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Optimized Utilization of the Co-products from Bioethanol Processing and Oat Grain: Effect of Blending on Biochemical, Biodegradation, and Nutritional Profiles

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ABSTRACT: The objective of this study was to (1) optimize the utilization of wheat-based dried distillers grains with soluble (wDDGS) by blending with oat (*Avena sativa* L.) grain as an alternative feed for beef cattle when the barley price is high and (2) investigate the effect of blending on biochemical, biodegradation, and nutritional profiles. Oat grains were blended with wDDGS produced in western Canada at different levels (4:0, 3:1, 2:2, and 1:3 on %DM basis in two batches, denoted O0, O25, O50, and O75, respectively). The study revealed that increasing the wDDGS resulted in increasing most nutrient contents linearly ($P < 0.05$) except for starch and cell wall materials, which were linearly decreased (from 43.6 to 12.0% and from 34.5 to 29.1% of DM for starch and NDF, respectively). When wDDGS was increased in the blend/mixture, intestinally absorbable protein and degradable balance of protein increased ($P < 0.05$). Overall, through blending or combining with the cereal grain, the co-products from bioethanol processing could be optimally utilized. The best combination of oat to wDDGS ratio was 75% to 25%.

KEYWORDS: *bioethanol processing co-products, biodegradation, feed, nutritional profiles, wheat byproducts*

■ INTRODUCTION

How to efficiently utilize the co-products (such wheat-based dried distillers grains with soluble (wDDGS)) through blending with cereal grains is a crucial question that several industries (e.g., bioethanol processing industry, feed industry, animal industry) are facing.

Cattle production relies on the inclusion of cereal grains to increase the dietary energy concentration of finishing rations. This improves live gain performance and leads to desirable carcass characteristics of grain-finished beef. In western Canada and in the northwestern United States, barley (*Hordeum vulgare* L.) is the most important feed cereal grain for growing and finishing rations for cattle.[1−4] Oat grain (*Avena sativa* L.) is used to a lesser extent. With regard to oil content, oat (5.2%) is greater than barley (2.2%) and corn (4.3%).[5] Despite this difference, oat typically has lower metabolizable energy content (ME; 2.78 Mcal/kg DM) relative to corn (3.18 Mcal/kg DM) or barley (3.04 Mcal/kg DM).[5] The latter has limited the use of oat in feedlot diets primarily to backgrounding programs in which animals are not fed for maximum growth rate.[1,6] The lower energy value is due to the greater proportion of hull in oat kernel relative to corn and barley. About 25% of oat grain is hull.[1,5,6] To increase oat grain use in beef feedlot diets, we need to consider highly available nutrient (ME and MP) feed sources to be blended.

wDDGS is a widely available co-product.[7,8] Energy values in wDDGS are comparable to those of barley[3] and corn. The CP and undegradable protein content are also high in wDDGS.[8−11] Therefore, wDDGS could be considered to supplement oat grain-based diet for beef cattle in backgrounding and finishing programs if it can offer a cost-effective feasible source of protein and energy supplement. So far, inclusion of wDDGS in oat-based diet for finishing cattle has not been evaluated. The objective of this study was to investigate the effect of blending wDDGS with oat grains on structural, biochemical, and nutritional profiles and rumen and intestinal nutrient utilization.

■ MATERIALS AND METHODS

Bioethanol Co-products and Oat Cereal Grain Sampling. Oat grains were blended with wDDGS produced in western Canada at different levels (4:0, 3:1, 2:2, and 1:3 on %DM basis in two batches, denoted O0, O25, O50, and O75, respectively).

