

# Effect of novel fiber ingredients on ileal and total tract digestibility of energy and nutrients in semi-purified diets fed to growing pigs

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## Abstract

**BACKGROUND:** Consumption of different dietary fibers may influence the digestibility of carbohydrates and other nutrients. Therefore the objectives of this experiment were to determine the effect of novel fiber ingredients on the apparent ileal digestibility (AID) and apparent total tract digestibility (ATTD) of gross energy (GE), dry matter (DM), crude protein (CP) and total dietary fiber (TDF) in pigs and to calculate the standardized digestibility of analyzed TDF in four novel fiber ingredients.

**RESULTS:** The AID of DM and GE in diets containing novel fiber ingredients was less ( $P < 0.05$ ) than in a maltodextrin diet. Addition of cellulose or pullulan, but not resistant starch (RS) 60, RS 75 or soluble corn fiber 70, reduced ( $P < 0.05$ ) the AID of CP. The average ileal and total tract endogenous losses of analyzed TDF were calculated at 25.25 and 42.87 g kg<sup>-1</sup> DM intake, respectively.

**CONCLUSION:** Addition of novel fiber ingredients to a maltodextrin-based diet had different effects on the AID of DM, CP, GE and TDF. Measurements of the standardized digestibility of analyzed TDF may be a better indicator of TDF fermentability than measurements of AID and ATTD of TDF, because some endogenous metabolites may be analyzed as TDF.

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**Keywords:** apparent ileal digestibility; metabolizable energy; novel fiber ingredients; pigs; total dietary fiber

## INTRODUCTION

The lack of dietary fiber in highly processed foods contributes to some of the metabolic diseases in the western world.<sup>1</sup> Intake of dietary fiber is recommended at 20–38 g day<sup>-1</sup>, but the recommended intake is seldom met.<sup>2</sup> Novel carbohydrates that act as dietary fiber, such as resistant starch, soluble corn fiber (SCF 70) and pullulan, are commercially available and can be mixed into most food preparations to increase the concentration of dietary fiber.<sup>3</sup> The physiological behaviors that define the health benefits associated with intake of dietary fiber are influenced by the physicochemical characteristics of the carbohydrates in the fiber. However, because the characteristics of dietary fiber are diverse, the physiological behavior of dietary fiber is expected to differ among different sources of fiber.<sup>4</sup> The health benefits that many novel fiber sources provide depend mainly on the composition and digestibility of carbohydrates in the small intestine and the fermentability of carbohydrates that enter the large intestine. The low small intestinal digestibility of carbohydrates in novel fiber sources reduces postprandial glucose and insulin responses in humans and dogs, which may be beneficial in diabetic management.<sup>5,6</sup> Fermentation of carbohydrates in the large bowel may also increase the absorption of short-chain fatty acids, which may have benefits in controlling colonic diseases.<sup>7</sup> The reduced absorption of energy as glucose in the small intestine may also reduce the bioavailable energy of novel fiber sources compared with foods rich in starch, which may assist in weight management.<sup>8</sup> The type of carbohydrate and its subsequent digestibility, therefore, play an important

role in providing potential health benefits associated with the consumption of dietary fiber.

Determining energy and nutrient digestibility of food ingredients in humans is expensive and tedious, but the pig has been recognized as a good model for estimating nutrient and energy digestibility in humans.<sup>9–11</sup> The objective of this experiment was to determine the effect of novel fibers on the apparent ileal digestibility (AID) and apparent total tract digestibility (ATTD) of gross energy (GE), dry matter (DM), crude protein (CP) and total dietary fiber (TDF) in diets containing four novel fiber ingredients and to calculate the hindgut digestibility (HGD) of GE, DM, CP and TDF in these diets when fed to growing pigs. A second objective was to measure the endogenous flow of substrates that are analyzed as TDF and to calculate the standardized ileal digestibility (SID) and standardized total tract digestibility (STTD) of TDF in the four novel fiber ingredients when fed to pigs.

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## EXPERIMENTAL

The protocol for the experiment was reviewed and approved by the Institutional Animal Care and Use Committee at the University of Illinois.

