments, the nutritional model would be applied to evaluate the metabolic characteristics of the feeds to save sources and make adjustments for formulating diets, there is also limited studies to compare metabolic characteristics among different Canadian oat varieties. In this phase, NRC-2001 model and the DVE/OEB system were applied to evaluate the metabolic characteristics and feed milk value of different oat varieties to select the optimal oat variety replacing barely.

5.3 Study Objectives

To determine the impact of oat variety and type (feed type vs. milling type) on metabolic characteristics and truly digestible nutrient supply, and feed milk value (FMV).

5.4 Study Hypothesis

Four oat varieties would have differences on metabolic characteristics, truly digestible nutrient supply, and feed milk value (FMV) with expecting that feed type (CDC Nasser and CDC Haymaker) of oat would have higher nutritional value.

5.5 Materials and Methods

The University of Saskatchewan Animal Care Committee approved the animal study under the Animal Use Protocol No. 19910012 and animals were cared for and handled in accordance with the Canadian Council of Animal Care (CCAC, 1993, 2009) regulations.

5.5.1 Sample treatments

Three different varieties of oat grain (CDC Haymaker, CDC Nasser, and CDC Arborg) were obtained from Crop Development Center (CDC), University of Saskatchewan, Canada. One variety (Summit) was developed by Agriculture and Agri-Food Canada, Cereal Research Center (AAFC-CRC), Winnipeg, MB. Specifically, CDC Haymaker oat was a feed type with average 24.9% of hull. Summit already is a popular milling type while CDC Arborg is newer milling type, with average 21.6% and 20.1% of hull, respectively. CDC Nasser oat has 21.8% of hull, which is a feed type (SaskSeed Guide, 2023). These four varieties of oats were grown in the same Crop Development Center research fields and harvested from three consecutive years (2018, 2019, 2020), 12 samples in total, were used in this study.

5.5.2 Prediction nutrient supply with DVE/OEB system

The true protein digested in the small intestine (DVE) and rumen degradable protein balance (OEB) was predicted by the Dutch evaluation system (DVE/OEB) according to the following equations (Tamminga et al., 1994; Yu, 2005). DVE makes up of digestible feed protein escaping rumen degradation, microbial protein and correction of endogenous protein losses. Therefore, DVE (g/kg DM) = DVME + DVBE – ENDP, where DVME was absorbable fraction of microbial crude protein; DVME (g/kg DM) = 0.85 × 0.75 × MREE, where 0.85 was the assumed digestibility of microbial protein, and 0.75 was assumed to be presented as amino acids; DVBE was absorbable fraction of ruminal undegraded feed protein; DVBE (g/kg DM) = dRUP × BCP; BCP (g/kg DM) = 1.11 × CP × %RUP, where RUP = U + D × Kp / (Kp + Kd), and Kp = 0.06 h^{-1}; 1.11 was regression coefficient of in vivo on in situ degradation data; ENDP was the correction factor for endogenous protein lost during the digestion process; ENDP (g/kg) = 0.75 × UDM, where UDM was amount of undigested DM excreted in feces estimated as undigested organic matter plus undigested ash. While OEB represents the difference between potential microbial protein synthesis on the base of available rumen degradable protein (MREN) and on the base of available rumen degradable energy extracted from anaerobic fermentation (MREE). So, OEB (g/kg of DM) = MREN – MREE, where MREN = CP × [1 – (1.11 × RUP (% CP)/ 100)], and 1.11 was the regression coefficient of in vivo and in situ degradation data; MREE (g/kg DM) = FOM (g/kg) × 0.15, FOM was fermented organic matter in the rumen, and 0.15 represented 150 g of microbial protein was assumed to be synthesized per kg FOM.

5.5.3 Prediction nutrient supply with NRC-2001 model

The nutrient supply was calculated with following equations from NRC-2001 model. Rumen undegradable protein (RUP): RUP = CP × RUP; Rumen degradable protein (RDP): RDP = CP ×

RDP, where RDP = S + D × Kd / (Kd + Kp), and Kp = 0.06 h^{-1}; Rumen microbial protein synthesis (MCP): MCP = 0.13 × TDN, where 0.13 stands for 130 g of microbial protein assuming to be synthesized per kg of TDN; Truly absorbed microbial protein (AMCP): AMCP = 0.80 × 0.80 × MCP^{NRC}, where 0.80 was assumed digestibility and true protein available from MCP; Truly absorbed rumen undegraded protein in the small intestine (ARUP): ARUP = dRUP × RUP; Rumen endogenous crude protein (ECP): ECP = 6.25 × 1.9 × DM /1000; Truly absorbed endogenous protein in the small intestine (AECP): AECP = 0.50 × 0.80 × ECP, where 80% of rumen endogenous crude protein was assumed to be true protein, and 50% of rumen endogenous crude protein was assumed to pass into the duodenum; Metabolizable protein (MP): MP = ARUP + AMCP + AECP; Degraded protein balance (DPB): $DPB^{NRC} = RDP^{NRC} - 1.18MCP_{TDN}$, where MCP_{TDN} represented the microbial protein synthesis based on TDN.

5.5.4 Evaluation of feed milk value

Feed milk value (FMV) was evaluated by the protein metabolic characteristics from DVE/OEB system and NRC-2001 model.

5.5.5 Statics analysis

The treatment design was a one-way structure. Experimental design was RCBD design with varieties as a fixed effect, and years as a random block effect. Statistical analysis of metabolic characteristics, truly digestible nutrient supply, and feed milk value were performed using MIXED procedure of SAS version 9.4 (SAS Institute, Inc., Cary, NC, US). RCBD model was in use during analysis:

$$Y_{ij} = \mu + T_i + \beta_j + e_{ij},$$

where Y_{ij} was an observation of the dependent variable ij; μ was the population mean of variable; T_i was the effect of varieties as a fixed effect (i = 1 to 4); β_j was the block effect of year (j = 2018, 2019, 2020), and e_{ij} was the random error associated with the observation ij. Multi treatment comparison was carried out using Tukey's method and SAS orthogonal contrast was used for comparison between the feed type and milling type oat. Significance was declared at $P<0.05$ and tendency at $0.05<P\leq0.10$.

5.6 Results and Discussion

5.6.1 Effect of oat varieties and types (feed type vs. milling type) on nutrient supply with DVE/OEB system

In the DVE/OEB system, the protein values of dairy cattle feeds are all express as the amount of protein (microbial and feed sources) that is actually digested and absorbed from the animal's small intestine. This system can provide important information on quantifying rumen and post-rumen protein digestion in ruminants (Yu & Niu, 2009). In this system, the feed has a DVE value, standing for truly absorbed protein in the small intestine, and the feed also has a rumen degraded protein balance value (called OEB in this system), standing for the balance between microbial protein synthesis that may come from available rumen degradable protein and the energy could be extracted from the rumen during anaerobic fermentation. The positive OEB value means the potential loss of N from the rumen while negative OEB value means N shortage in the rumen and that will impair the microbial protein synthesis. So, the optimum OEB value of the feed is around zero or slightly above (Tamminga et al., 1994; Yu, 2005). The metabolic characteristics, and true nutrient supply of different varieties of oat using the DVE/OEB system are presented in Table 5.1. Results showed that oat varieties had significant impact on the microbial protein synthesized in the rumen based on available nitrogen (MREN) and microbial protein synthesized in the rumen based on available energy (MREE). CDC Haymaker oat had higher MREN contents than CDC Nasser oat (101 vs. 58 g/kg DM, $P<0.05$), and CDC Haymaker had similar MREN content with

CDC Arborg and Summit oat (80 and 76 g/kg DM). CDC Nasser oat had lowest MREE content (5 g/kg DM, $P<0.05$), and CDC Arborg, Summit, and CDC Haymaker oat had similar MREE contents (54, 46, and 58 g/kg DM). There were significant differences on truly absorbed microbial protein in the small intestine (DVME), endogenous protein loss (ENDP), and undigestible dry matter (UDM). CDC Nasser oat had lowest DVME content (3 g/kg DM, $P<0.05$), and CDC Arborg, Summit and CDC Haymaker oat had similar DVME contents (35, 29, and 37 g/kg DM). On the contrary, CDC Nasser oat had highest ENDP and UDM contents in these four oat varieties (41 and 549 g/kg DM, $P<0.05$). CDC Arborg, Summit and CDC Haymaker oat also had similar ENDP (27, 29, and 29 g/kg DM) and UDM (362, 380, and 387 g/kg DM) contents. No significant difference was found on truly absorbed bypass protein in the small intestine (DVEB), but CDC Nasser oat had largest DVEB value among oat varieties. In addition, CDC Nasser oat also had lowest total truly digested protein in the small intestine (DVE) (18 g/kg DM, $P<0.05$). CDC Arborg had similar DVE content with Summit and CDC Nasser oat (58 vs. 45 and 50 g/kg DM). However, CDC Nasser oat had largest degraded protein balance (OEB) value in these oat varieties (53 g/kg DM), which had larger OEB value than CDC Arborg and Summit oat (26 and 30 g/kg DM, $P<0.05$) and had similar OEB value with CDC Haymaker oat (43 g/kg DM). The results indicated that all these oat varieties had much larger OEB values than 0, and they had nitrogen losses from rumen. In Yu and Niu's study (2009), they reported that the value of CDC SO-1 oat, with low lignin and high fat content, was 7 g/kg DM that was smaller than CDC Nasser from our study (53 g/kg DM). There were also big discrepancies on the DVE values between these two studies. Compared to Tosta's study (2019), their OEB values of oat were negative, but ours were positive. It indicated that roller milling gap changes also had big influence on it. Our roller miller gap was 1.00 mm, and it was not enough for breaking down the hulls of grains and digesting the nutrients of grains totally. So, there was nitrogen losses from the rumen. Oat types (feed type vs. milling type) had significant impact on MREN, MREE, DVME, ENDP, UDM, DVE, and OEB ($P<0.05$), and feed oat had larger OEB values than milling oat and all the OEB values were positive, which indicates that there would be a trend of potential loss of N from the rumen when added these oat grains to the dairy cows' diet with roller miller gap of 1.00 mm.