Chemical Analysis and Fractionation of Protein and Carbohydrates. The following conventional chemical compositions were analyzed in terms of soluble carbohydrates, starch, EE, OM, total CHO, NSC, CP, true protein, NDICP, ADICP, soluble CP, NPN, ADF, ADL, NDF, cellulosic compounds.[12−18] Samples were analyzed in duplicates. If percent error exceeded 5%, the analysis was repeated. The detailed methodology was reported previously. Energy values, protein and carbohydrates were determined.[5,18,19]

Rumen Degradation Kinetic and Ratio of N to Energy. In situ Rumen degradation and effective fermentation ratios were determined[20,21] with two cannulated Holstein cows. The detailed animal diet, animal care, feeding arrangements and in situ procedures were reported before.[22,23] In vitro intestinal digestibility was determined.[24]

The NLIN program [25] was used to determined degradation kinetic. Effective degradation (ED) and hourly effective N to energy ratio,[26] rumen undegraded starch (RUST) and protein (RUP) were estimated.[26,27]

Absorbable Protein in the Small Intestine. Rumen microbial protein (AMCP), undegradable protein (ARUP), total metablizable

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Table 1. Effect of Blending Oat Grain with Wheat-Based Dried Distillers Grains with Solubles (wDDGS) on Chemical Profiles and Energy Values for Cattle

item[c]	treatment[a] O0	O25	O50	O75	SEM	contrast[b] linear
basic chemical profile (g/kg DM)						
ash	33.7d	39.8c	45.3b	51.0a	0.74	0.001
crude fat	41.0	45.0	47.3	49.5	2.12	0.013
structural carbohydrate profile (g/kg DM)						
neutral detergent fiber	345.2a	296.7ab	294.0ab	290.1b	12.26	0.011
acid detergent fiber	179.3	165.5	174.7	188.5	9.75	0.413
acid detergent lignin	25.0c	32.0bc	39.0ab	43.8a	1.74	0.000
hemicellulose	179.0b	200.8b	224.8ab	255.5a	12.75	0.001
cellulose	154.7	137.5	135.7	144.5	8.75	0.492
nonstructural carbohydrate profile (g/kg DM)						
starch	435.7a	324.5b	217.5c	120.3c	25.10	0.001
sugar	17.0d	35.5c	47.8b	59.0a	1.06	0.001
crude protein profile (g/kg CP)						
CP (g/kg DM)	138.8d	214.2c	273.5b	340.5a	8.15	0.001
soluble CP (SCP)	407.3	397.7	397.0	392.8	19.76	0.626
non-protein N (NPN; g/kg SCP)	556.5b	679.5ab	750.0a	783.5a	32.11	0.001
neutral detergent insoluble CP	99.0c	326.0b	385.7ab	456.2a	26.23	0.001
acid detergent insoluble CP	16.3d	109.8c	137.0b	163.0a	3.63	0.001
total digestible nutrient at a maintenance level (g/kg DM)						
total digestible nutrients$_{1\times}$	785.7	780.8	764.9	752.5	9.58	0.019
energy values for dairy cattle (Mcal/kg DM)						
digestible energy for production	32.0	32.7	32.8	33.2	0.32	0.029
metabolizable energy for production	27.9	28.6	28.7	29.1	0.33	0.027
net energy for lactation	17.8	18.3	18.4	18.6	0.24	0.023
energy values for beef cattle (Mcal/kg DM)						
net energy for maintenance	19.1	19.6	19.7	20.0	0.24	0.030
net energy for gain	12.7	13.2	13.2	13.5	0.21	0.030

[a]Oat and wDDGS were mixed in ratios of 100:0, 75:25, 50:50, and 25:75% (DM% basis; denoted O0, O25,O50, and O75, respectively). [b]There was no quadratic or cubic effect ($P > 0.05$). [c]Means ($n = 2$) within a row with different letters differ ($P < 0.05$).

Table 2. Effect of Blending Oat Grain with Wheat-Based Dried Distillers Grains with Solubles (wDDGS) on Protein and Carbohydrate Subfractions[26]

