Optimal level of physically effective neutral detergent fibre in corn stover cracked-corn-based finishing diets on the growth performance, dietary energetics, carcase characteristics, and nutrient digestion in fattening lambs

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ABSTRACT
Two trials were conducted to determine the optimal physically effective neutral detergent fibre (peNDF) level in corn stover-cracked-corn-based finishing diets for feedlot lambs. Concentrations of peNDF (10.0, 12.5, 15.0, and 17.5%) were controlled by replacing cracked corn grain with corn stover. In Trial 1, 32 Rambouillet × Katahdin intact male lambs (body weight [BW], 28.47 ± 2.70 kg) were used in a 63-d feeding trial. Dry matter intake (DMI), average daily gain (ADG), and feed efficiency (GF) were greater at the 12.5% peNDF level (quadratic component, P < 0.05). The dressing percentage increased linearly (P < 0.01) as peNDF decreased, but hot carcase weight (HCW) was greater for lambs fed 12.5% peNDF (quadratic effect, P < 0.01) than those fed different concentrations. In Trial 2, eight ruminally cannulated Pelibuey lambs (29.3 ± 4.2 kg BW) were used in a replicated 4 × 4 Latin square design to evaluate the effects of the treatment on total tract digestion. Ruminal pH, registered at 4-h post-feeding, linearly decreased (P < 0.01) from 6.70 to 5.77 as the level of peNDF decreased. The digestibility of dry matter (DM), organic matter (OM), and NDF increased linearly (P < 0.01) as the peNDF level decreased, but the apparent digestible energy (Mcal/kg) showed a quadratic effect (P < 0.01) with a peNDF of 12.5%. The findings show that the estimated optimal peNDF level in cracked-corn-based finishing diets for lambs in the finishing phase of fattening is approximately 11.5%.

HIGHLIGHTS
- Physically effective NDF levels in finishing rations for lambs were tested; the study provides better understanding of peNDF level on finishing lambs
- Levels lower than 12.5% and greater than 15.0% peNDF decrease performance and carcase yield
- Total tract digestion and energy efficiency were maximal at 11.5% peNDF

Introduction
Fibre plays an important role in maintaining the normal functioning of the rumen in animals fed high-concentrate diets. However, the optimal incorporation of fibre in finishing diets should counteract the two main limitations of this ingredient in finishing: the limitations in ingestion of the diet and the dilution of dietary energy as a result of its low-energy content. Therefore, efforts have been made to determine the optimal neutral detergent fibre (NDF) level in finishing diets where the negative associative effects of NDF are avoided without undermining its role as a functional feed in fattening.

The main source of NDF in finishing diets is forage, but not all NDF fractions can stimulate chewing and rumination. Mertens (1997) defined physically effective neutral detergent fibre (peNDF) as the fraction of NDF that stimulates rumination and contributes to proper ruminal digesta mat consistency. The peNDF concept integrates information on chemical constituents (NDF) and structural features (particle size) that act together and interdependently to stabilise ruminal fermentation.
and acid-base balance (Zebeli et al. 2012). Therefore, peNDF can be a useful tool to determine the minimum NDF level (including the intensity of processing) required for finishing diets for a normally functioning rumen. An average of 25 million metric tons of corn stover is intended annually for animal feed (Borja et al. 2013), which represents a major source of forage, accounting for up to 40% of forage availability (Beuchelt et al. 2015). Owing to the chemical properties (low protein [2–6%] and high NDF content [62–72%]; Donnelly et al. 2018; Tuturoong et al. 2020) of corn stover, it is a good source of functional feed in finishing diets. Cracked corn is a common processing method used in feedlot lamb rations. Given the NDF concentration (~11%; NRC 2007) of cracked corn and its inclusion level in finishing diets (~70%), cracked corn can contribute almost 40% of the total NDF to the ration. It has been determined that corn NDF has a lower extent of degradation than that of grass NDF (Varga and Hoover 1983). Owing to the physical characteristics of the particles of dry-processed corn, its peNDF value can range from 0.60 to 0.88 (Fox and Tedeschi 2002; Maulfair and Heinrichs 2013). Thus, cracked corn also contributed to the peNDF of the diets. Therefore, the peNDF of corn must be considered by ration formulators to determine the optimal participation of forages in high-energy diets to maximise grain inclusion without experiencing negative effects on dry matter intake (DMI) and weight gain. Very limited information on peNDF requirements in cracked-corn-based diets for finishing lambs can be found in the available literature. Smith (2008) and de Klerk (2016) concluded that the inclusion of 13.5% forage level provides the peNDF requirements for finished lambs; however, 13.5% forage inclusion was the lowest tested level in a cracked-corn-based moderated-energy finishing diet (~2.00 Mcal/kg NE\(_m\)), wherein alfalfa hay (milled through a 1.25-cm screen) was used as forage source. It is well known that alfalfa fibre is not a good source of peNDF because its fibre is very brittle and breaks easily, permitting a rapid rate of passage from the rumen (Ware and Zinn 2003). In current feeding systems for lambs, low-quality forage (i.e. straw) instead of alfalfa hay is extensively used in finishing diets. In addition, the use of finishing diets for feedlot lambs containing up to 2.15 Mcal net energy for maintenance (NE\(_m\))/kg and, consequently, a lower peNDF level, is not uncommon. Therefore, we hypothesised that cracked corn plays an important role as a peNDF source in finishing cracked-corn-based diets, which include low-quality forage as a fibre source. For the reason above, the objective was to evaluate four levels of peNDF, considering cracked corn and corn stover as source of peNDF, on the growth performance, dietary energetics, carcass characteristics, and nutrient digestion in lambs fed high-energy finishing diets (>2.14 Mcal NE\(_m\)/kg diet) during the final phase of fattening.