5.6.2 Effect of oat varieties and types (feed type vs. milling type) on nutrient supply with NRC-2001 system

The effect of oat varieties and types (feed type vs. milling type) of truly digestible nutrient supply and feed milk value using NRC model are presented in Table 5.2. Results demonstrated that there were significant impacts on microbial protein synthesized in the rumen based on available energy (MCP_{TDN}), microbial protein synthesized in the rumen based on available protein (MCP_{RDP}), and truly absorbed rumen undegradable protein in the small intestine (AMCP) ($P<0.05$). More specifically, CDC Nasser oat had higher MCP_{TDN} comparing to CDC Arborg and CDC Haymaker oat (98 vs. 91 and 91 g/kg DM, $P<0.05$), and had similar MCP_{TDN} content with Summit oat (94 g/kg DM). However, the value of MCP_{RDP} (55 g/kg DM) and AMCP (35 g/kg DM) of CDC Nasser oat were smallest in these four varieties. CDC Haymaker oat had higher MCP_{RDP} (86 g/kg DM) and AMCP (54 g/kg DM) than CDC Nasser oat ($P<0.05$), and CDC Haymaker oat had similar MCP_{RDP} (75 and 71 g/kg DM) and AMCP (48 and 45.4 g/kg DM) contents with CDC Arborg and Summit oat although they are from different types. For the truly absorbed rumen undegradable protein in the small intestine (ARUP), truly absorbed rumen endogenous protein in the small intestine (AECP), and rumen endogenous protein (ECP), no significant effects were found on these characteristics among the four varieties. There was significant impact on total metabolizable protein supply in the small intestine (MP) in these four varieties ($P<0.05$), and CDC Haymaker had higher MP content than that of Summit oat (106 vs. 90 g/kg DM, P<0.05), which had similar MP content with CDC Arborg and CDC Nasser oat (97 and 92 g/kg DM). There was also significant impact on degraded protein balance (DPB) value in these four oat varieties, CDC Haymaker and CDC Arborg oat had larger DPB value than CDC Nasser oat (-5, -20 vs. -51 g/kg DM, P<0.05), and had similar DPB value with Summit oat (-28 g/kg DM). Lastly, oat types (feed type vs. milling type) had significant impact on MCP_{TDN}, MCP_{RDP}, AMCP, and DPB but no significant differences on other characteristics of truly nutrient supply based on NRC-2001 system. In the study by Yu et al. (2008), they observed that CDC SO-1 oat, with low lignin and high fat contents like CDC Nasser oat, had highest MP content comparing to other conventional oat varieties, and its DPB value was much close to zero comparing with other oat varieties although they were all negative. In our study, there was no significant difference on MP among CDC Nasser, CDC Haymaker and CDC Arborg oat while the value of MP of CDC Haymaker was largest instead of CDC Nasser oat, and DPB value of four oat varieties were also negative and the DPB value of CDC Haymaker oat was closest to zero, which indicated the potential imbalance between microbial protein synthesis from available rumen degradable CP and potential energy from anaerobic fermentation in the rumen.

5.6.3 Effect of oat varieties and types (feed type vs. milling type) on feed milk value

The effect of oat varieties and types (feed type vs. milling type) on feed milk value (FMV) were presented in Table 5.1 and 5.2. These feed milk values are only based on protein values. The FMV content of CDC Nasser oat was lowest in these four varieties (0.35 kg milk /kg feed, P<0.05) based on the Dutch DVE/OEB system. CDC Arborg oat had higher FMV content than Summit oat (1.18 vs. 0.92 kg milk /kg feed, P<0.05), and had similar FMV content with CDC Haymaker oat (1.05 kg milk /kg feed). Oat types also had significant impact on the FMV parameters (P<0.05). It was in contrast with Tosta's study, which observed CDC Nasser oat had no significant difference on FMV with other oat varieties and they had similar FMV content ranged from 2.05 to 2.10 that were much larger than ours (Tosta, 2019). So, changing the gap of roller milling also had big influence on the FMV of CDC Nasser oat based on DVE/OEB system like rumen degradation kinetics.

Based on the NRC-2001 model, oat varieties also had significant impact on the FMV content ($P<0.05$), but oat types had no significant impact on the FMV. CDC Haymaker oat had higher FMV than Summit oat (2.15 vs. 1.83 kg milk /kg feed, $P<0.05$), and had similar FMV with CDC Arborg and CDC Nasser oat (1.98 and 1.86 kg milk /kg feed). It was pretty similar with Tosta's study, and CDC Nasser oat also had no significant difference on FMV content with other oat varieties, and the FMV values were pretty similar with Tosta's FMV values (Tosta, 2019). However, Prates et al. (2018) found that CDC Nasser oat had significant difference on FMV with common oat varieties. Comparing with other cereal grains like barley, the values of FMV of oat were smaller based on both systems (Prates et al., 2018; Tosta, 2019).

Table 5.1. Effect of oat varieties and types (feed type vs. milling type) on truly digestible nutrient supply and feed milk value using the DVE/OEB system.

Items	Oat variety				SEM	P value	Contrast P value Milling Type vs Feed Type
	CDC Arborg (Milling)	Summit (Milling)	CDC Nasser (Feed)	CDC Haymaker (Forage)			
Truly digestible nutrient supply to dairy cattle							
MREN (g/kg DM)	80^{ab}	76^{ab}	58^{b}	101^{a}	7.5	0.021	0.040
MREE (g/kg DM)	54^{a}	46^{a}	5^{b}	58^{a}	4.8	0.001	<0.01
DVME (g/kg DM)	35^{a}	29^{a}	3^{b}	37^{a}	3.0	0.001	<0.01
DVEB (g/kg DM)	50	45	56	42	5.2	0.308	0.229
ENDP (g/kg DM)	27^{b}	29^{b}	41^{a}	29^{b}	1.8	0.008	0.002
UDM (g/kg DM)	362^{b}	380^{b}	549^{a}	387^{b}	23.9	0.008	0.002
Total truly digested protein in the small intestine							
DVE (g/kg DM)	58^{a}	45^{a}	18^{b}	50^{a}	3.1	0.002	0.001
Degraded protein balance							
OEB^{DVE} (g/kg DM)	26^{b}	30^{b}	53^{a}	43^{ab}	2.3	0.019	0.005
Feed milk value based on DVE							
FMV^{DVE} (kg milk /kg feed)	1.18^{a}	0.92^{b}	0.35^{c}	1.02^{ab}	0.051	0.001	<0.01

Notes: MREN = N_MCP = RDP: microbial protein synthesized in the rumen based on available nitrogen; MREE = E_MP: microbial protein synthesized in the rumen based on available energy; DVME = AMP^{DVE}: truly absorbed microbial protein in the small intestine; DVEB = $ABCP^{DVE}$: truly absorbed bypass protein in the small intestine; ENDP: endogenous protein loss; UDM: undigestible dry matter; DVE (DVE = DVME + DVEB −ENDP) : truly digested protein in the small intestine; OEB^{DVE} (OEB = MREN – MREE): degraded protein balance; FMV: feed milk value. SEM: standard error of mean; $^{a-b}$ Means with the different letters in the same row are significant different (P < 0.05); Multi-treatment comparison: Tukey method.

Table 5.2. Effect of oat varieties and types (feed type vs. milling type) on truly digestible nutrient supply and feed milk value using the NRC-2001 model.

Items	Oat variety				SEM	P value	Contrast P value Milling Type vs Feed Type
	CDC Arborg (Milling)	Summit (Milling)	CDC Nasser (Feed)	CDC Haymaker (Forage)			
Truly digestible nutrient supply to dairy cattle							
MCP_{TDN} (g/kg DM)	91^{b}	94^{ab}	98^{a}	91^{b}	1.0	0.009	0.008
MCP_{RDP}^{NRC} (g/kg DM)	75^{ab}	71^{ab}	55^{b}	86^{a}	6.9	0.025	0.029
$AMCP^{NRC}$ (g/kg DM)	48^{ab}	45.4^{ab}	35^{b}	54^{a}	4.2	0.014	0.014
$ARUP^{NRC}$ (g/kg DM)	45	40.3	53	48	7.0	0.561	0.256
$AECP^{NRC}$ (g/kg DM)	4.32	4.32	4.34	4.32	0.014	0.463	0.147
ECP (g/kg DM)	10.80	10.79	10.84	10.80	0.036	0.497	0.166
Total metabolizable protein supply in the small intestine							
MP^{NRC} (g/kg DM)	97^{ab}	90^{b}	92^{ab}	106^{a}	3.5	0.046	0.666
Degraded protein balance							
DPB^{NRC} (g/kg DM)	-20^{a}	-28^{ab}	-51^{b}	-5^{a}	8.2	0.013	0.014
Feed milk value based on MP							
FMV^{NRC} (kg milk /kg feed)	1.98^{ab}	1.83^{b}	1.86^{ab}	2.15^{a}	0.071	0.047	0.675

Notes: MCP_{TDN}: microbial protein synthesized in the rumen based on available energy (discounted TDN); MCP_{RDP}^{NRC}: microbial protein synthesized in the rumen based on the available protein (calculated as 0.85 of rumen degradable protein); $AMCP^{NRC}$: truly absorbed microbial protein in the small intestine; $ARUP^{NRC}$: truly absorbed rumen undegradable protein in the small intestine; $AECP^{NRC}$: truly absorbed rumen endogenous protein in the small intestine; ECP: rumen endogenous protein; MP^{NRC} (MP = AMCP + ARUP + AECP): metabolizable protein; DPB^{NRC}: degraded protein balance; FMV: feed milk value. SEM: standard error of mean; $^{a-b}$ Means with the different letters in the same row are significant different ($P < 0.05$); Multi-treatment comparison: Tukey method.