item[c]	treatment[a] O0	O25	O50	O75	SEM	contrast[b] linear	quadratic
protein subfractions (g/kg CP)							
PA (soluble)	227.0b	27.0ab	29.7ab	30.8a	1.89	0.008	0.403
PB1 (rapidly degradable)	180.5a	127.4ab	997.0b	847.0b	14.22	0.001	0.205
PB2 (medium degradable)	493.5a	276.4b	217.5bc	151.0c	15.87	0.001	0.001
PB3 (slowly degradable)	83.0b	216.4a	248.4a	293.5a	28.24	0.001	0.144
PC (undegradable)	16.2d	109.5c	137.1b	162.9a	3.57	0.001	0.600
true protein	756.9a	620.2b	565.6bc	529.2c	20.60	0.001	0.031
carbohydrate subfractions (g/kg CHO)							
total CHO (g/kg DM)	786.4a	701.2b	633.9c	559.1d	6.90	0.001	0.459
nonstructural CHO	560.1ab	577.4a	535.9ab	483.0b	19.90	0.010	0.103
CA (soluble)	14.5d	117.0c	192.5b	268.2a	15.64	0.001	0.410
CB1 (rapidly degradable)	545.6a	460.5ab	343.5bc	214.8c	31.60	0.001	0.504
CB2 (slowly degradable)	303.0	313.0	316.0	329.0	17.15	0.116	0.189
CC (undegradable)	76.6d	110.1c	148.1b	188.3a	6.20	0.001	0.599

[a]Oat and wDDGS were mixed in ratios of 100:0, 75:25, 50:50, and 25:75% (DM basis; denoted O0, O25, O50, and O75, respectively). [b]There was no cubic effect ($P > 0.05$). [c]Means ($n = 2$) within a row with different letters differ ($P < 0.05$).

protein that are absorbable in the small intestine (DVE, MP) and degradable balance of protein (OEB, PBD) were estimated.[18,26,30,31]

Statistical Analysis. A MIXED procedure of SAS 9.2 with a CRD model ($Y_{ij} = \mu + T_i + e_{ij}$) was used.[32] Tukey-Kramer procedure was applied for treatment means comparison. A significant level is defined at $P < 0.05$ Curve-linear relationship of level of co-products was determined.

■ RESULTS

Effect of Blending wDDGS with Oat Grain on Biochemical and Bionutrient Features. Adding more wDDGS resulted in linearly increasing ash, EE, ADF, cellulosic compounds CP, NPN, sugar, NDICP, and ADICP ($P < 0.05$) while decreasing starch, and NDF linearly ($P < 0.05$) at the

Table 3. Effect of Blending Oat Grain with Wheat-Based Dried Distillers Grains with Solubles (wDDGS) Inclusion on Organic Matter and Protein Rumen Degradation Characteristics

item[c]	treatment[a]					contrast[b]
	O0	O25	O50	O75	SEM	linear
rumen degradation kinetics of organic matter (g/kg OM)						
lag time (/h)	0.2	0.2	0.0	0.0	0.09	0.516
soluble OM (S_{OM})	13.1	81.2	144.6	188.5	45.04	0.043
potentially degradable OM (D_{OM})	655.6	647.5	628.4	610.3	19.34	0.147
undegradable OM (U_{OM})	331.3	271.4	227.0	201.2	38.30	0.064
degradation rate (K_d; /h)	0.19	0.12	0.11	0.09	0.06	0.319
rumen undegradable-OM (RUOM; g/kg DM)	499.0	485.0	442.0	418.0	89.24	0.512
effective degradable-OM (EDOM)	483.5	495.2	537.4	560.2	93.18	0.549
effective degradable-OM (g/kg DM)	467.4	476.0	513.4	531.9	89.72	0.596
rumen degradation kinetics of crude protein (g/kg CP)						
lag time (/h)	0.2	0.2	0.0	0.0	0.14	0.261
soluble CP (S_{CP})	76.0	267.0	293.0	321.0	127.50	0.253
potentially degradable CP (D_{CP})	733.0	631.0	626.0	594.0	107.20	0.428
undegradable CP (U_{CP})	191.0	102.0	81.2	85.0	26.70	0.031
degradation rate (K_d; /h)	0.19	0.11	0.08	0.08	0.05	0.199
rumen undegradable CP (RUP: g/kg DM)	51.0	84.0	96.0	117.0	29.00	0.171
effective degradable-CP	611.0	629.0	646.4	660.2	112.30	0.647
effective degradable-CP (g/kg DM)	75.0	138.0	175.6	230.8	26.40	0.015

[a]Oat and wDDGS were mixed in ratios of 100:0, 75:25, 50:50, and 25:75% (DM basis; denoted O0, O25, O50, and O75, respectively). [b]There was no quadratic or cubic effect ($P > 0.05$). [c]Means ($n = 2$) within a row with different letters differ ($P < 0.05$).