### Animals, housing and experimental design

Twelve growing barrows (initial body weight (BW):  $20.0 \pm 2.8$  kg) that were the offspring of line 337 boars mated to C-22 females (Pig Improvement Company, Hendersonville, TN, USA) were each surgically fitted with a T-cannula in the distal ileum.<sup>12</sup> After surgery, pigs were housed in individual pens that were equipped with a feeder and a nipple drinker. Pigs were allowed 10 days to recover from surgery, during which time a corn/soybean meal grower diet ( $200 \text{ g kg}^{-1}$  CP) was provided on an *ad libitum* basis. Prior to the start of the experiment, pigs were transferred to metabolism cages that were equipped with individual feeders and nipple drinkers as well as screens to allow for separate collection of feed refusals and feces. Pigs were randomly allotted to a replicated  $6 \times 5$  Youden square design with six pigs and five periods per square. In each period, pigs within each square were fed one of six experimental diets, so there were ten replicate pigs per treatment.

### Ingredients, diets and feeding

Four novel fiber ingredients were used in this experiment (Table 1). Two of these fiber ingredients were resistant starches containing  $600 \text{ g kg}^{-1}$  TDF (RS 60) or  $750 \text{ g kg}^{-1}$  TDF (RS 75). A source of soluble corn fiber (SCF 70) and pullulan were also included in the experiment. Soluble corn fiber is a product of corn starch hydrolysis, which has an average degree of polymerization of 10.<sup>13</sup> Pullulan is a polysaccharide that is produced via fermentation by *Aureobasidium pullulans*. It has a degree of polymerization of 3000 and a molecular weight of 486 000 Da.<sup>5,13</sup> The four novel fiber ingredients were supplied by Tate and Lyle (Decatur, IL, USA). Both RS 60 and SCF 70 are commercial products marketed under the PROMITOR™ brand name. Synthetic cellulose (Solka floc, International Fiber Corp., Urbana, OH, USA) was included as a negative control.

A maltodextrin/casein-based control diet was formulated (Table 2). Five additional diets were prepared by replacing  $100 \text{ g kg}^{-1}$  maltodextrin in the control diet with  $100 \text{ g kg}^{-1}$

**Table 1.** Analyzed concentrations of gross energy, dry matter, crude protein, and total dietary fiber in maltodextrin (MD), cellulose, resistant starch 60 (RS 60), resistant starch 75 (RS 75), soluble corn fiber 70 (SCF 70), and pullulan, as-fed basis<sup>a</sup>

Item	Ingredient					
	MD	Cellulose	RS 60	RS 75	SCF 70	Pullulan
Gross energy (MJ kg <sup>-1</sup> )	16.4	16.6	15.6	16.0	15.7	16.1
Dry matter (g kg <sup>-1</sup> )	974	962	901	930	939	948
Crude protein (g kg <sup>-1</sup> )	7	7	7	7	4	4
Total dietary fiber <sup>b</sup> (g kg <sup>-1</sup> )	12	1000	629	756	100 <sup>c</sup>	854

<sup>a</sup> All samples were analyzed for acid-hydrolyzed diethyl ether, but none was measured.

<sup>b</sup> Using AOAC method 991.43.<sup>17</sup>

<sup>c</sup> Soluble corn fiber 70 contains  $700 \text{ g kg}^{-1}$  TDF using AOAC method 2001.03.<sup>25</sup>

**Table 2.** Ingredient composition of experimental diets containing maltodextrin (MD), cellulose, resistant starch 60 (RS 60), resistant starch 75 (RS 75), soluble corn fiber 70 (SCF 70), and pullulan, as-fed basis