5.7 Chapter Summary and Conclusion

Differences were observed for MREN, MREE (g/kg DM), DVME (g/kg DM), ENDP (g/kg DM), UDM (g/kg DM), DVE (g/kg DM), OEB (g/kg DM) and FMV (kg milk /kg feed) based on DVE/OEB system on oat varieties and types ($P<0.05$). Detailly, CDC Nasser oat had lowest MREN, MREE, DVME, DVE and FMV although there was no significant difference on MREN among CDC Arborg, Summit, and CDC Nasser oat. CDC Nasser oat had highest ENDP and UDM contents among four oat varieties. All the OEB values of oat were positive and much larger than zero. It suggests that there would be a trend of potential loss of N from the rumen when added these oat grains to the dairy cows' diet with roller miller gap of 1.00 mm. In addition, oat varieties had significant impact on the MCP_{TDN}, MCP_{RDP}, AMCP, MP, DPB and FMV based on the NRC-2001 system. CDC Haymaker oat had largest MP supply content in the small intestine among varieties but had no significant difference with CDC Arborg and CDC Nasser oat. So, CDC Haymaker oat had largest FMV compared to other oat varieties although there was no significant difference among CDC Arborg, CDC Nasser and CDC Haymaker oat. All the oat varieties had negative DPB values, indicating the potential imbalance between microbial protein synthesis from available rumen degradable CP and potential energy from anaerobic fermentation in the rumen. In other words, the microbial protein synthesis was potentially impaired in the rumen because of a shortage of N in the rumen. There were significant differences on MCP_{TDN}, MCP_{RDP}, AMCP and DPB between two types of oat based on NRC-2001 model. Feed type of oat also had better FMV comparing to milling oat.

6. GENERAL DISCUSSION AND CONCLUSION

Oat is a common cereal grain in Canada, and its production has been gradually increased in the last two decades. Oat grains had higher fat content and they can provide more energy for livestock, especially for lactating dairy cows that need high requirement of energy. There are many oat varieties in Canada. So, selecting the optimal oat variety to replace the barley could fully utilize the value of oat as feedstuff. The main characteristics were summarized in the appendix table. In the first phase, results showed that CDC Nasser oat had highest ether extracts (EE) content and lowest acid detergent lignin (ADL) when compared to other oat varieties, which results in CDC Nasser oat having the highest energy values. This is in line with previous report that CDC Nasser oat is similar with CDC SO-1 oat bred to provide high oil and low lignin content, as well as the results of Toast (2019), Fuhr (2006) and Prates and Yu (2017). Though there were no significant differences on EE and ADL comparing to other oat varieties in the study by Prates and Yu, the value of EE and ADL of CDC Nasser or CDC SO-1 oat were highest. It indicated that CDC Nasser oat had higher digestible fiber comparing to other oat varieties due to its lower lignin (ADL) content. CDC Haymaker oat had highest crude protein (CP) content among four oat varieties ($P<0.05$). The value of CP, neutral detergent fiber (NDF), and acid detergent fiber (ADF) of CDC Haymaker oat was largest among varieties indicating that CDC Haymaker oat had highest hull content. Oat types had significant impact on EE, CP, NPN, ADL, and total CHO between feed type and milling type. Milling oat had higher non-fiber carbohydrate values such as starch than feed oat, while feed oat had higher structure carbohydrate values than milling oat although there were no significant differences between them. CDC Nasser oat had highest total digestible nutrients (TDN, %DM) comparing to other oat varieties ($P<0.05$). For those energy values of CDC Nasser oat, they were pretty similar with barleys reported by Yu et al. (2003), NRC (2001), and

NRC (1996), suggesting that CDC Nasser oat could be used as a substitute for barley as a potential energy source in dairy and beef ration. In addition, oat types had significant impact on all the energy values between feed type and milling type, and feed oat had relatively higher energy values than milling oat. Based on the CNCPS 6.5 model, CDC Nasser oat had lowest indigestible fiber fractions (CC) among varieties, and feed oat had relatively higher indigestible carbohydrates than milling oat. Niu et al. (2007) and Tosta (2019) also reported similar results with ours.

In the second phase, results revealed that CDC Haymaker and CDC Arborg oat had higher degradation rate (Kd) of DM, CP, and starch than that of CDC Nasser oat, the values of Kd (DM, CP, starch) of CDC Haymaker oat were highest while CDC Nasser's was lowest among varieties, and CDC Arborg oat had relatively higher effective degradability of DM, CP, and starch in the rumen without affecting the effective degradability of N to OM. CDC Nasser oat had highest rumen bypass dry matter (BDM, g/kg DM) and rumen bypass feed starch (BST, g/kg DM) but its effective degradability of dry matter (EDDM, g/kg DM), effective degradability of feed crude protein (EDCP, g/kg DM), and effective degradability of feed starch (EDST, g/kg DM) were lowest in these varieties. In the study by Fuhr (2006), they also reported that the Kd value on DM of LLH-HOG oat with low lignin and high oil content (similar with CDC Nasser oat in our study) was also smallest compared to other oat varieties or barley grain but no significant differences among them. There was also no significant difference on Kd of CP, EDDM, EDCP between oat varieties while LLH-HOG oat also had lower undegradable fractions of DM, which was similar with ours. Damiran and Yu (2010) found that oat varieties had no significant impact on the Kd of DM, CP, and starch, but CDC SO-1 oat with low lignin and high oil content had highest EDCP. Moreover, there were also no significant differences on Kd (DM, CP and starch), BDM, EDDM, BST, and EDST among oat varieties (CDC Nasser, CDC Arborg, and CDC Ruffian oat varieties) in the study by Tosta (2019). Comparing to other cereal grains like barley, oat had higher Kd (DM, CP, and starch), BDM, EDST and lower EDDM, BCP, BST compared to barley (CDC Austenson barley) that had similar ADL content with Nasser oat (CDC Austenson barley: 0.80% DM, CDC Nasser oat: 1.55% DM). Comparing to Tosta's study, those Kd values of DM, CP, and starch and EDDM, EDCP, EDST values were much smaller from our study. It was mainly the difference of roller milling gap. Our roller milling gap was 1.00 mm that was larger than theirs, 0.5 mm. So, it influenced all the nutrient degradation in the rumen even in the intestine. Different processing methods and even same method with different roller milling gaps had big influences on the nutrient digestion in the rumen and intestine. Our study indicated that roller miller gap of 1.00 mm was not enough for cracking the hull of grain, and microbes were still hard to penetrate the hull and digest these grains. So, there were some potential nutrients losses when adding these oat grains with roller miller gap of 1.00 mm into the dairy cattle's ration. Other studies also reported that oat had highest Kd of protein and starch comparing to barley, wheat, sorghum, and corn (Herrera-Saldana et al., 1990; Pan et al., 2021; Prestløkken, 1999). Previous studies also found that different cereal grains have different protein-starch matrix structure even same cereal grain in different varieties, which could result in differences of rumen digestion (McAllister et al., 1993; Yu et al., 2004). Typically, oat had spherical protein-starch bodies in a rather loose arrangement while the protein in barley formed a fairly rigid matrix in which starch granules were embedded (Webster & Wood, 2011). This indicated that it was harder for rumen microbes to penetrate and digest the cereal grains with rigid protein-starch matrix. There was also greater variability in the composition of proteins. For example, barley mainly had globulins and insoluble prolamins while oat mainly had globulin and soluble albumins (El Halal et al., 2019; Hoseney, 1994). So, differences of protein and starch degradation in the rumen may be attributed to these reasons. In our study, CDC Nasser oat with lower lignin and high oil content had lowest value of Kd (DM, CP, and starch). It was mainly the difference of roller milling gap compared to Tosta's study, and this roller milling gap change had bigger influence on CDC Nasser oat than other oat varieties. On the other hand, it may be due to the fact it has tighter protein-starch matrix. CDC Nasser oat had lower lignin content, and it needs this tighter structure to keep it hard state when they get mature. Last but not least, higher oil content in CDC Nasser oat also probably influences the degradation rate of DM, CP, and starch. Compared to milling oat, feed oat had larger NDF Kd value. As for the intestinal nutrient digestibility, the values of intestinal digestibility of rumen bypass dry matter (%dBDM), intestinal digestibility of rumen bypass protein (%dBCP), and intestinal digestibility of rumen bypass starch (%dBST) of Summit oat were largest, although oat varieties had no significant impact on the %dBST. It indicated that feeding Summit oat to dairy cows probably provided more nutrients to the small intestine. While the values of total digestible dry matter (TDDM), total digestible protein (TDCP), and total digestible starch (TDST) of CDC Nasser oat were smallest among varieties. Milling oat had higher %dBDM, IDBDM, TDDM, %dBST, and TDST values than feed oat. According to the previous studies, the %dBCP of CDC Nasser oat was smallest comparing to barley, corn and wheat (Peng et al., 2014; Żebrowska et al., 1997). In the current study, Arborg oat had similar ratio of effective degradability of N to effective degradability of organic matter (OM) of the oat (ED_N/ED_OM) with Summit and CDC Nasser oat, which had lower ED_N/ED_OM content than CDC Haymaker oat. The ED_N/ED_OM of CDC Arborg oat was closest to the optimal ratio of 25 g N/kg OM.