Table 4. Effect of Blending Oat Grain with Wheat-Based Dried Distillers Grains with Solubles (wDDGS) on Starch and Neutral Detergent Fiber Rumen Degradation Characteristics

item[c]	treatment[a]					contrast[b]
	O0	O25	O50	O75	SEM	linear
rumen degradation kinetics of starch (ST) (DVE/OEB system)						
soluble ST (S_{ST})	115.1	81.9	60.9	44.7	57.19	0.402
potentially degradable ST (D_{ST})	884.9	918.1	939.1	955.3	57.19	0.402
degradation rate (K_d; /h)	0.20	0.13	0.12	0.09	0.07	0.366
rumen undegradable ST (RUST; g/kg DM)	103.8	98.8	69.8	47.0	16.45	0.054
effective degradable ST (EDST)	750.4	679.3	663.7	598.2	97.80	0.341
effective degradable ST (g/kg DM)	331.9	225.9	147.8	73.5	58.59	0.031
rumen degradation kinetics of NDF (g/kg NDF)						
lag time (/h)	1.2	1.7	0.0	0.0	0.98	0.287
potentially degradable NDF (D_{NDF})	674.8	424.4	500.2	576.5	76.62	0.441
undegradable NDF (U_{NDF})	325.2	575.6	499.8	423.5	138.26	0.741
degradation rate (K_d; /h)	0.01	0.07	0.07	0.057	0.019	0.166
rumen undegradable-NDF (RUNDF; g/kg DM)	243.1	230.3	206.4	193.3	31.77	0.290
effective degradable-NDF (EDNDF)	214.7	230.6	285.5	281.7	56.15	0.366
effective degradable-NDF (g/kg DM)	62.9	67.5	82.3	75.7	12.79	0.403

[a]Oat and wheat DDGS were combined in ratios (wt/wt, as is weight basis) of 100:0 (O0), 75:25(O25), 50:50 (O50), and 25:75 (O75). [b]There was no quadratic or cubic effect ($P > 0.05$). [c]Means ($n = 2$) within a row with different letters differ ($P < 0.05$).

same time (Table 1). Energy values were decreased linearly ($P < 0.05$).

Effect of Blending Co-products with Oat Grain on Protein and Carbohydrate Subfractions. Bypassed and soluble protein and carbohydrate increased linearly ($P < 0.05$) with increasing wDDGS content, whereas medium degradable CP and true protein, and nonstructural carbohydrate, fast CHO degradable fraction linearly decreased ($P < 0.05$) with increasing inclusion level of wDDGS (Table 2).

Degradation Kinetics: Effect of Blending Co-products with Oat Grain. Tables 3 and 4 show the effects of using wDDGS to partially replacing oat grain on degradation kinetics. The soluble fraction of OM increased linearly ($P < 0.05$), whereas the potentially degradable fraction of OM declined numerically ($P = 0.15$; Table 3) when adding more wDDGS. Degradation rate of OM and rumen undegradable OM numerically decreased ($P > 0.05$; Table 3), whereas degradable OM numerically increased as wDDGS portion increased in the mixture. In situ soluble and degradable fractions (% of total CP) numerically increased ($P > 0.05$; Table 3). When wDDGS was increased in the blend, the rate and magnitude of degradable protein fraction were numerically decreased. Effective degradable CP increased linearly ($P < 0.05$; Table 3) and undegradable CP decreased linearly ($P < 0.05$) when the wDDGS inclusion was increased in the mixture (in g/kg DM).