**Materials and methods**

**Growth performance and carcase trial (trial 1)**

This trial was conducted at the ‘Los Pirules’ ranch, located in Jaltepec Axapusco, Estado de México (19° 43’ N; 98° 38’ W) and 2,490 m above sea level. The weather is a semi-humid temperate with rains in the summer (García 2004). The average annual temperature is 16 °C, and the annual rainfall is 550 mm.

**Animals, treatments, and experimental design**

Thirty-two Rambouillet × Katahdin (average initial live weight, 28.46 ± 2.70 kg) male lambs were used in a growth performance experiment to evaluate the effects of treatments on growth performance, dietary energetics, and carcass characteristics. The average ambient temperature and relative humidity during the course of the experiment were 16.5 °C and 21%, respectively. Four weeks before the experiment started, lambs were treated for endoparasites (Albendaphorte 10%, Animal Health and Welfare, México City, México) and injected with 2 mL of vitamin A (500,000 IU, 75,000 IU vitamin D\(_3\), and 50 IU vitamin E; Synt-ADE®, Zoetis México, México City) and were gradually adapted to dietary treatment containing 12.5% peNDF to reduce the risk of digestive disturbance when they received the respective treatment at the beginning of the experiment. Upon initiation of the experiment, all lambs were weighed individually on an electronic scale before the morning meal (TORREY TIL/S: 107 2691, TOR REY electronics Inc., Houston, TX, USA) and individually assigned randomly within two weight blocks to 32 pens. The experiment consisted of four treatments (eight lambs in each treatment) with eight replicates per treatment. The individual pens used in the experiment were of 3 m\(^2\) area with overhead shade, automatic waterers, and 1-m fence-line feed bunks. Dietary treatments were randomly assigned to pens within blocks, resulting in eight replicates per treatment. The lambs were allowed ad libitum access to the dietary treatments. Dietary treatments consisted of iso-nitrogenous mixed diets with four peNDF concentrations (10.0, 12.5, 15.0, or 17.5%). Urea (PNP source)
and zeolite (as diluent) were used to maintain protein equivalence in all dietary treatments, which was slightly higher (dry matter [DM], 14.5 vs. 14.0%) than that recommended by Estrada-Angulo et al. (2018) for the final phase of finishing lambs weighing /C24 30 kg (Table 1). To reach the targeted peNDF concentration, cracked corn grain (CCG) was replaced with corn stover (CS), which was ground in a hammer mill (Azteca 20, Molinos Azteca, Guadalajara, M exico) with a 3.81-cm screen before incorporation into the total mixed ration (Table 1). Corn grains were prepared by passing whole regional white corn through rollers (46/261 cm rollers, 5.5 corrugations/cm; Memco, Mills Rolls, Mill Engineering & Machinery Co., Oklahoma, CA, USA). The roll pressure was adjusted so that the kernels were broken to produce a bulk density of approximately 0.60 kg/L. The bulk densities of the ground CS and CCG were measured using a standard bushel tester (OHAUS Grain Scale Model 8324915, Parsipanii, NJ, USA). The chemical composition and physical characteristics of the ground CS and CCG used are listed in Table 2.

Daily feed allotments to each lamb were adjusted to allow minimal (<5% of total offered) refusal feed remaining in the feed bunk just prior to the morning feeding. The amount of feed offered and the refusals were weighed daily. Lambs were provided fresh feed ad libitum, offered three times daily, distributed in proportions of 30:20:50 at 08:00, 12:00, and 16:00 h, respectively. Feed bunks were assessed visually between 07:40 and 07:50 h each morning, refusals were collected and weighed, and feed intake was determined. Adjustments, either to increase or decrease daily feed delivery, were made during the afternoon feeding. The lambs were weighed individually at the beginning of the trial and at the time of harvest. The initial shrunk body weight (SBW) was

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Table 1. Composition of dietary treatments used in Exp. 1 and Exp. 2.

| Item | 10.0 | 12.5 | 15.0 | 17.5 |
|------|------|------|------|------|
| Cracked corn<sup>b</sup> | 778 | 726 | 674 | 623 |
| Ground corn stover<sup>c</sup> | 52 | 104 | 156 | 207 |
| Soybean meal | 110 | 110 | 110 | 110 |
| Tallow | 20 | 20 | 20 | 20 |
| Urea | 6.5 | 7.5 | 8.5 | 9.5 |
| Premix mineral<sup>d</sup> | 16.5 | 16.5 | 16.5 | 16.5 |
| Zeolite | 7 | 6 | 5 | 4 |
| Limestone | 10 | 10 | 10 | 10 |
| Dry matter, g/kg | 917.1 | 912.6 | 910.6 | 923 |

<sup>a</sup>Physical effective NDF represents effective dietary NDF calculated as NDF content (%DM) multiplied by physical effectiveness factor determined as the DM proportion of particles retained above 1.18 mm determined using Penn State Particle Separator 2002 model.