In the third phase, results found that CDC Nasser oat had lowest truly digested protein in the small intestine (DVE, g/kg DM) and feed milk value (FMV, kg milk /kg feed) among these varieties based on Dutch DVE/OEB system ($P<0.05$). In other words, CDC Arborg, CDC Haymaker, and

Summit oat had similar DVE and FMV contents. While CDC Nasser oat had highest endogenous protein loss (ENDP, g/kg DM) and undigestible dry matter (UDM, g/kg DM) ($P<0.05$). CDC Nasser oat also had largest degraded protein balance (OEB, g/kg DM) value but there was no significant difference in OEB between CDC Nasser and CDC Haymaker oat. The degraded protein balance (OEB) value of CDC Nasser oat was 53 g/kg DM in our study, which was much larger than the OEB value of CDC SO-1 oat (6.95 g/kg DM) from Yu and Niu (2009), and all the oat varieties had much larger OEB values than zero indicating adding these oat with roller miller gap of 1.00 mm into the ration of dairy cattle would have potential N loss from the rumen. Oat types had significant impact on the MREN, MREE, DVME, ENDP, UDM, DVE, OEB and FMV between feed oat and milling oat ($P<0.05$). Feed oat tend to have larger OEB values than milling oat. On the basis of NRC-2001 model, CDC Haymaker had higher truly absorbed microbial protein in the small intestine (AMCP) than CDC Nasser oat, and had similar AMCP with Arborg and Summit oat. CDC Haymaker had similar degraded protein balance (DPB, g/kg DM) with CDC Arborg and Summit, but CDC Haymaker and CDC Arborg oat had higher DPB values than CDC Nasser oat ($P<0.05$). CDC Haymaker oat had similar metabolizable protein supply in the small intestine (MP) and FMV with CDC Arborg and CDC Nasser oat, and had higher MP content and FMV than Summit oat. It was different with the result of Yu et al. (2008), and they observed that CDC SO-1 oat had highest MP content compared to conventional oat varieties. Oat types had significant impact on MCP_{TDN}, MCP_{RDP}, AMCP, and DPB, but Feed type tended to have a better FMV value compared to milling oat.

In conclusion, CDC Arborg, CDC Haymaker, and Summit oat had similar chemical profiles, energy values, and protein and carbohydrate fractions. CDC Nasser oat had highest EE and lowest ADL content in these four varieties. So, CDC Nasser oat had lowest indigestible fiber fraction (CC) because of lowest ADL content and CDC Nasser oat had largest energy values and total digestible nutrients (TDN) values among four varieties. Oat types had significant impact on EE, CP, NPN, ADL and total CHO between feed type and milling type. Milling oat had higher non-fiber carbohydrate values, while feed oat had higher structure carbohydrate values than milling oat. The values of Kd (DM, CP, and starch) of CDC Haymaker oat were largest while CDC Nasser's were smallest, and CDC Nasser oat also had lowest EDDM, EDCP, and EDST among varieties. The values of %dBDM, %dBCP, %dBST of AC Summit oat were largest, and CDC Arborg oat was closest to the optimal ratio of ED_N/ED_OM of 25 g N/kg OM. In third phase, CDC Arborg, Summit and CDC Haymaker oat had similar MREN, MREE, DVME, ENDP, UDM, DVE, OEB and FMV contents, and all the oat varieties had much larger OEB values than zero based on DVE/OEB system indicating they had potential N losses in the rumen. Oat varieties had significant impact on MCP_{TDN}, MCP_{RDP}, AMCP, MP, DPB and FMV based on the NRC-2001 model. This study indicated that CDC Nasser oat had lower indigestible carbohydrates and had higher energy values. It could be a good source of energy for dairy cows. However, its EDDM, EDCP, EDST, and FMV (based on DVE/OEB system) were lowest, and it could lead to potential loss of N from the rumen when this variety of oat fed to dairy cows with roller milling gap of 1.00 mm. CDC Haymaker oat had higher values on CP, EDDM, EDCP, EDST and FMV (DVE/OEB) among varieties. CDC Haymaker oat had higher values on crude protein, EDDM, EDCP, EDST and FMV (DVE/OEB) among varieties. However, its indigestible neutral detergent fiber was highest. All the varieties of oat grains can be added to the ration of dairy cows, but CDC Nasser oat was the optimal oat variety to replace barley grain based on the TDN values from this study. Compared to the previous study by Tosta from our group, the Kd (DM, CP, and starch) values and effective degradability values from our study were much smaller than theirs because the roller milling gap from our study was 1.00 mm that was larger than their roller milling gap of 0.5 mm. It indicated that roller milling gap of 1.00 mm was not enough for cracking the hull of oat grain, which led to the loss of nutrients.

This is a pilot study, and these results are predictions based on the models. In the future, in order to further evaluate and select the optimal oat variety to replace the barley grain, animal experiments and RUSITEC experiments will be conducted with these four oat varieties and the most popular barley to see if they would have any effect on the cow performance and methane emissions. The synchrotron based on mid-infrared spectroscopy and micro-CT scans will also be carried out to see what the differences of protein-starch matrix or other inner structures among different oat varieties and barley are.

7. REFERENCES

Arya, S. (2010). Effects of dietary inclusion levels of a low lignin hull, high-oil groat oat on the performance, carcass characteristics and rumen fermentation characteristics of feedlot cattle. MSc Thesis. University of Saskatchewan, Saskatoon, Canada.

Bai, J., Ren, Y., Li, Y., Fan, M., Qian, H., Wang, L., Wu, G., Zhang, H., Qi, X., Xu, M., & Rao, Z. (2019). Physiological functionalities and mechanisms of β-glucans. Trends in Food Science & Technology, 88, 57–66. https://doi.org/10.1016/j.tifs.2019.03.023

Ban, Y. (2016). Molecular Structural, Physiochemical and Nutritional Characterization of New Lines of Brassica Carinata and the Co-products. M.Sc. Thesis. University of Saskatchewan, Saskatoon, Canada.

Bernard Rene, B. (1997). Oat: Wild and Cultivated, a monograph of the genus Avena L. (Poaceae). Ottawa: Thorn Press.

Błaszczyk, K., Wilczak, J., Harasym, J., Gudej, S., Suchecka, D., Królikowski, T., Lange, E., & Gromadzka-Ostrowska, J. (2015). Impact of low and high molecular weight oat beta-glucan on oxidative stress and antioxidant defense in spleen of rats with LPS induced enteritis. Food Hydrocolloids, 51, 272–280. https://doi.org/10.1016/j.foodhyd.2015.05.025

Boffetta, P., Thies, F., & Kris-Etherton, P. (2014). Epidemiological studies of oat consumption and risk of cancer and overall mortality. British Journal of Nutrition, 112(S2), S14–S18. https://doi.org/10.1017/S0007114514002268

Brown, L., Rosner, B., Willett, W. W., & Sacks, F. M. (1999). Cholesterol-lowering effects of dietary fiber: A meta-analysis. The American Journal of Clinical Nutrition, 69(1), 30–42. https://doi.org/10.1093/ajcn/69.1.30

Calsamiglia, S., & Stern, M. D. (1995). A three-step in vitro procedure for estimating intestinal digestion of protein in ruminants2. Journal of Animal Science, 73(5), 1459–1465. https://doi.org/10.2527/1995.7351459x

Canadian Grain Commission. (2022). Production statistics and harvest quality of western Canadian oat in 2022. https://grainscanada.gc.ca/en/grain-research/export-quality/cereals/oats/2022/preliminary/

CCAC. (1993). Guide to care and use of experimental animals (2nd ed., Vol. 1). Canadian Council of Animal Care.

Crosbie, G. B., Tarr, A. W., Portmann, P. A., & Rowe, J. B. (1985). Variation in Hull Composition and Digestibility Among Oat Genotypes. Crop Science, 25(4), 678–680. https://doi.org/10.2135/cropsci1985.0011183X002500040023x

Damiran, D., & Yu, P. (2010). Structural Makeup, Biopolymer Conformation, and Biodegradation Characteristics of a Newly Developed Super Genotype of Oat (CDC SO-I versus Conventional Varieties): A Novel Approach. Journal of Agricultural and Food Chemistry, 58(4), 2377–2387. https://doi.org/10.1021/jf903514t

Daou, C., & Zhang, H. (2012). Oat Beta-Glucan: Its Role in Health Promotion and Prevention of Diseases. Comprehensive Reviews in Food Science and Food Safety, 11(4), 355–365. https://doi.org/10.1111/j.1541-4337.2012.00189.x

Eastridge, M. L. (2002). Energy in the New Dairy NRC. https://dairy.osu.edu/sites/dairy/files/imce/PDF/Feed_PDF/Energy%20New%20Dairy%20NRC.pdf

Ekern, A., Havrevoll, Ø., Haug, A., Berg, J., Lindstad, P., & Skeie, S. (2003). Oat and Barley Based Concentrate Supplements for Dairy Cows. Acta Agriculture Scandinavica, Section A - Animal Science, 53(2), 65–73. https://doi.org/10.1080/09064700310012476

El Halal, S. L. M., Kringel, D. H., Zavareze, E. D. R., & Dias, A. R. G. (2019). Methods for Extracting Cereal Starches from Different Sources: A Review. Starch - Stärke, 71(11–12), 1900128. https://doi.org/10.1002/star.201900128