Both starch rumen undegradable and degradable contents decreased linearly ($P < 0.05$; Table 4). Among feed mixtures, there were not different ($P > 0.05$) with other parameters of

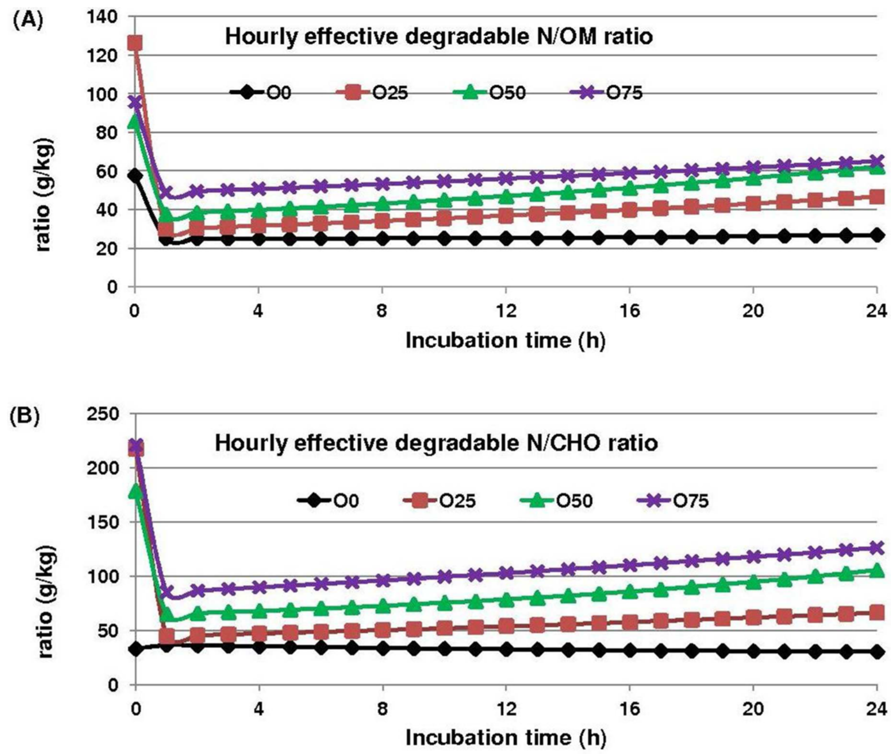

Figure 1. Effect of blending oat with wheat-based dried distillers grains with solubles (wDDGS) on hourly effective degradability ratios between N and organic matter (OM) (A) or carbohydrate (CHO) (B).

starch degradation kinetics. Overall, NDF degradation rate and effective degradable content, as well as rumen undegradable NDF, increased numerically ($P > 0.05$; Table 4) when wDDGS was increased in the blend/mixture.

Hourly Effective Degradation Ratio To Show Synchronization of N to Energy: Effect of Blending Co-products with Oat Grain. The results (Figure 1) show that the oat grain had the optimal ratio and the O25 blend showed slightly higher than the optimal ratio, whereas the O50 and O75 blend treatments elevated than optimal rumen degradation ratio. Also, insoluble available N to insoluble available energy (OM, CHO) and as well as total rumen available N to total rumen available OM and CHO increased linearly ($P < 0.05$) (Table 5).

Effect of Blending wDDGS with Oat Grain on Absorbable True Protein Supply to the Small Intestine. According to the DVE/OEB system,[26] all feeds were not different ($P > 0.05$) on absorbable microbial protein (AMCP; 47 g/kg DM). Whereas, according to NRC,[18] all three oat–wDDGS mixtures had greater absorbable microbial protein ($P < 0.05$; Table 6) than oat (43 vs av 59 g/kg DM). Increasing wDDGS results in an up to 1.7 times numerical increase of absorbable RUP (ARUP). MP, DVE, OEB, and DPB were all increased linearly ($P < 0.05$; Table 6; up to 1.8-fold) as wDDGS increased in the mixture.

DISCUSSION

Effect of Blending wDDGS with Oat Grain on Chemical and Energy Profiles and Rumen Degradation Kinetics. As described by Damiran et al.,[33] nutrient profile and energy of wDDGS were within the ranges of previous findings.[3,8,9,11] It is obvious that the differences in nutrients and degradation kinetics of the mixtures/blends in the current study were reflected by a different type of cereal grain (oat).