Ingredient (g kg <sup>-1</sup> )	Diet					
	MD	Cellulose	RS 60	RS 75	SCF 70	Pullulan
MD	590.0	490.0	490.0	490.0	490.0	490.0
Sucrose	200.0	200.0	200.0	200.0	200.0	200.0
Casein	140.0	140.0	140.0	140.0	140.0	140.0
Soybean oil	40.0	40.0	40.0	40.0	40.0	40.0
Ground limestone	9.5	9.5	9.5	9.5	9.5	9.5
Dicalcium phosphate	7.0	7.0	7.0	7.0	7.0	7.0
NaCl	4.0	4.0	4.0	4.0	4.0	4.0
Vitamin/mineral premix <sup>a</sup>	3.0	3.0	3.0	3.0	3.0	3.0
DL-Methionine	1.5	1.5	1.5	1.5	1.5	1.5
Chromic oxide	5.0	5.0	5.0	5.0	5.0	5.0
Cellulose	—	100.0	—	—	—	—
RS 60	—	—	100.0	—	—	—
RS 75	—	—	—	100.0	—	—
SCF 70	—	—	—	—	100.0	—
Pullulan	—	—	—	—	—	100.0
Total	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0

<sup>a</sup> Provided the following (kg<sup>-1</sup> complete diet): vitamin A as retinyl acetate, 3828 µg; vitamin D<sub>3</sub> as cholecalciferol, 55.1 µg; vitamin E as DL- $\alpha$ -tocopheryl acetate, 66 µg; vitamin K as menadione nicotinamide bisulfate, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.58 mg; pyridoxine as pyridoxine hydrochloride, 0.24 mg; vitamin B<sub>12</sub>, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin as nicotinamide and nicotinic acid, 44 mg; folic acid, 1.58 mg; biotin, 0.44 mg; Cu, 10 mg as copper sulfate; Fe, 125 mg as iron sulfate; I, 1.26 mg as potassium iodate; Mn, 60 mg as manganese sulfate; Se, 0.3 mg as sodium selenite; Zn, 100 mg as zinc oxide.

of each of the four novel fiber ingredients or with  $100 \text{ g kg}^{-1}$  cellulose. Sucrose was added at  $200 \text{ g kg}^{-1}$  in all diets to improve diet palatability. Soybean oil, minerals and vitamins were also added to the diets. Chromic oxide, an indigestible marker, was included at  $5 \text{ g kg}^{-1}$  in all diets.

The daily feed allowance was calculated as 2.5 times the estimated maintenance requirement for energy (i.e.  $0.44 \text{ MJ metabolizable energy (ME) kg}^{-1} \text{ BW}^{0.75}$ ).<sup>14</sup> The daily feed ration was divided into two equal meals that were provided at 08:00 and 16:00, except on ileal collection days when feed was provided before and after ileal collection at 06:00 and 18:00 respectively. Water was available at all times.

### Data and sample collection

Pig body weights were recorded at the beginning of each period, and the amount of feed provided each day was recorded. Pigs were allowed 5 days to adapt to the experimental diets. Fecal samples were collected on days 6 and 7. On days 8 and 9, a 225 mL plastic bag was attached to the opened cannula barrel using a cable tie, and digesta that flowed into the bag were collected from 06:00 to 18:00. Bags were removed and replaced hourly. Collected digesta were immediately stored at  $-20^\circ \text{C}$ .

At the conclusion of the experiment, fecal and ileal samples obtained over the two-day collection periods were thawed, mixed within animal and diet, and a subsample was collected for chemical analysis. A sample of each diet and of each ingredient was also

collected. Digesta samples were lyophilized and ground before chemical analysis.

### Sample analysis

Diets, ingredients and ileal and fecal samples were analyzed for DM, CP and TDF based on AOAC methods.<sup>15–17</sup> For TDF analysis, a 1.000 g sample was prepared (AOAC method 985.29E)<sup>18</sup> and digested by 50  $\mu\text{L}$  of heat-stable  $\alpha$ -amylase for 15 min at 95–100 °C, 100  $\mu\text{L}$  of protease for 30 min at 60 °C and 300  $\mu\text{L}$  of amyloglucosidase for 30 min at 60 °C. The digested sample was then treated with 225 mL of 950 mL L<sup>-1</sup> ethanol for 1 h at 60 °C. The alcohol-treated enzyme sample was filtered in a crucible and the residue was washed twice with 15 mL of 780 mL L<sup>-1</sup> ethanol, 950 mL L<sup>-1</sup> ethanol and acetone. The crucible was dried in a 105 °C oven overnight and weighed to calculate the TDF. Gross energy of diets, ingredients, ileal samples and fecal samples was determined using bomb calorimetry (Model 6300, PARR Instruments, Moline, IL, USA). Chromium concentration of diets and ileal and fecal samples was determined by inductively coupled plasma atomic emission spectrometry.<sup>19</sup> Samples were prepared for chromium analysis using nitric acid/perchloric acid.<sup>20</sup> Water-binding capacity of the diets was also measured.<sup>21</sup> Briefly, 1000  $\pm$  5 mg of sample was weighed in a pre-dried centrifuged tube and the sample was hydrated with 30 mL of distilled water for 18 h. After centrifugation, the supernatant was separated from the sample by inverting the tube and letting water drain from the pellet for 1 h. The fresh and dried weights of the pellet were recorded. Water-binding capacity was calculated as the difference between the fresh and the dry weight of the pellet (g) divided by the dry weight of the pellet.