ElSawy, A., ElMaddawy, Z., & BoGhazel, H. (2015). The Growth Promoting Effect of Beta-glucan in Comparison with Sodium Butyrate in Broiler Chicks. Alexandria Journal of Veterinary Sciences, 44(1), 23. https://doi.org/10.5455/ajvs.163992

Fant, P., Ramin, M., & Huhtanen, P. (2021). Replacement of barley with oat and dehulled oat: Effects on milk production, enteric methane emissions, and energy utilization in dairy cows fed a grass silage-based diet. Journal of Dairy Science, 104(12), 12540–12552. https://doi.org/10.3168/jds.2021-20409

Fant, P., Ramin, M., Jaakkola, S., Grimberg, Å., Carlsson, A. S., & Huhtanen, P. (2020). Effects of different barley and oat varieties on methane production, digestibility, and fermentation pattern in vitro. Journal of Dairy Science, 103(2), 1404–1415. https://doi.org/10.3168/jds.2019-16995

FAO & US Department of Agriculture. (2023). Worldwide production of grain in 2022/23. In Statista. https://www.statista.com/statistics/263977/world-grain-production-by-type/

Fearon, A. M., Mayne, C. S., & Charlton, C. T. (1998). Effect of naked oat in the dairy cow's diet on the oxidative stability of the milk fat. Journal of the Science of Food and Agriculture, 76(4), 546–552. https://doi.org/10.1002/(SICI)1097-0010(199804)76:4<546::AID-JSFA987>3.0.CO;2-S

Fearon, A. M., Mayne, C. S., & Marsden, S. (1996). The Effect of Inclusion of Naked Oat in the Concentrate Offered to Dairy Cows on Milk Production, Milk Fat Composition and Properties. Journal of the Science of Food and Agriculture, 72(3), 273–282. https://doi.org/10.1002/(SICI)1097-0010(199611)72:3<273::AID-JSFA655>3.0.CO;2-P

Ferreira, L. G., Endrighi, M., Lisenko, K. G., De Oliveira, M. R. D., Damasceno, M. R., Claudino, J. A., Gutierres, P. G., Peconick, A. P., Saad, F. M. D. O. B., & Zangeronimo, M. G. (2018). Oat beta-glucan as a dietary supplement for dogs. PLOS ONE, 13(7), e0201133. https://doi.org/10.1371/journal.pone.0201133

Fisher, L. J., & Logan, V. S. (1969). Comparison of corn and oat based concentrates for lactating dairy cows. Canadian Journal of Animal Science, 49(1), 85–90. https://doi.org/10.4141/cjas69-012

Food and Drug Administration, HHS. (2008). Food labeling: Health claims; soluble fiber from certain foods and risk of coronary heart disease. Final rule. Fed Regist. (p. 73(159):47828-9).

Fox, D. G., Sniffen, C. J., O'Connor, J. D., Russell, J. B., & Van Soest, P. J. (1992). A net carbohydrate and protein system for evaluating cattle diets: III. Cattle requirements and diet adequacy. Journal of Animal Science, 70(11), 3578–3596. https://doi.org/10.2527/1992.70113578x

Fox, D. G., Tedeschi, L. O., Tylutki, T. P., Russell, J. B., Van Amburgh, M. E., Chase, L. E., Pell, A. N., & Overton, T. R. (2004). The Cornell Net Carbohydrate and Protein System model for evaluating herd nutrition and nutrient excretion. Animal Feed Science and Technology, 112(1–4), 29–78. https://doi.org/10.1016/j.anifeedsci.2003.10.006

FPGenetics. (2014). AC Summit oat. http://redriverseeds.com/wp-content/uploads/2014/04/Summit-Oats-PDF.pdf

FPGenetics. (2020). CDC Arborg oat. https://trawinseeds.ca/wp-content/uploads/2020/05/CDC-Arborg-Oat-2020.pdf

Frølich, W., & Nyman, M. (1988). Minerals, phytate and dietary fibre in different fractions of oat-grain. Journal of Cereal Science, 7(1), 73–82. https://doi.org/10.1016/S0733-5210(88)80061-4

Fuhr, L. G. M. (2006). Low lignin hull, high oil groat oat grain in lactating dairy cow rations. M.Sc. Thesis, University of Saskatchewan, Saskatoon, Canada.

GÁLFI, P. (2012). Benefits of the application of a beta glucan formulation APG® 3-6 in animal health care and performance. Doctoral dissertation. Szent István University.

Gargallo, S., Calsamiglia, S., & Ferret, A. (2006). Technical note: A modified three-step in vitro procedure to determine intestinal digestion of proteins. Journal of Animal Science, 84(8), 2163–2167. https://doi.org/10.2527/jas.2004-704

Garleb, K. A., Bourquin, L. D., Hsu, J. T., Wagner, G. W., Schmidt, S. J., & Fahey, G. C. (1991). Isolation and chemical analyses of nonfermented fiber fractions of oat hulls and cottonseed hulls. Journal of Animal Science, 69(3), 1255. https://doi.org/10.2527/1991.6931255x

Givens, D. I., Davies, T. W., & Laverick, R. M. (2004). Effect of variety, nitrogen fertiliser and various agronomic factors on the nutritive value of husked and naked oat grain. Animal Feed Science and Technology, 113(1–4), 169–181. https://doi.org/10.1016/j.anifeedsci.2003.11.009

Gozho, G. N., & Mutsvangwa, T. (2008). Influence of Carbohydrate Source on Ruminal Fermentation Characteristics, Performance, and Microbial Protein Synthesis in Dairy Cows. Journal of Dairy Science, 91(7), 2726–2735. https://doi.org/10.3168/jds.2007-0809

Grundy, M. M.-L., Fardet, A., Tosh, S. M., Rich, G. T., & Wilde, P. J. (2018). Processing of oat: The impact on oat's cholesterol lowering effect. Food & Function, 9(3), 1328–1343. https://doi.org/10.1039/C7FO02006F

Guevara, V. H. (2020). Molecular structural and nutritional evaluation of Faba bean plants as hay and silage for ruminants: Effect of tannin concentration, cutting stage, and frost-damage PhD. Thesis. University of Saskatchewan, Saskatoon, Canada.

Harris, H. R. (1949). The hull content of North Dakota barley varieties. https://library.ndsu.edu/ir/bitstream/handle/10365/23489/ndfr_19490501_v11_iss05_156.pdf?sequence=1

Heinrichs, J., Ishler, V., & Maulfair, D. (2018). Feed Efficiency in Lactating Cows and Relationship to Income Over Feed Costs. https://extension.psu.edu/feed-efficiency-in-lactating-cows-and-relationship-to-income-over-feed-costs

Herrera-Saldana, R. E., Huber, J. T., & Poore, M. H. (1990). Dry Matter, Crude Protein, and Starch Degradability of Five Cereal Grains. Journal of Dairy Science, 73(9), 2386–2393. https://doi.org/10.3168/jds.S0022-0302(90)78922-9

Higgs, R. J., Chase, L. E., Ross, D. A., & Van Amburgh, M. E. (2015). Updating the Cornell Net Carbohydrate and Protein System feed library and analyzing model sensitivity to feed inputs. Journal of Dairy Science, 98(9), 6340–6360. https://doi.org/10.3168/jds.2015-9379

Ho, H. V. T., Sievenpiper, J. L., Zurbau, A., Blanco Mejia, S., Jovanovski, E., Au-Yeung, F., Jenkins, A. L., & Vuksan, V. (2016). The effect of oat β -glucan on LDL-cholesterol, non-HDL-cholesterol and apoB for CVD risk reduction: A systematic review and meta-analysis of randomised-controlled trials. British Journal of Nutrition, 116(8), 1369–1382. https://doi.org/10.1017/S000711451600341X

Hoseney, R. C. (1994). Principles of cereal science and technology. American Association of Cereal Chemists, St. Paul, MN.

Huang, X., Khan, N. A., Zhang, X., & Yu, P. (2015). Effects of canola meal pellet conditioning temperature and time on ruminal and intestinal digestion, hourly effective degradation ratio, and potential nitrogen to energy synchronization in dairy cows. Journal of Dairy Science, 98(12), 8836–8845. https://doi.org/10.3168/jds.2014-9295

Humer, E., & Zebeli, Q. (2017). Grains in ruminant feeding and potentials to enhance their nutritive and health value by chemical processing. Animal Feed Science and Technology, 226, 133–151. https://doi.org/10.1016/j.anifeedsci.2017.02.005

Index Mundi. (2023). Leading oat producing countries worldwide in 2022. In Statista. https://www.statista.com/statistics/1073550/global-leading-oats-producers/

Islam, M., & Lee, S.-S. (2019). Advanced estimation and mitigation strategies: A cumulative approach to enteric methane abatement from ruminants. Journal of Animal Science and Technology, 61(3), 122–137. https://doi.org/10.5187/jast.2019.61.3.122

Johnson, R. R. (1976). Influence of Carbohydrate Solubility on Non-protein Nitrogen Utilization in the Ruminant. Journal of Animal Science, 43(1), 184–191. https://doi.org/10.2527/jas1976.431184x

Joint Health Claims Initiative. (2004). Final Report on Generic Health Claim for Oat and Reduction of Blood Cholesterol. http://webarchive.nationalarchives.gov.uk/nobanner/20130404135254/http://www.jhci.org.uk/approv/ oats.htm

Jung, H. G., Mertens, D. R., & Payne, A. J. (1997). Correlation of Acid Detergent Lignin and Klason Lignin with Digestibility of Forage Dry Matter and Neutral Detergent Fiber. Journal of Dairy Science, 80(8), 1622–1628. https://doi.org/10.3168/jds.S0022-0302(97)76093-4

Lanzas, C., Tedeschi, L. O., Seo, S., & Fox, D. G. (2007). Evaluation of Protein Fractionation Systems Used in Formulating Rations for Dairy Cattle. Journal of Dairy Science, 90(1), 507–521. https://doi.org/10.3168/jds.S0022-0302(07)72653-X

Licitra, G., Hernandez, T. M., & Van Soest, P. J. (1996). Standardization of procedures for nitrogen fractionation of ruminant feeds. Animal Feed Science and Technology, 57(4), 347–358. https://doi.org/10.1016/0377-8401(95)00837-3

Lopes, F., Ruh, K., & Combs, D. K. (2015). Validation of an approach to predict total-tract fiber digestibility using a standardized in vitro technique for different diets fed to high-producing dairy cows. Journal of Dairy Science, 98(4), 2596–2602. https://doi.org/10.3168/jds.2014-8665

Maria, E. (2018). Effect of genotypes, tannin level and processing methods on the physiochemical, nutritional and structural characteristics of faba bean grown in western Canada. M.Sc. Thesis. University of Saskatchewan, Saskatoon, Canada.