<sup>b</sup>Prepared by passing whole corn through hammer mill to obtain a final bulk density of approximately 0.60 kg/L.

<sup>c</sup>Grinded in a hammer mill with a 2.5 cm screen.

<sup>d</sup>Contained: Calcium, 127 g/kg; Phosphorous, 1.2 g/kg; Magnesium, 8.1 g/kg; NaCl, 300 g/kg; Zn 4.0 g/kg, vitamin A, 225 U/g; vitamin E, 1.26 U/g.

<sup>e</sup>Dietary composition was determined by analysing subsamples collected and composited throughout the experiment. Accuracy was ensured by adequate replication with acceptance of mean values that were within 5% of each other.

<sup>f</sup>Based on tabular net energy (NE) values for individual feed ingredients (NRC, 2007)

Table 2. Chemical composition and particle size distribution of grind corn stover (CS) and white cracked corn grain (CCG) offered to finishing lambs.

| Item | CS | CCG |
|------|----|-----|
| Dry matter content, g/kg | 862 | 934 |
| Chemical composition, g/kg of DM | | |
| Crude protein | 40.3 | 92.1 |
| NDF | 643.2 | 113.0 |
| Ash | — | 710.4 |
| Bulk density (kg/L) | 0.126 | 0.657 |
| Particle size distribution<sup>a</sup> | | |
| >1.18 mm | 89.66 | 81.60 |
| <1.18 mm and pan | 10.34 | 18.40 |
| peNDF, %<sup>b</sup> | 57.66 | 9.22 |

<sup>a</sup>Determined using Penn State Particle Separator (3-sieve model 2002 version; The Pennsylvania State University, University Park, State College, PA, USA).

<sup>b</sup>Physical effective NDF represents effective dietary NDF calculated as NDF content (%DM) multiplied by physical effectiveness factor determined as the DM proportion of particles retained above 1.18 mm.
determined as the full BW × 0.96 (weight adjustment equivalent to withdrawal of food and water for 18 h; Cannas et al. 2004; NASEM 2016). Upon completion of the study, all lambs were weighed following an 18-h fast (food but not drinking water was withdrawn) to obtain the final SBW. The experiment lasted for 63 d.

Sampling and laboratory analyses

Feed samples were collected from each elaborated batch, while feed refusal was collected daily and composited weekly for DM analysis (oven drying at 105 °C until no further weight loss; method 930.15; AOAC 2000). Corn grain, CS, and elaborated feed samples were subjected to the following analyses: DM (oven drying at 105 °C until no further weight loss; method 930.15; AOAC 2000); protein (CP; N × 6.25, method 2002.11; AOAC 2005); ash (method 942.09; AOAC 2005); NDF (Van Soest et al. 1991), incorporating heat stable x-amylase (Ankom Technology, Macedon, NY, USA) at 1 mL per 100 mL of NDF solution (Midland Scientific, Omaha, NE) corrected for NDF-ash, starch (Zinn et al. 1999), and gross energy (using an adiabatic bomb, Model 6400, Parr Instrument Co., Moline, IL, USA). The organic matter (OM) content of the feed and digesta samples was estimated as DM concentration minus ash content. Additionally, dietary treatments were subjected to the determination of Ca (Method 968.08, AOAC 2005) and P (Method 965.17, AOAC 2005). Particles retained above 1.8 mm were determined in CS and CCG using the Penn State Particle Separator (3-sieve model 2002 version; The Pennsylvania State University, University Park, State College, PA, USA). Physically effective NDF represents the effective dietary NDF, calculated as the NDF content (% DM) multiplied by the physical effectiveness factor determined as the DM proportion of particles retained above 1.18 mm.

Calculations

The average daily gain (ADG) was determined as the daily correction of the final and initial SBW divided by the corresponding d on the feed. The gain efficiency was determined as the ADG divided by the corresponding DMI. One approach for evaluating the efficiency of dietary energy utilisation in growth-performance trials is the ratio of observed-to-expected DMI and observed-to-expected dietary net energy (NE). Energy intake is expected based on the dietary NE concentration and measures of growth performance. This estimation of expected DMI was performed based on the observed ADG, average SBW, and NE values of the diet (Table 1) according to the following equation:

\[
\text{Expected DMI, kg/d} = \left( \frac{\text{EM/NE}_m}{\text{EG/NE}_g} \right) + (\text{EG/NE}_g) \quad (1)
\]

where EM is the energy required for maintenance (Mcal/d) = 0.056 × SBW^{0.75}; EG (energy gain, Mcal/d) = 0.276 × ADG × SBW^{0.75}; and NE_m and NE_g are the corresponding NE values based on the ingredient composition of the experimental diet (Table 1, NRC 2007). The coefficient (0.276) was taken from NRC (1985), assuming a mature weight of 110 kg for Rambouillet × Katahdin male lambs. The observed dietary NE was calculated using the EM and EG values, and the DMI observed during the experiment by means of the quadratic formula:

\[
x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2c} \quad (2)
\]

where \(x = \text{NE}_m\), \(a = 0.41\) EM, \(b = 0.877\) EM + 0.41 DMI + EG, and \(c = -0.877\) DMI (Zinn et al. 2008).