Table 5. Effect of Blending Oat Grain with Wheat-Based Dried Distillers Grains with Solubles (wDDGS) on Ruminal Degradation Ratios between N and OM or CHO (g/kg)

	feed[a]					P value[b]
item[c]	O0	O25	O50	O75	SEM	linear
FN/FOM	27.2b	46.9ab	54.6a	68.9a	4.09	0.002
FN/FCHO	33.5c	70.8bc	88.5ab	131.4a	9.15	0.002
EN/EOM	24.2	33.3	42.0	53.1	7.12	0.040
EN/ECHO	33.6	49.4	70.4	95.1	17.11	0.055
SN/SOM	27.8	126.5	85.8	96.0	17.18	0.388
SN/SCHO	33.2	179.0	217.8	221.5	74.68	0.190

[a]Oat and wDDGS were mixed in ratios of 100:0, 75:25, 50:50, and 25:75% (DM basis; denoted O0, O25, O50, and O75, respectively). [b]The quadratic and cubic effects were not detected ($P > 0.05$). [c]Means ($n = 2$) within a row with different letters differ ($P < 0.05$). FN/FOM of FCHO, total rumen available N/OM or CHO; EN/EOM or ECHO, insoluble rumen available N/OM or CHO; SN/SOM or CHO, soluble rumen N/OM or CHO. The ratios were calculated according to the methoe of Tamminga et al.[27]

The nutritional profile of oat in this study was comparable to previously reported results[6,34,35] and is lower in energy and similar in CP compared with barley.[21] Energy values were slightly greater in wDDGS than in oat. Ruminal degradation kinetics were reported before for oat[35] and wDDGS,[36] but were not reported for oat–wDDGS mixtures/blends. Biodegradation kinetics of wDDGS in the current study was in the range with results of Nuez-Ortin and Yu,[36] who later reported that the degradation rate was 6.1%/h and effective degradation of organic matter was 507 g/kg DM for the wDDGS. Damiran and Yu[35] found that CDC Dancer oat had 0.46/h and CDC Derby oat had 0.44/h degradation rate of DM. Oat in the current study had much lower degradation rates (0.19/h OM

Table 6. Effect of Oillers Grains with Solubles (wDDGS) on Calculated Protein Supply (Grams per Kilogram DM) in Cattle According to NRC[18] Model and DVE/OEB Systems[25]

item[c]	treatment[a] O0	O25	O50	O75	SEM	P value[b] linear
truly absorbable rumen synthesized microbial protein in the small intestine (AMCP)						
AMCP (DVE/OEB)	41.5	45.2	49.1	51.1	7.71	0.397
AMCP (NRC)	42.5b	59.7a	58.4a	57.5a	0.83	0.001
truly absorbable rumen undegraded feed protein in the small intestine (ARUP)						
ARUP (DVE/OEB)	59.0	68.4	81.8	101.6	28.33	0.327
ARUP (NRC)	53.1	61.7	73.7	91.5	25.52	0.327
total truly absorbable protein in the small intestine or total metabolizable protein supply (DVE or MP)						
DVE (= AMCP + ARUP − ENDP)	75.6	93.0	113.5	137.0	17.98	0.044
MP (= AMCP + ARUP + AECP)	99.9	125.6	136.5	153.3	24.88	0.039
degraded protein balance (OEB or PDB)						
OEB (DVE/OEB)	6.3b	59.2ab	89.0ab	132.5a	18.31	0.008
DPB (NRC)	−32.5b	28.4ab	68.9ab	119.3a	23.26	0.009

[a]Oat and wDDGS were mixed in ratios of 100:0, 75:25, 50:50, and 25:75% (DM basis; denoted O0, O25, O50, and O75, respectively). [b]The quadratic and cubic effects were not detected ($P > 0.05$). [c]Means ($n = 2$) within a row with different letters differ ($P < 0.05$). ENDP, endogenous protein losses in the digestive tract;[25] AECP, absorbable endogenous protein in the small intestine.[18]

or 0.18/h DM). Our results (Table 3) showed that when wDDGS was increased, the soluble fraction (S) was 4.2 times increased. Rumen undegradable protein content (in g/kg of DM) was also increased. This was a reflection of the higher protein content in wDDGS compared to oat (402 vs 138 g/kg DM).