Martin, P. A., & Thomas, P. C. (1988). Dietary manipulation of the yield and composition of milk: Effects of dietary inclusions of barley and oat in untreated or formaldehyde-treated forms on milk fatty acid composition. Journal of the Science of Food and Agriculture, 43(2), 145–154. https://doi.org/10.1002/jsfa.2740430205

McAllister, T. A., Phillippe, R. C., Rode, L. M., & Cheng, K.-J. (1993). Effect of the protein matrix on the digestion of cereal grains by ruminal microorganisms. Journal of Animal Science, 71(1), 205–212. https://doi.org/10.2527/1993.711205x

McKay, Z. C., Mulligan, F. J., Lynch, M. B., Rajauria, G., Miller, C., & Pierce, K. M. (2019). The effects of cereal type and α-tocopherol level on milk production, milk composition, rumen fermentation, and nitrogen excretion of spring-calving dairy cows in late lactation. Journal of Dairy Science, 102(8), 7118–7133. https://doi.org/10.3168/jds.2019-16270

Moran, J. B. (1986). Cereal grains in complete diets for dairy cows: A comparison of rolled barley, wheat and oat and of three methods of processing oat. Animal Science, 43(1), 27–36. https://doi.org/10.1017/S0003356100018316

Murphy, J. P., & Hoffman, L. A. (1992). The Origin, History, and Production of Oat. In Oat Science and Technology; John Wiley & Sons, Ltd.: Hoboken, NJ, USA. (pp. 1–28).

Mustafa, A. F., Christensen, D. A., & McKinnon, J. J. (1998). Chemical characterization and ruminal nutrient degradability of hulled and hull-less oat. Journal of the Science of Food and Agriculture, 77(4), 449–455. https://doi.org/10.1002/(SICI)1097-0010(199808)77:4<449::AID-JSFA51>3.0.CO;2-Q

National Academies of Sciences, Engineering, and Medicine. (2016). Nutrient Requirements of Beef Cattle, 8th Edition. Washington, DC: The National Academies Press.

Niu, Z., Rossnagel, B. G., & Yu, P. (2007). Chemical characteristics and nutritive values of three oat varieties for ruminants.

Noftsger, S., & St-Pierre, N. R. (2003). Supplementation of Methionine and Selection of Highly Digestible Rumen Undegradable Protein to Improve Nitrogen Efficiency for Milk Production. Journal of Dairy Science, 86(3), 958–969. https://doi.org/10.3168/jds.S0022-0302(03)73679-0

NRC. (1996). Nutrient Requirements of Beef Cattle, 7th Edition. National Research Council, National Academy of Science, Washington, DC, USA.

NRC. (2001). Nutrient Requirement of Dairy Cattle, 7th Edition. National Research Council, National Academy of Science, Washington, DC, USA.

NRC. (2021). Nutrient Requirement of Dairy Cattle, 8th Edition. National Research Council, National Academy of Science, Washington, DC, USA.

Nuez-Ortín, W. G., & Yu, P. (2010). Estimation of ruminal and intestinal digestion profiles, hourly effective degradation ratio and potential N to energy synchronization of co-products from bioethanol processing: Ruminal and intestinal digestion profiles of co-products of bioethanol production. Journal of the Science of Food and Agriculture, 90(12), 2058–2067. https://doi.org/10.1002/jsfa.4052

O'Connor, J. D., Sniffen, C. J., Fox, D. G., & Chalupa, W. (1993). A net carbohydrate and protein system for evaluating cattle diets: IV. Predicting amino acid adequacy. Journal of Animal Science, 71(5), 1298–1311. https://doi.org/10.2527/1993.7151298x

Opio, C., Gerber, P., Mottet, A., Falcucci, A., Tempio, G., MacLeod, M., Vellinga, T., Henderson, B., & Steinfeld, H. (2013). Greenhouse gas emissions from ruminant supply chains – a global life cycle assessment. Food and Agriculture Organization of the United Nations. http://www.fao.org/3/i3461e/i3461e.pdf

Ørskov, E. R. (1986). Starch Digestion and Utilization in Ruminants. Journal of Animal Science, 63(5), 1624–1633. https://doi.org/10.2527/jas1986.6351624x

Ørskov, E. R., & McDonald, I. (1979). The estimation of protein degradability in the rumen from incubation measurements weighted according to rate of passage. The Journal of Agricultural Science, 92(2), 499–503. https://doi.org/10.1017/S0021859600063048

Othman, R. A., Moghadasian, M. H., & Jones, P. J. (2011). Cholesterol-lowering effects of oat β-glucan: Nutrition Reviews©, Vol. ••(••): ••-••. Nutrition Reviews, 69(6), 299–309. https://doi.org/10.1111/j.1753-4887.2011.00401.x

Pan, L., Huang, K. H., Middlebrook, T., Zhang, D., Bryden, W. L., & Li, X. (2021). Rumen Degradability of Barley, Oat, Sorghum, Triticale, and Wheat In Situ and the Effect of Pelleting. Agriculture, 11(7), 647. https://doi.org/10.3390/agriculture11070647

Peng, Q., Khan, N. A., Wang, Z., & Yu, P. (2014). Relationship of feeds protein structural makeup in common Prairie feeds with protein solubility, in situ ruminal degradation and intestinal digestibility. Animal Feed Science and Technology, 194, 58–70. https://doi.org/10.1016/j.anifeedsci.2014.05.004

Petit, H. V., & Alary, S. (1999). Milk Yield and Composition of Dairy Cows Fed Concentrate Based on Naked Oat. Journal of Dairy Science, 82(5), 1004–1007. https://doi.org/10.3168/jds.S0022-0302(99)75320-8

Prates, L. L., Nagy, C., & Yu, P. (2023). Thermal processing induced changes on molecular structure spectral profile of carbohydrates and ruminal degradation and intestinal digestion characteristics of oat grains (Avena sativa) in dairy cows: Comparison among dry heating vs. moisture heating vs. microwave irradiation. Canadian Journal of Animal Science, 103(2), 204–217. https://doi.org/10.1139/cjas-2022-0061

Prates, L. L., Refat, B., Lei, Y., Louzada-Prates, M., & Yu, P. (2018). Relationship of carbohydrates and lignin molecular structure spectral profiles to nutrient profile in newly developed oat cultivars and barley grain. Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 188, 495–506. https://doi.org/10.1016/j.saa.2017.07.042

Prates, L. L., & Yu, P. (2017). Detect unique molecular structure associated with physiochemical properties in CDC varieties of oat grain with unique nutrient traits [Feed Type vs. Milling Type] in comparison with barley grain using advanced molecular spectroscopy as a non-destructive biological tool. Journal of Cereal Science, 74, 37–45. https://doi.org/10.1016/j.jcs.2017.01.006

Prestløkken, E. (1999). In situ ruminal degradation and intestinal digestibility of dry matter and protein in expanded feedstuffs. Animal Feed Science and Technology, 77(1–2), 1–23. https://doi.org/10.1016/S0377-8401(98)00246-6

Ramin, M., Fant, P., & Huhtanen, P. (2021). The effects of gradual replacement of barley with oat on enteric methane emissions, rumen fermentation, milk production, and energy utilization in dairy cows. Journal of Dairy Science, 104(5), 5617–5630. https://doi.org/10.3168/jds.2020-19644

Rigout, S., Lemosquet, S., Van Eys, J. E., Blum, J. W., & Rulquin, H. (2002). Duodenal Glucose Increases Glucose Fluxes and Lactose Synthesis in Grass Silage-Fed Dairy Cows. Journal of Dairy Science, 85(3), 595–606. https://doi.org/10.3168/jds.S0022-0302(02)74113-1

Roe, M. B., Sniffen, C. J., & Chase, L. E. (1990). Techniques for measuring protein fractions in feedstuffs. In Proceedings-Cornell Nutrition Conference for Feed Manufacturers, pp 81-88.