Carcase data

All lambs were harvested on the same day. The procedure was conducted according to the guidelines of federal law for humanitarian care and animal protection during the slaughter process (NOM-033-SAG-2014) through percussion using captive bolt. The lambs were skinned, the gastrointestinal organs were separated, and the carcasses were weighed.

Statistical analysis

Performance and carcase data were analysed as a randomised complete block design, with ‘lamb’ as the experimental unit. All data were tested for normality using the Shapiro–Wilk test. MIXED procedure in SAS (2004; SAS Inst. Inc., Cary, NC, USA) was used to analyse the variables. The treatment effects were tested for the linear, quadratic, and cubic components of the peNDF levels. When the quadratic effects were significant, the estimated quadratic equations were constructed as a linear regression of the response variable on the peNDF and peNDF²peNDF values. Regression coefficients were estimated by ordinary least squares using the REG procedure of SAS. The peNDF value at the highest point of the response curve was estimated as \(-\beta_1/2\beta_2\) and replaced into the prediction equation to obtain the estimated response variable and with them, the inflexion point. In addition, separation of the means by T-test multiple comparisons between the peNDF levels was performed. Polynomials were considered significant.
when the \( p \)-value was \( \leq .05 \), and tendencies were identified when the \( p \)-value was \( >.05 \) and \( \leq .10 \).

**Digestion trial (trial 2)**

This trial was conducted at the Teaching and Research Centre for Animal Health and Production (CEPIPSA), located on the 29th kilometre of the Federal Mexico-Cuernavaca highway (19° 13’ N, 99° 08’ W) and 2,800 m above sea level. The weather is semi-cold, semi-humid, with rain in the summer (García 2004). The average annual temperature is 10°C, and the annual rainfall is 1,200 mm.

**Animals and experimental design**

Eight male Pelibuey lambs (shrunken weight of 29.28 ± 4.22 kg) fitted with ‘T’ type cannulas in the rumen were used in a replicated 4 × 4 Latin square experiment to evaluate the effects of the treatments on the total tract digestion and ruminal pH. Three weeks prior to initiating the experiment, all lambs received identical health processing to the lambs used in Trial 1 and gradually adapted to dietary treatment with 10.0% peNDF. Lambs were housed in individual metabolism crates (1.5 × 1.8 × 0.7 m) in an indoor facility, with access to water at all times. The treatments were the same as those used in Trial 1 (Table 1). Diets were fed in two equal proportions at 8:00 and 20:00 h daily ad libitum, and daily feed allotments to each lamb were adjusted to allow minimal (<5% of total offered) residual feed remaining in the feed bunk just prior to the morning feeding. The amount of feed offered and the refusals were weighed daily. Refusal was composted and stored at 4°C for subsequent analyses. The experimental period was 21 d, with 16 d of adjustment to the respective dietary treatment and 5 d of sample collection.

**Sampling and laboratory analyses**

Three days prior to sampling, all lambs were fitted with a harness and faeces collection bag to become accustomed to them. During the collection period, faeces (4 d for sample collection) and ruminal samples (last day of each period for ruminal sampling) were collected from each lamb. Faecal samples were collected daily at 19:00 h, weighed fresh, and then stored at \(-20^\circ\) C for subsequent analysis. Samples from each lamb and within each collection period were analysed. On day five of each collection period, approximately 100 mL of ruminal fluid was obtained from each lamb 4 h post-feeding (12:00 h) via the ruminal cannula. A ruminal sample was taken from the ruminal ventral sac by a vacuum pump (Cole Parmer Instrument, Vernon Hill, IL, USA) using a Tygon tube (1.9 cm i.d.; USP Lima, OH, USA). The ruminal pH of the fresh samples was determined immediately (Orion 261 S, Fisher Scientific, Pittsburgh, PA, USA). Feed, faeces, and refusal samples were subjected to the same analyses as the feed samples of Trial 1. Digestibility was determined as: digestibility coefficient = (nutrient intake, g/nutrient in faeces, g)/nutrient intake, g.

**Statistical analysis**

The effects of the treatments on the digestion characteristics and ruminal pH were analysed as a replicated 4 × 4 Latin square design following the MIXED procedure indicated by SAS (2004; SAS Inst. Inc., Cary, NC, USA). ‘Treatment’ was the fixed effect, and ‘lamb’ and ‘period’ were the random effects. The treatment effects were tested for the linear, quadratic, and cubic components of the peNDF levels. Polynomials were considered significant when the \( p \)-value was \( \leq .05 \), and tendencies were identified when the \( p \)-value was \( >.05 \) and \( \leq .10 \).

**Results**

**Chemical composition and particle size distribution of ingredients and diets**

The final dietary peNDF concentrations (Table 1) were in close agreement (ratios of 1.03, 1.02, 1.02, and 1.02) with the targeted 10.0, 12.5, 15.0%, and 17.5% peNDF.