### Calculations and statistical analysis

The AID of GE was calculated for all diets using the equation<sup>22</sup>

$$\text{AID}_{\text{GE}} = \left\{ 1 - \left[ \left( \text{GE}_{\text{digesta}} / \text{GE}_{\text{feed}} \right) \times \left( \text{Cr}_{\text{feed}} / \text{Cr}_{\text{digesta}} \right) \right] \right\} \times 100 \quad (1)$$

in which AID<sub>GE</sub> (%) is the apparent ileal digestibility of GE, GE<sub>digesta</sub> is the concentration of GE (MJ kg<sup>-1</sup>) in the ileal digesta DM, GE<sub>feed</sub> is the concentration of GE (MJ kg<sup>-1</sup>) in the feed DM, Cr<sub>feed</sub> is the concentration of chromium (g kg<sup>-1</sup>) in the feed DM and Cr<sub>digesta</sub> is the concentration of chromium (g kg<sup>-1</sup>) in the ileal digesta DM. The AID of DM, CP and TDF was calculated using the same equation.

The ATTD (%) of GE, DM, CP and TDF was also computed using Eqn 1, except that the concentration of GE, CP, DM, TDF and chromium in the feces was used rather than the concentration in the ileal digesta. The HGD (%) of GE was calculated by subtracting the ileal digestibility of GE from the total tract digestibility of GE.<sup>23</sup> The HGD of DM, CP and TDF was calculated using the same equation.

Substrates from the ileal endogenous loss that are analyzed as TDF (g kg<sup>-1</sup> DM intake) were calculated based on the flow of analyzed TDF obtained from feeding the maltodextrin diet using the equation<sup>22</sup>

$$\text{basal ileal endogenous loss} = \text{TDF}_{\text{digesta}} \times \left( \text{Cr}_{\text{feed}} / \text{Cr}_{\text{digesta}} \right) \quad (2)$$

in which TDF<sub>digesta</sub> is the concentration of TDF (g kg<sup>-1</sup>) in the ileal digesta. The total tract endogenous loss of TDF (g kg<sup>-1</sup> DM intake) was also calculated using Eqn 2, but the concentration of TDF in the feces was used instead of the concentration of TDF in the ileal digesta.

The SID of TDF (SID<sub>TDF</sub>) was calculated by correcting the AID of TDF for the analyzed basal ileal endogenous TDF for each diet using the equation<sup>22</sup>

$$\text{SID}_{\text{TDF}} = \text{AID} + (\text{basal ileal endogenous loss} / \text{TDF}_{\text{feed}}) \quad (3)$$

The STTD of TDF was calculated using the same equation, except that the ATTD of TDF was used instead of the AID of TDF and the analyzed total tract endogenous loss of TDF was used instead of the analyzed ileal endogenous loss of TDF.

Data were analyzed using the PROC MIXED (SAS Institute Inc., Cary, NC, USA). The UNIVARIATE procedure was used to verify the normality of data. Outliers were defined as pigs having at least three observations that deviated from the treatment mean by more than 1.5 times the interquartile range.<sup>24</sup> Three pigs were considered outliers and were removed from the data set. Six pigs voided no fecal samples at the time of collection and were also removed from the data set. Therefore there were eight pigs for the SCF 70 diet, seven pigs for the pullulan diet and nine pigs for the other diets.