Oat effective degradable protein was close (75 g/kg DM) to the NRC feedlot finishing cattle requirement (68 g/kg DM). This value was similar to effective degradable protein in barley grain (79 g/kg DM).[21] When the wDDGS inclusion level was increased in the mixture, the effective degradable protein was greatly increased. Effectively degradable to undegradable protein ratios were 1.57, 1.69, 1.83, and 1.94 for O0, O25, O50, and O75, respectively. These data are affected by temperature of drying and soluble fractions back to the processing.[33,37]

The rate of starch degradability of oat (0.20/h) was faster than that of barley (0.12/h), which we found[21] previously. The latter is in agreement with Herrera-Saldana et al.,[38] who stated that starch degradation rate is faster for oat than for barley after processing. Rapid starch degradation, particularly with high-grain diets, can induce subacute ruminal acidosis, resulting in variable and reduced DMI.[39]

Oat in this study had lower rate and extent of fiber (NDF) degradation than both barley[21] and corn,[36] which may explain why beef cattle fed cereal oat grain exhibit a marked reduction in DMI.[6] Feedstuffs that have slowly degradable cell walls may cause slower passage rate and consequently cause beef cattle to consume less feed.[40]

Effect of Blending Co-products with Oat Grain on Available Intestinal Protein. The microbial protein synthesis needs an optimal ruminal available dietary N and energy ratio[27−29] (ratio, 25−32 g N/kg OM or CHO truly digested in rumen; OEB, zero).[26] This study showed that oat has better degradable N to energy ratios (Table 6).

Previously we found barley (OEB, −17.6 g/kg[21]) and corn (OEB, −54.0 g/kg[33]) had below optimal N to energy ratios with negative degraded protein balance, unlike oat in this study. Adding 25% wDDGS to oat resulted in around optimal degradation ratio, but adding 50% and 75% resulted in higher ratios than the optimal ratios, which will result in CP being deaminated.[41] When wDDGS is blended up to 25% of oat-based diet, the oat−wDDGS mixture becomes an exceptional diet that serves as both a good protein (protein true value) and an energy source for cattle. In addition, NDF would reaches optimal level according NRC.[18]

It is concluded that increasing wDDGS in an oat−wDDGS mixture/blend resulted in increases of the metabolizable protein for feedlot cattle; however, oversupply of protein in the rumen increases as well. Through blending wDDGS with oat up to ca. 25% of DM resulted in a more optimal ratio, which provides optimal energy and protein for microbial protein synthesis. This blending treatment was a good candidate for feedlot cattle diet.

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Notes

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■ ABBREVIATIONS USED

ADF, acid detergent fiber; ADICP, acid detergent insoluble crude protein; ADL, acid detergent lignin; AMCP, absorbable microbial protein; ARUP, absorbable rumen undegradable feed protein; CA, soluble carbohydrate fraction; CB1, rapidly degradable carbohydrate fraction; CB2, slowly degradable carbohydrate fraction; CC, undegradable cell walls fraction; CHO, total carbohydrates; CNCPS, Cornell Net Carbohydrate and Protein System; D, insoluble potentially degradable in situ fraction; DM, dry matter; DMI, dry matter intake; DPB, degradable protein balance; DVE, total truly absorbable protein in the small intestine; EDDM, EDN, EDCP, EDOM, EDST, and EDNDF, effective degradation of feed DM, N, CP, OM, starch, and NDF, respectively; EN, insoluble rumen available protein; EOM, insoluble rumen available OM; K_d, rate of degradation of D fraction; K_p, passage rate; MP, metabolizable protein supply; NDF, neutral detergent fiber; NDICP, neutral detergent insoluble crude protein; NE_g, net energy for growth; NE_m, net energy for maintenance; NPN, nonprotein nitrogen; OEB, degradable protein balance; OM, organic matter; PA, soluble protein fraction; PB1, rapidly degradable protein fraction; PB2, intermediately degradable protein fraction; PB3, slowly degradable protein fraction; PC, undegradable protein fraction; RUOM, RUP, RUST, and RUNDF, rumen undegradable feed OM, CP, starch, or NDF, respectively; S, soluble in situ fraction; SCHO, carbohydrates soluble in rumen; SCP, soluble crude protein; SN, N soluble in rumen; TDN, total digestible nutrients; U, undegradable in situ fraction; wDDGS, wheat-based dried distillers grains with soluble

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