The roughage densities of 0.126 for CS and 0.657 for CCG determined here indicate the coarse processing of these ingredients. According to particle size distribution, CCG had 9% fewer particles as compared to that of CS (>1.18 mm than CS [81.60 vs. 89.66%]).

Due to the differences in the chemical composition between the CS and CCG replacements (Table 2), the NDF in the diets increased (from 13.68 to 22.02%), while starch was reduced (from 59.93 to 51.44%) as the level of CS increased (Table 1). Therefore, at similar intake levels, as the level of CS increased in the diet, the intake of peNDF increased (\( p < .01 \)), but starch intake was reduced (\( p < .01 \)).

**Growth performance, dietary energetics, and carcase characteristics**

The effects of peNDF treatment on the growth performance, dietary energetics, and carcase characteristics are shown in Table 3. DMI, ADG, and feed efficiency
were greater at the 12.5% peNDF level (quadratic component, \( p < .05 \)) as compared to those at the other levels. As peNDF decreased in the diet, the observed dietary NE increased (linear component, \( p < .01 \)). However, the average observed/expected dietary NE ratio tended (\( p/C20.09 \)) to be 3.5% lower (0.965) for lambs fed 10 and 17.5% peNDF, while the average observed/expected dietary NE ratio for lambs fed 12.5 and 15.0% peNDF were close (0.99) to 1.00. The observed/expected DMI ratio tended (\( p = .06 \)) to be lower for 12.5% peNDF lambs; therefore, the efficiency of dietary energy utilisation (the observed-to-expected dietary NE ratio) was optimised at 12.5% peNDF level. The estimated optimal response values (estimated by regression) for the DMI, ADG, and GF were 12.34, 11.45, and 10.81%, respectively. The dressing percentage increased linearly (\( p < .01 \)) as peNDF decreased, but the apparent digestible energy (Mcal/kg) showed a quadratic effect (\( P < 0.01 \)) with a peNDF of 12.5%. The estimated optimal response values (estimated by regression) for the apparent digestible energy were obtained at the 10.60% peNDF level.

**Discussion**

**Chemical composition and particle size distribution of ingredients and diets**

It has been demonstrated that plant maturity at the time of forage is harvested, and the particle sizes of both the processed forage and corn grain are the factors with the greatest impact on the concentration of peNDF in finishing diets. In the case of CS, the NDF concentration is strongly influenced by the time of corn grain harvest, which is why its chemical composition varies widely (NDF of CS ranged from 62 to 83%; Donnelly et al. 2018). Early harvesting of corn decreases the NDF concentration in CS (Nogoy et al. 2019); therefore, the CS used in this experiment (64.32% NDF) was an early-harvest corn. Otherwise, the chemical composition of cereal grains is less variable. The white corn grain used in both trials was a Mexican commercial blend, and its chemical composition (starch and NDF) was in close agreement with those published previously for this type of corn (Castro-Pérez et al. 2013).

Regarding the particle size characteristics, bulk density is a good index of particle density (associated with the degree of processing): the greater the bulk density, the lower the particle size distribution. Therefore, the particle size distribution of the ingredients and diets were optimised at 12.5% peNDF level.
density, the smaller the particle size. The bulk density of ground CS obtained here (0.126 kg/L) was within the range previously reported (0.050–0.130 kg/L; Chevanan et al. 2008; Thoreson et al. 2010). On the other hand, the bulk density of CCG was 10% greater (0.66 kg/L) than the target level of 0.60 kg/L, therefore, the final product (cracked corn) was more coarse-processing than projected, even so, the bulk density of cracked corn used in this experiment agreed according to the bulk density value of 0.64 kg/L for coarse cracked corn described by FAO (2012).

In forage sources, the intensity of processing (degree of milling) and NDF content determine its peNDF value. Specifically, for corn straw, the estimated peNDF, with ranges of 51% to 62%, have been reported (Gentry et al. 2016), a range that includes the value of 58% estimated in the present experiment for CS, which represented 89.66% of the total NDF in CS, which is very close to that reported by Mertens (2002) for low-quality forages. In grain corn, particle size is the main factor that affects its NDF value because its NDF content is quite constant (10.0 ± 1.83%; NASEM 2016). Given that the intensity of processing applied to corn grain in this experiment, the peNDF value obtained was 7% lower than the maximum value reported for cracked corn by Maulfair and Heinrichs (2013). Thus, CS and CCG contributed almost the entire (>98%) peNDF content in all the experimental dietary treatments. According to the peNDF content in corn grain and its participation level in each treatment, corn grain contributed 70.5, 52.7, 40.8, and 32.5% of the total peNDF contained in the 10, 12.5, 15, and 17.5% treatments, respectively.