An ANOVA was conducted with diet as main effect and period as random effect. Differences among treatment means were separated using the LSMEANS statement and PDIFF option of PROC MIXED. The pig was the experimental unit for all analyses, and an  $\alpha$  value of 0.05 was used to assess significance among treatment means. An  $\alpha$  value between 0.05 and 0.10 was considered a tendency towards significance.

## RESULTS

The concentration of CP in maltodextrin, cellulose and the four novel fibers was below 10 g kg<sup>-1</sup> (Table 1). Maltodextrin was analyzed to contain only 12 g kg<sup>-1</sup> TDF, whereas cellulose was 1000 g kg<sup>-1</sup> TDF. By the analytical method used (AOAC 991.43),<sup>17</sup> the TDF content of SCF 70 was 100 g kg<sup>-1</sup>, although if the analytical method AOAC 2001.03 is used,<sup>25</sup> SCF 70 contains 700 g kg<sup>-1</sup> TDF.<sup>5</sup> The TDF concentration in the novel fiber ingredients ranged between 629 and 854 g kg<sup>-1</sup>. The GE concentration in the novel fibers was between 15.6 and 16.1 MJ kg<sup>-1</sup>, and the DM concentration was between 901 and 948 g kg<sup>-1</sup>. However, the GE and DM concentrations in maltodextrin and cellulose were 16.4 and 16.6 MJ kg<sup>-1</sup> and 974 and 962 g kg<sup>-1</sup>, respectively. Because of the low analyzed TDF in maltodextrin and SCF 70, the TDF concentration in diets containing these ingredients was also low (22 and 28 g kg<sup>-1</sup> respectively; Table 3).

The AID of GE in diets containing the novel fiber ingredients was less ( $P < 0.05$ ) than that in the diet containing maltodextrin, and the AID of GE in the diet containing RS 75 was also less ( $P < 0.05$ ) than that in diets containing RS 60, SCF 70 or pullulan (Table 4). However, the AID of GE in the diet containing cellulose was the least ( $P < 0.05$ ) among all diets. The ATTD of GE was not different among diets, but the HGD of GE in diets containing cellulose, RS 60, RS 75 or SCF 70 was greater ( $P < 0.05$ ) than that in diets containing maltodextrin or pullulan.

The AID of TDF in diets containing RS 60 or pullulan was greater ( $P < 0.05$ ) than that in the diet containing cellulose, whereas the AID of TDF in diets containing RS 75 or SCF 70 was not different from that of the cellulose-containing diet. The ATTD and HGD of TDF in the diet containing SCF 70 were less ( $P < 0.05$ ) than the values obtained for the cellulose diet but greater ( $P < 0.01$ ) than those in the diet containing maltodextrin. However, no differences were observed among the remaining diets.

**Table 3.** Analyzed concentrations of gross energy, dry matter, crude protein, and total dietary fiber in experimental diets containing maltodextrin (MD), cellulose, resistant starch 60 (RS 60), resistant starch 75 (RS 75), soluble corn fiber 70 (SCF 70), and pullulan, as-fed basis

Item	Diet					
	MD	Cellulose	RS 60	RS 75	SCF 70	Pullulan
Gross energy (MJ kg <sup>-1</sup> )	17.6	17.8	17.6	17.6	17.7	17.8
Dry matter (g kg <sup>-1</sup> )	964	964	959	962	964	966
Crude protein (g kg <sup>-1</sup> )	132	135	136	136	133	133
Total dietary fiber (g kg <sup>-1</sup> )	22	122	109	124	28	110

The diet containing maltodextrin had the greatest ( $P < 0.05$ ) AID of DM among all diets. Diets containing cellulose and RS 75, however, had the least ( $P < 0.05$ ) AID of DM compared with the other diets. The ATTD of DM did not differ among diets containing the novel fiber ingredients and was also not different from the AID of DM in the maltodextrin diet. However, the ATTD of DM in the cellulose diet was less ( $P < 0.05$ ) than that in all other diets except the RS 75 and pullulan diets. The HGD of DM in diets containing cellulose, RS 60, RS 75 or SCF 70 was greater ( $P < 0.05$ ) than that in the maltodextrin diet, but the HGD of DM in the diet containing pullulan was not different from that obtained for the maltodextrin diet.