Russell, J. B., O'Connor, J. D., Fox, D. G., Van Soest, P. J., & Sniffen, C. J. (1992). A net carbohydrate and protein system for evaluating cattle diets: I. Ruminal fermentation. Journal of Animal Science, 70(11), 3551–3561. https://doi.org/10.2527/1992.70113551x

SaskSeed Guide. (2023). Varieties of Grain Crops. Government of Saskatchewan. https://saskseed.ca/wp-content/uploads/2020/12/2023-Varieties-of-Grain-Crops.pdf

Schingoethe, D. J., Voelker, H. H., & Ludens, F. C. (1982). High Protein Oat Grain for Lactating Dairy Cows and Growing Calves. Journal of Animal Science, 55(5), 1200–1205. https://doi.org/10.2527/jas1982.5551200x

SeCan. (2016). CDC Haymaker oat. https://trawinseeds.ca/wp-content/uploads/2020/05/CDC-Haymaker-Oat-2016.pdf

Shen, R.-L., Wang, Z., Dong, J.-L., Xiang, Q.-S., & Liu, Y.-Q. (2016). Effects of oat soluble and insoluble β-glucan on 1,2-dimethylhydrazine-induced early colon carcinogenesis in mice. Food and Agricultural Immunology, 27(5), 657–666. https://doi.org/10.1080/09540105.2016.1148664

Sinclair, L. A., Garnsworth, P. C., Newbold, J. R., & Buttery, P. J. (1993). Effect of synchronizing the rate of dietary energy and nitrogen release on rumen fermentation and microbial protein synthesis in sheep. The Journal of Agricultural Science, 120(2), 251–263. https://doi.org/10.1017/S002185960007430X

Singh, M., & Upadhyaya, H. (2015). Genetic and genomic resources for grain cereals improvement. Academic Press.

Small, E. (1999). New crops for Canadian agriculture. In Perspectives on new crops and new uses (pp. 15–52). Ash Press.

Sniffen, C. J., O'Connor, J. D., Van Soest, P. J., Fox, D. G., & Russell, J. B. (1992). A net carbohydrate and protein system for evaluating cattle diets: II. Carbohydrate and protein availability. Journal of Animal Science, 70(11), 3562–3577. https://doi.org/10.2527/1992.70113562x

Statistics Canada. (2023). Canada: Oat production. Prairie Oat Growers Association. https://poga.ca/wp-content/uploads/2022/06/Oat-story-and-industry-with-POGA-background_v2.pdf

Stern, M. O., Santos, K. A., & Satter, L. D. (1985). Protein Degradation in Rumen and Amino Acid Absorption in Small Intestine of Lactating Dairy Cattle Fed Heat-Treated Whole Soybeans. Journal of Dairy Science, 68(1), 45–56. https://doi.org/10.3168/jds.S0022-0302(85)80796-7

Stewart, D., & McDougall, G. (2014). Oat agriculture, cultivation and breeding targets: Implications for human nutrition and health. British Journal of Nutrition, 112(S2), S50–S57. https://doi.org/10.1017/S0007114514002736

Sun, T., Li, J., Qin, Y., Xie, J., Xue, B., Li, X., Gan, J., Bian, X., & Shao, Z. (2020). Rheological and functional properties of oat β-glucan with different molecular weight. Journal of Molecular Structure, 1209, 127944. https://doi.org/10.1016/j.molstruc.2020.127944

Tamminga, S., Brandsma, G. G., Dijkstra, J., van Duinkerken, G., van Vuuren, A. M., & Blok, M. C. (2007). Protein evaluation for ruminants: The DVE/OEB 2007-system. CVB Documentation Report, pp 53-58. Wageningen University, Wageningen, The Netherlands.

Tamminga, S., Van Straalen, W. M., Subnel, A. P. J., Meijer, R. G. M., Steg, A., Wever, C. J. G., & Blok, M. C. (1994). The Dutch protein evaluation system: The DVE/OEB-system.

Livestock Production Science, 40(2), 139–155. https://doi.org/10.1016/0301-6226(94)90043-4

Tas, B. M., Taweel, H. Z., Smit, H. J., Elgersma, A., Dijkstra, J., & Tamminga, S. (2006). Effects of Perennial Ryegrass Cultivars on Milk Yield and Nitrogen Utilization in Grazing Dairy Cows. Journal of Dairy Science, 89(9), 3494–3500. https://doi.org/10.3168/jds.S0022-0302(06)72388-8

Thies, F., Masson, L. F., Boffetta, P., & Kris-Etherton, P. (2014). Oat and CVD risk markers: A systematic literature review. British Journal of Nutrition, 112(S2), S19–S30. https://doi.org/10.1017/S0007114514002281

Thompson, R. K. (2001). Evaluation of ammonia treatment as a method of improving fiber digestion of oat hulls for ruminants. M.Sc. Thesis, University of Saskatchewan, Saskatoon, Canada.

Thompson, R. K., Mustafa, A. F., McKinnon, J. J., Maenz, D., & Rossnagel, B. (2000). Genotypic differences in chemical composition and ruminal degradability of oat hulls. Canadian Journal of Animal Science, 80(2), 377–379. https://doi.org/10.4141/A99-132

Tiwari, U., & Cummins, E. (2011). Meta-analysis of the effect of β-glucan intake on blood cholesterol and glucose levels. Nutrition, 27(10), 1008–1016. https://doi.org/10.1016/j.nut.2010.11.006

Tommervik, R. S., & Waldern, D. E. (1969). Comparative Feeding Value of Wheat, Corn, Barley, Milo, Oat, and a Mixed Concentrate Ration for Lactating Cows. Journal of Dairy Science, 52(1), 68–73. https://doi.org/10.3168/jds.S0022-0302(69)86503-3

Tosta, M. R. (2019). Physiochemical, nutritional, molecular structural characterization and dairy cow feeding value of oat grain in comparison with barley grain: Impact of variety and processing methods. M.Sc. Thesis, University of Saskatchewan, Saskatoon, Canada.

Tosta, M. R., Prates, L. L., Christensen, D. A., & Yu, P. (2019). Biodegradation kinetics by microorganisms, enzymatic biodigestion, and fractionation of protein in seeds of cool-climate-adapted oat: Comparison among oat varieties, between milling-type and feed-type oat, and with barley grain. Journal of Cereal Science, 89, 102814. https://doi.org/10.1016/j.jcs.2019.102814

Tylutki, T. P., Fox, D. G., Durbal, V. M., Tedeschi, L. O., Russell, J. B., Van Amburgh, M. E., Overton, T. R., Chase, L. E., & Pell, A. N. (2008). Cornell Net Carbohydrate and Protein System: A model for precision feeding of dairy cattle. Animal Feed Science and Technology, 143(1–4), 174–202. https://doi.org/10.1016/j.anifeedsci.2007.05.010

Uchiyama, H., Iwai, A., Asada, Y., Muramatsu, D., Aoki, S., Kawata, K., Kusano, K., Nagashima, K., Yasokawa, D., Okabe, M., & Miyazaki, T. (2012). A small scale study on the effects of oral administration of the β-glucan produced by Aureobasidium pullulans on milk quality and cytokine expressions of Holstein cows, and on bacterial flora in the intestines of Japanese black calves. BMC Research Notes, 5(1), 189. https://doi.org/10.1186/1756-0500-5-189

Van Amburgh, M. E., Chase, L. E., Overton, T. R., Ross, D. A., Rechtenwald, R. J., Higgs, R. J., & Tylutki, T. P. (2010). Updates to the Cornell Net Carbohydrate and Protein System v6.1 and implications for ration formulation. pp 144-159 in Proceedings of Cornell Nutrition Conference for Feed Manufacturers. Syracuse, NY, USA.

Van Amburgh, M. E., Collao-Saenz, E. A., Higgs, R. J., Ross, D. A., Recktenwald, E. B., Raffrenato, E., Chase, L. E., Overton, T. R., Mills, J. K., & Foskolos, A. (2015). The Cornell Net Carbohydrate and Protein System: Updates to the model and evaluation of version 6.5. Journal of Dairy Science, 98(9), 6361–6380. https://doi.org/10.3168/jds.2015-9378

Van Amburgh, M. E., Foskolos, A., Collao-Saenz, E. A., Higgs, R. J., & Ross, D. A. (2013). Updating the CNCPS feed library with new feed amino acid profiles and efficiencies of use: Evaluation of model predictions-version. https://ecommons.cornell.edu/bitstream/handle/1813/36493/CNC2013_VanAmburgh_m.pdf;sequence=1

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. https://doi.org/10.3168/jds.S0022-0302(91)78551-2

Van Soest, P., & Robertson, J. (1979). Systems of analysis for evaluating fibrous feeds. Page in Standardization of analytical methodology for feeds: Proceedings. International Development Research Centre, Ottawa, ON, CA.

Vanhatalo, A., Gäddnäs, T., & Heikkilä, T. (2008). Microbial protein synthesis, digestion and lactation responses of cows to grass or grass-red clover silage diet supplemented with barley or oat. Agricultural and Food Science, 15(3), 252. https://doi.org/10.2137/145960606779216236

Waltz, D. M., Stern, M. D., & Illg, D. J. (1989). Effect of Ruminal Protein Degradation of Blood Meal and Feather Meal on the Intestinal Amino Acid Supply to Lactating Cows. Journal of Dairy Science, 72(6), 1509–1518. https://doi.org/10.3168/jds.S0022-0302(89)79261-4

Webster, F. H., & Wood, P. J. (Eds.). (2011). OAT: Chemistry and Technology (Second Edition). AACC International, Inc. https://doi.org/10.1094/9781891127649

Welch, R. W. (1995). The Oat Crop: Production and Utilization. Chapman &Hall, London, UK.

White, E. M. (1995). Structure and development of oat. In R. W. Welch (Ed.), The Oat Crop (pp. 88–119). Springer Netherlands. https://doi.org/10.1007/978-94-011-0015-1_4

Whitehead, A., Beck, E. J., Tosh, S., & Wolever, T. M. (2014). Cholesterol-lowering effects of oat β-glucan: A meta-analysis of randomized controlled trials. The American Journal of Clinical Nutrition, 100(6), 1413–1421. https://doi.org/10.3945/ajcn.114.086108

Winfield, K., Hall, M., & Paynter, B. (2007). Milling oat and feed oat quality—What are the differences?