**Growth performance, dietary energetics, and carcase characteristics**

It was observed that 12.5% peNDF concentration plateaued DM intake, given that the lambs that were fed with lower (10.5% peNDF) and greater (15 and 17.5%) peNDF levels showed a lower DM intake. The total daily NE consumed was very similar (2.72 vs 2.74 Mcal NEm/d) between treatments 10.5% and 12.5%, which indicates that total energy intake could be the main limiting factor for DMI in lambs that were fed with levels equal to or lower than 12.5% peNDF. Otherwise, in lambs that were fed with a greater level of peNDF than 12.5%, the constraints of ruminal bulk fill could be exceeded by reducing DMI. This supports the findings of Flores-Mar et al. (2017), which indicated that when diet formulations for finishing lambs exceed 9% forage NDF, constraints of ruminal bulk fill are exceeded; thus, not allowing lambs to express their potential maximum intake. Ma et al. (2019) developed an equation to predict the DMI in lambs fed finishing

**Table 4. Treatment effects on ruminal pH and total tract digestion of ruminally cannulated lambs fed different physically effective NDF (peNDF) level in diet.**

| Item | 10.0 | 12.5 | 15.0 | 17.5 | SEM | Lineal | Quadratic |
|------|------|------|------|------|-----|--------|-----------|
| Lambs | 8 | 8 | 8 | 8 | 5.77 | 0.04 | <0.01 | 0.28 |
| Ruminal pH | 5.77 | 6.03 | 6.49 | 6.69 | 0.04 | <0.01 | 0.52 |
| Intake | | | | | | <0.01 | 0.05 |
| Dry matter, g/d | 728 | 726 | 777 | 790 | 16.7 | 0.04 | <0.01 | 0.21 |
| Organic matter, g/d | 687 | 682 | 726 | 737 | 15.6 | 0.04 | <0.01 | 0.45 |
| Neutral detergent fibre, g/d | 996 | 119 | 150 | 174 | 2.8 | 0.04 | <0.01 | 0.72 |
| Nitrogen, g/d | 16.8 | 16.8 | 18.0 | 18.4 | 0.8 | 0.02 | <0.01 | 0.03 |
| Starch, g/d | 406 | 379 | 377 | 354 | 9.8 | 0.02 | <0.01 | 0.72 |
| Gross energy, Mcal/d | 3.16 | 3.15 | 3.34 | 3.36 | 0.07 | 0.06 | 0.88 |
| Faecal excretion | | | | | | <0.01 | 0.01 |
| Dry matter, g/d | 122 | 117 | 152 | 174 | 6.02 | 0.04 | <0.01 | 0.01 |
| Organic matter, g/d | 92.9 | 87.4 | 110 | 119 | 4.44 | 0.04 | <0.01 | 0.03 |
| Neutral detergent fibre, g/d | 45.6 | 56.3 | 74.6 | 90.4 | 2.45 | 0.04 | <0.01 | 0.15 |
| Nitrogen, g/d | 1.35 | 0.93 | 1.83 | 2.16 | 0.07 | 0.04 | <0.01 | 0.01 |
| Starch, g/d | 0.446 | 0.429 | 0.575 | 0.638 | 0.019 | <0.01 | 0.01 |
| Gross energy, Mcal/d | 83.27 | 83.91 | 80.39 | 77.99 | 0.58 | <0.01 | 0.02 |
| Organic matter, % | 86.49 | 87.17 | 84.81 | 83.74 | 0.62 | <0.01 | 0.07 |
| Neutral detergent fibre, % | 54.08 | 52.48 | 50.26 | 48.06 | 1.43 | <0.01 | 0.76 |
| Nitrogen, % | 75.85 | 74.44 | 72.00 | 72.22 | 2.03 | 0.13 | <0.01 | 0.37 |
| Starch, % | 99.69 | 99.78 | 99.57 | 99.47 | 0.28 | 0.59 | <0.01 | 0.31 |
| Gross energy, Mcal/d | 85.90 | 86.34 | 82.79 | 80.99 | 0.60 | <0.01 | <0.01 |
| Digestible energy, Mcal/kg | 3.73 | 3.74 | 3.56 | 3.44 | 0.03 | <0.01 | <0.01 |
| Total tract digestion | | | | | | <0.01 | 0.01 |
| Dry matter intake, % | 83.27 | 83.91 | 80.39 | 77.99 | 0.58 | <0.01 | 0.02 |
| Organic matter, % | 86.49 | 87.17 | 84.81 | 83.74 | 0.62 | <0.01 | 0.07 |
| Neutral detergent fibre, % | 54.08 | 52.48 | 50.26 | 48.06 | 1.43 | <0.01 | 0.76 |
| Nitrogen, % | 75.85 | 74.44 | 72.00 | 72.22 | 2.03 | 0.13 | <0.01 | 0.37 |
| Starch, g/d | 99.69 | 99.78 | 99.57 | 99.47 | 0.28 | 0.59 | <0.01 | 0.31 |
| Gross energy, Mcal/d | 85.90 | 86.34 | 82.79 | 80.99 | 0.60 | <0.01 | <0.01 |
| Digestible energy, Mcal/kg | 3.73 | 3.74 | 3.56 | 3.44 | 0.03 | <0.01 | <0.01 |

*Physical effective NDF represents effective dietary NDF calculated as NDF content (%DM) multiplied by physical effectiveness factor determined as the DM proportion of particles retained above 1.18 mm determined using Penn State Particle Separator (3-sieve model 2002 version; The Pennsylvania State University, University Park, State College, PA, USA).*

*bRuminal pH measured at 4 h post-feeding (morning meal).*
diets using the LW (kg) as follows: DMI, kg/d = 0.471 × 0.024 LW, $R^2 = 0.68$ ($n = 576$).