Ying, Y. (2015). Nutritional and Microstructural Responses in Cereal Grains to Heat-Related Processing Methods [M.Sc. Thesis]. University of Saskatchewan, Saskatoon, SK, CA.

Yu, P. (2005). Prediction of protein supply to ruminants from concentrates: Comparison of the NRC-2001 model with the DVE/OEB system. Journal of the Science of Food and Agriculture, 85(4), 527–538. https://doi.org/10.1002/jsfa.2015

Yu, P., Christensen, D. A., Christensen, C. R., Drew, M. D., Rossnagel, B. G., & McKinnon, J. J. (2004). Use of synchrotron FTIR microspectroscopy to identify chemical differences in barley endosperm tissue in relation to rumen degradation characteristics. Canadian Journal of Animal Science, 84(3), 523–527. https://doi.org/10.4141/A03-102

Yu, P., Christensen, D. A., & McKinnon, J. J. (2003). Comparison of the National Research Council-2001 Model with the Dutch System (DVE/OEB) in the Prediction of Nutrient Supply to Dairy Cows from Forages. Journal of Dairy Science, 86(6), 2178–2192. https://doi.org/10.3168/jds.S0022-0302(03)73808-9

Yu, P., Goelema, J. O., & Tamminga, S. (2000). Using the DVE/OEB model to determine optimal conditions of pressure toasting on horse beans (Vicia faba) for the dairy feed industry. Animal Feed Science and Technology, 86(3–4), 165–176. https://doi.org/10.1016/S0377-8401(00)00171-1

Yu, P., Meier, J. A., Christensen, D. A., Rossnagel, B. G., & McKinnon, J. J. (2003). Using the NRC-2001 model and the DVE/OEB system to evaluate nutritive values of Harrington (malting-type) and Valier (feed-type) barley for ruminants. Animal Feed Science and Technology, 107(1–4), 45–60. https://doi.org/10.1016/S0377-8401(03)00062-2

Yu, P., & Niu, Z. (2009). Using a complex non-TDN based model (the DVE/OEB system) to predict microbial protein synthesis, endogenous protein, degradation balance, and total truly absorbed protein supply of different varieties of cereal oat for ruminants. Animal Science Journal, 80(3), 273–279. https://doi.org/10.1111/j.1740-0929.2009.00641.x

Yu, P., Niu, Z., & Christensen, D. A. (2010). Effects of partially replacing barley or corn with raw and micronised CDC SO-I oat on productive performance of lactating dairy cows. Archives of Animal Nutrition, 64(5), 425–436. https://doi.org/10.1080/1745039X.2010.496949

Yu, P., Rossnagel, B. G., & Niu, Z. (2008). Protein value of a new genotype oat (CDC SO-I) for the NRC dairy model: Protein degradation balance and kinetics, protein fractions and total metabolizable protein supply. Canadian Journal of Animal Science, 88(3), 507–513. https://doi.org/10.4141/CJAS07137

Żebrowska, T., Długołęcka, Z., Pająk, J., & Korczyński, W. (1997). Rumen degradability of concentrate protein,amino acids and starch, and their digestibilityin the small intestine of cows. Journal of Animal and Feed Sciences, 6(4), 451–470. https://doi.org/10.22358/jafs/69558/1997

Zohary, D., Hopf, M., & Weiss, E. (2012). Domestication of Plants in the Old World: The origin and spread of domesticated plants in Southwest Asia, Europe, and the Mediterranean Basin. Oxford University Press. https://doi.org/10.1093/acprof:osobl/9780199549061.001.0001

8. APPENDIX

Summary Table 1. The main characteristics of four varieties of oat.

Items	Oat variety: CDC Arborg (Milling)	Oat variety: Summit (Milling)	Oat variety: CDC Nasser (Feed)	Oat variety: CDC Haymaker (Forage)	SEM	P value	Contrast P value Milling Type vs. Feed Type
From Reference (SaskSeed Guide, 2023)							
Yield (Area 1&2)	105	93	98	82			
Test Weight (g/0.5L)	250	256	233	225			
Hull, %	20.1	21.6	21.8	24.9			
Plump, %	85	81	79	87			
Smut	R	R	R	MR			
From Our Thesis							
DM, %	90.93	90.84	91.20	91.00	0.274	0.587	0.211
EE, %DM	1.82^{b}	2.20^{b}	4.05^{a}	1.85^{b}	0.094	<0.01	<0.01
CP, %DM	15.78^{b}	15.40^{b}	14.69^{b}	17.57^{a}	0.293	0.002	0.035
Starch, %DM	46.85	47.89	47.60	42.84	2.354	0.452	0.938
NDF, %DM	30.69	25.84	29.30	30.74	2.041	0.348	0.691
ADF, %DM	15.76	13.54	14.27	16.41	1.297	0.428	0.819
ADL, %DM	3.60^{a}	3.29^{a}	1.63^{b}	4.19^{a}	0.228	<0.01	<0.01
iNDF120h, %DM	19.75^{ab}	18.00^{b}	18.21^{ab}	25.26^{a}	1.616	0.038	0.722
tdCP	15.65^{b}	15.25^{b}	14.58^{b}	17.42^{a}	0.281	0.001	0.036
TDN_{1x}	75.52^{bc}	78.16^{b}	81.91^{a}	73.18^{c}	0.621	<0.01	<0.01
Kd (%/h), DM	10.53^{a}	7.61^{ab}	2.36^{b}	11.36^{a}	1.500	0.011	<0.01
BDM (=RUDM, g/kg DM)	537^{b}	582^{b}	726^{a}	599^{b}	28.7	0.003	0.001

EDDM (=RDDM, g/kg DM)	463^{a}	418^{a}	274^{b}	401^{a}	28.7	0.003	0.001
Kd (%/h), CP	10.88^{a}	9.59^{ab}	2.64^{b}	13.33^{a}	1.569	0.017	0.009
BCP^{NRC} or RUP (g/kg DM)	78	78	87	82	8.4	0.684	0.289
EDCP (=RDP, g/kg DM)	88^{ab}	84^{ab}	64^{b}	102^{a}	8.2	0.025	0.029
Kd (%/h), NDF	1.18	1.06	1.55	1.37	0.187	0.303	0.092
BNDF (=RUNDF, g/kg DM)	244	218	239	274	13.0	0.085	0.611
EDNDF (=RDNDF g/kg DM)	63	41	54	33	12.6	0.393	0.905
Kd (%/h), Starch	11.84^{ab}	7.85^{b}	2.76^{c}	15.07^{a}	1.039	<0.01	<0.01
BST (=RUST, g/kg DM)	157^{b}	194^{b}	325^{a}	121^{b}	24.3	0.002	0.001
EDST (=RDST g/kg DM)	312^{a}	285^{a}	151^{b}	307^{a}	16.4	<0.01	<0.01
TDDM (g/kg DM)	625^{a}	605^{a}	401^{b}	552^{a}	35.3	0.003	<0.01
TDCP (g/kg DM)	134^{b}	144^{ab}	129^{b}	158^{a}	3.8	0.002	<0.041
TDNDF (g/kg DM)	66	37	75	44	18.1	0.453	0.330
TDST (g/kg DM)	367^{a}	381^{a}	233^{b}	332^{ab}	33.9	0.015	0.003
DVE (g/kg DM)	58^{a}	45^{a}	18^{b}	50^{a}	3.1	0.002	0.001
OEB^{DVE} (g/kg DM)	26^{b}	30^{b}	53^{a}	43^{ab}	2.3	0.019	0.005
FMV^{DVE} (kg milk /kg feed)	1.18^{a}	0.92^{b}	0.35^{c}	1.02^{ab}	0.051	0.001	<0.01
MP^{NRC} (g/kg DM)	97^{ab}	90^{b}	92^{ab}	106^{a}	3.5	0.046	0.666
FMV^{NRC} (kg milk /kg feed)	1.98^{ab}	1.83^{b}	1.86^{ab}	2.15^{a}	0.070	0.047	0.675

Notes: SEM: standard error of mean; $^{a-b}$ Means with the different letters in the same row are significant different ($P < 0.05$); Multi-treatment comparison: Tukey method; DM: dry matter; EE: ether extract (crude fat); CP: crude protein; ADF: acid detergent fiber; ADL: acid detergent lignin; NDF: neutral detergent fiber; $iNDF_{120h}$: indigestible neutral detergent fiber at 120 h; tdCP: truly digestible crude protein; TDN_{1x}: total digestible nutrient at one time maintenance; Kd: the rate of degradation of D fraction (%/h); BDM or RUDM: rumen bypass dry matter; EDDM or RDDM: effective degradability of dry matter; BCP or RUP: rumen bypass or undegraded feed crude protein; EDCP or RDP: effective degradability of feed crude protein; BNDF or RUNDF: rumen bypass or undegraded feed neutral detergent fiber; EDNDF or RDNDF: effective degradability of feed neutral detergent fiber; BST or RUST: rumen bypass or undegraded feed starch; EDST or RDST: effective degradability of feed starch; TDDM: total digestible dry matter (in g/kg DM); TDCP: total digestible protein (in g/kg DM); TDNDF: total digestible neutral detergent fiber (in g/kg DM); TDST: total digestible starch (in g/kg DM); DVE: truly digested protein in the small intestine; OEB^{DVE}: degraded protein balance; FMV^{DVE}: feed milk value based on the DVE/OEB system; MP^{NRC}: metabolizable protein; FMV^{NRC}: feed milk value based on the NRC-2001 model.