Given that the peNDF of forage not only represents its particular functionality in promoting digestive function but also represents the character of the forage that can limit energy intake and, consequently, has a negative influence on productive performance, one of the main concerns is that it determines the optimal NDF level in finishing diets where the negative associative effects of the NDF are avoided without undermining its role as a functional feed for fattening. However, there is controversy about peNDF requirements in finishing diets for feedlot cattle and sheep. On one hand, it has been recommended that the optimal peNDF for optimal intake and energy utilisation for growing-finishing cattle is within the range of 12–18% (Mertens 2002). On the other hand, Fox and Tedeschi (2002) exposed their recommendation of 7–10% peNDF levels based on the equations of Pitt et al. (1996), with the aim of maintaining ruminal pH above 5.7.

Observed/expected dietary NE and DMI ratios are important and practical applications of current standards for energetics in nutrition research (Zinn et al. 2008). The estimation of dietary energy and the observed/expected DMI ratio (apparent energy retention per unit DMI) revealed differences in the efficiency of energy utilisation of the diet itself, independent of confounding effects of ADG and DMI associated with gain-to-feed ratios. Thus, they provide important insights into the potential effects of treatments on the efficiency of energy utilisation. An observed/expected dietary NE ratio of 1.00 indicates that the performance corresponded to the expected dietary NE and DMI. A coefficient greater than 1.00 is indicative of a greater efficiency of dietary energy utilisation, whereas a coefficient lower than 1.00 indicates a lower-than-expected efficiency of energy utilisation. In the case of the observed/expected DMI ratio, the interpretation of the ratio is exactly the opposite. Values below 1.00 indicate greater energy retention per unit of DMI. For lambs fed 10 and 17.5% peNDF, the average observed/expected dietary NE ratio tended ($p \leq 0.09$) to be 3.5% lower (0.965), while the average observed/expected dietary NE ratios for lambs fed with 12.5% and 15.0% peNDF were close (0.99) to 1.00. Therefore, the decrease in ingested energy was not proportional to the decrease in weight gain in lambs fed with 10.0 and 17.5% peNDF. This lower efficiency in dietary energy utilisation could be explained by an increase in the NE of maintenance requirements in these lambs. An alternative approach for expressing the effects of treatments on animal energetics in the present experiment would be to keep the NE value of the diet constant and present treatment effects solely as a function of changes in the maintenance coefficient (MQ), as follows:

$$MQ = \frac{(NE_m \times [DMI-(\{EG/NE_g\}]/SBW^{0.75})}{SBW^{0.75}}$$

where $NE_m$ and $NE_g$ correspond to the NE of the diet (Table 1), $EG = 276 \times ADG \times SBW^{0.75}$, and SBW is the average SBW. Accordingly, an average increase in maintenance coefficient of 12% (0.063) over the MQ value of 0.056 indicated by NRC (2007) was observed in lambs fed 10.0% and 17.5% NDF. This alteration in MQ could be due to higher susceptibility to subacute acidosis in lambs that were fed with 10.0% peNDF treatment. On the other hand, the greater physical intake required with a high-forage diet to achieve potential growth is likely to result in greater gut fill, an increase in energy expenditure on rumination and digestion, and a greater production of acetic acid in the rumen (Dong et al. 2015). This is supported by the findings of Shi et al. (2018), who reported that the efficiency of energy utilisation in heifers was lower with high-forage diets than with low-forage diets. The similar values of dietary NE estimated in the digestion and performance trials in this study provide confirmatory evidence that the measures obtained here are not aberrant but support previous findings about the efficiency of energy utilisation in low- and high-forage diets.

Increases in carcase weight with increases in energy intake are consistent responses in lambs (Salinas-Chavira et al. 2017; Gallo et al. 2019) and cattle (Swanson et al. 2017) and are related to the rate of daily weight gain. Increasing levels of bulky forage in diets can lead to increased digestive tract size/weight, owing to its slow digestion and longer permanence in the tract. As a result, the gastrointestinal tract is greater in mass and thus has a negative effect on the DP of lambs.

**Nutrient digestion and 4-h post-feeding ruminal pH**

According to its particle size distribution, NDF content (Table 2), and level of participation in diets (Table 1), CCG represented almost 70% of peNDF contained in the high-grain diet. It is well known that one of the most commonly used indicators to predict ruminal pH from the chemical composition of the diet is the concentration of peNDF. As dietary increases in NDF (with concomitant decreases in starch), ruminal pH increases because the peNDF fraction can stimulate chewing and rumination and lowers the availability of soluble sugars in the rumen environment (Kinser et al. 1988). The relationship between peNDF and ruminal pH has
been described by the equation (Pitt et al. 1996):

$$\text{pH} = 5.425 + 0.04229 \times \text{peNDF} \; (\% \; \text{DM}) \; (4)$$

Applying the equation to the peNDF of each treatment, predicted pH values represent 1.02, 0.99, 0.94, and 0.93 of the ruminal pH values observed here. Apparently, the equation of Pitt et al. (1996) is a more valuable tool for predicting ruminal pH in high-grain diets (i.e. < 13% peNDF). This can be partially explained by the fact that high-forage diets have a longer particle size, which may increase sorting of the diet when offered ad libitum (Llanch et al. 2020), a behaviour already linked to lower and variable ruminal pH in cattle (DeVries et al. 2008). However, this statement must be taken with caution because the data of pH was taken at single one-point data, and as mentioned previously, this may not represent an average of overall pH readings at different times of the day. Nevertheless, the close ratio with predicted pH values for the peNDF diets could confirm that coarse cracked corn is also an important source of peNDF for the diet; therefore, supplying peNDF from CCG must be considered as a useful tool to determine the optimal forage participation in diets.

The opposite effect on DMI (the lower peNDF, the greater DMI) observed in Trial 1 (growth performance trial) compared with Trial 2 (digestion trial) was mainly due to the low-level intake registered in the digestion trial. Cannulated lambs in the digestion trial had an average intake of 62 g/kg LW$^{0.75}$, while lambs in the performance trial (Trial 1) intake averaged 90 g/kg LW$^{0.75}$. This low level of intake did not permit the effect of filling by peNDF, limiting the intake. Generally, lambs with cannulas and contained individually show lower intake than those with intact lambs (Van et al. 2007). The increase in DMI observed in the digestion trial as the peNDF content increased, which is consistent with previous studies in which lambs can compensate for the dilutive effect of NDF by increasing the DMI to maintain energy intake (Zali and Yansari 2015). Even when sufficient data regarding the relationship between peNDF and DMI are available in dairy cattle (Beauchemin and Yang 2005; Zebeli et al. 2012), the mechanism describing how peNDF might affect DMI in low-forage diets for feedlot cattle (Pereira et al. 2021) and for fattening lambs (Salinas-Chavira et al. 2017) are not well defined yet.

A decrease in nutrient digestion when forage replaces concentrates in diets is a consistent response in lambs (Kinser et al. 1988) and cattle (Oh et al. 2016). This is due to the substitution of corn grains with less digestible ingredients such as forage. This effect becomes more evident when the replacement forage source has low digestibility, such as the CS used in the present experiment. However, the magnitude of this effect can vary by several factors (i.e. associative effects between ingredients, degree of processing, among others; Oh et al. 2016). Therefore, the digestibility of the dietary components OM and NDF in finishing diets depends on the level of replacement, the forage source, and the particle size of the forage used, among others (Kinser et al. 1988; Salinas-Chavira et al. 2017). For example, Smith (2008) evaluated peNDF levels of 13 to 15% in finishing diets for lambs using alfalfa hay (ground through a 12.5-mm screen) as a roughage source. The apparent digestibility of CP and NDF was greater ($p < 0.05$) for the highest peNDF level (15%), without any effect on the apparent digestibility of OM, GE, or growth performance. In opposite, de Klerk (2016) reported, similar to our results, a linearly decrease on OM, CP, and GE digestibility in lambs when increasing inclusion level of alfalfa hay from 15% to 59% in diet. The inconsistencies between these reports are related to the level of fibre used. The physical characteristics of alfalfa fibres cause it to be very brittle and break easily, permitting a rapid rate of passage from the rumen; thus, at moderate levels of inclusion (i.e. 15%), the negative effect on its digestibility is less noticeable. On the other hand, when the fibre source comes from straws, the negative effects on DM intake and nutrient digestibility become more important even at a moderate level of inclusion, as what happened in this experiment.

Even when the digestibility of nutrients increased linearly as the peNDF level decreased, the apparent digestible energy (Mcal/kg) was greatest at 12.5% peNDF. Thus, the fact that the apparent digestible energy (Mcal/kg) was highest at 12.5% peNDF, even when the digestible nutrient intake was higher (5% more starch and 16% lower NDF) than for the 10.0% peNDF treatment, indicating that the optimal utilisation of dietary energy was at the 12.5% peNDF level. The concentration of NEm (Mcal/kg) can be estimated from the observed digestible energy as follows (Galayen et al. 2016):

$$\text{NE}_{m} \; \text{Mcal/kg} = 0.70113ED – 0.53754 \; (5)$$

Conclusions

Coarse cracked corn in finishing diets used in the final phase of lamb fattening (~30 kg LW) represents a peNDF source and must be considered by diet formulators when including forage sources as functional ingredients in finishing diets. Based on the DMI, ADG, and dietary energy utilisation in the growth performance trials and on the digestion utilisation of nutrients in Trial 2, the optimal peNDF level in cracked-corn-based finishing diets using a CS as forage was 12.5%; however, based on the estimated optimal response...
(estimated by regression), the level was approximately 11.5%. Lower peNDF levels decrease the efficiency of dietary NE utilization, while peNDF levels higher than 15.0% negatively affect energy efficiency, daily gain, and carcase characteristics because of lower nutrient digestion and the diluting effects of NDF on dietary energy.

The results observed here support the importance of considering the contribution of peNDF of grain when based grain diets are offered to lambs, which should always be done considering the type (source of roughage) and size of particle of the forage used. This is a useful tool to determine the optimal level of peNDF (and forage level used) in finishing diets.

**Ethical approval**

The protocols used in this study were reviewed and approved by the Universidad Nacional Autónoma de México, Use and Care Administrative Committee (protocol number MC-2018/1–6).

**Disclosure statement**

No potential conflict of interest was reported by the author(s).

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**Data availability statement**

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

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