The addition of cellulose and pullulan, but not RS 60, RS 75 or SCF 70, to the maltodextrin-based diet reduced ( $P < 0.05$ ) the AID of CP. The ATTD of CP was not affected by the addition of fiber ingredients to the maltodextrin diet, but the HGD of CP in the cellulose diet was greater ( $P < 0.05$ ) than that in all other diets except the SCF 70 diet.

The average ileal endogenous loss and average total tract endogenous loss of analyzed TDF obtained from this experiment were 25.25 and 42.87 g kg<sup>-1</sup> DM intake respectively. The SID of TDF did not differ in diets containing RS 60, SCF 70 or pullulan but was greater ( $P < 0.05$ ) than that in the cellulose diet (Table 5). The SID and STTD of TDF in the RS 60 and RS 75 diets were not different from each other, but the STTD of TDF in the SCF 70 diet was greater ( $P < 0.05$ ) than that in the cellulose and pullulan diets. Digestibility of TDF in the hindgut was not different among the fiber-containing diets.

## DISCUSSION

Effects of dietary fibers obtained from traditional food ingredients such as cereal brans and vegetables on the digestibility of carbohydrates and other nutrients have been studied in humans.<sup>26,27</sup> However, with the update of the dietary fiber definition, novel carbohydrate ingredients such as resistant starch have been incorporated in foods and beverages to increase dietary fiber intake.<sup>3,28</sup>

In this experiment a semi-purified diet was used to study the effects of different novel fiber ingredients on DM, GE, CP and TDF digestibility. The use of semi-purified ingredients avoids confounding factors (i.e. different components of a feedstuff) and isolates the effects of the addition of novel fiber ingredients. Maltodextrin was used as the basal carbohydrate for all diets because it is a very digestible carbohydrate. Although no additional dietary fiber was incorporated into the maltodextrin diet, a small

proportion of the diet was analyzed as TDF. The maltodextrin ingredient also contained a small amount of TDF, which indicates that maltodextrin may not be completely digestible or that the TDF method may have analytical limitations. The TDF value analyzed by AOAC method 991.43 is the sum of insoluble dietary fiber and soluble dietary fiber, but this procedure does not take into account the low-molecular-weight carbohydrates that are soluble in ethanol. The low concentrations of analyzed TDF in SCF 70 and the diet containing SCF 70 also demonstrate the limitations of AOAC method 991.43 to measure dietary fiber fractions that are of low molecular weight. The fiber components in SCF 70 are low-molecular-weight carbohydrates that are soluble in ethanol.<sup>29</sup> Therefore these low-molecular-weight dietary fiber fractions are poorly recovered in this TDF analysis. This indicates that AOAC method 991.43 is not a suitable procedure for TDF determination in SCF 70, because when AOAC method 2001.03 is used, the concentration of analyzed TDF in SCF 70 is 700 g kg<sup>-1</sup>,<sup>5</sup> which is most likely because this procedure also analyzes the low-molecular-weight carbohydrates as fiber. Because low-molecular-weight carbohydrates are readily fermented by intestinal microbes, it is unlikely that there were measureable quantities of these fractions in the ileal digesta or feces collected from the pigs.

The maltodextrin diet is very digestible and it was expected that very little or no dietary DM would be present in the ileal digesta from pigs fed this diet. However, some undigested material was analyzed as TDF in the ileal digesta and feces from pigs fed the maltodextrin diet, and this is the reason why negative values for AID and ATTD of TDF were calculated. The ileal digesta are composed of undigested DM from the diet as well as endogenous enzymes, sloughed epithelial cells, bacterial cells and mucin.<sup>22,30</sup> In the feces the concentration of mucin is low because most of the mucin is fermented in the hindgut, but the concentration of microbial matter in the feces is high.<sup>31,32</sup> The negative AID and ATTD of analyzed TDF in the maltodextrin diet strongly indicate that certain compounds in the endogenous losses and microbial matter may be analyzed as carbohydrates. Other experiments have reported a similar observation.<sup>33,34</sup>

The AID and ATTD of analyzed TDF in the diet containing SCF 70 were also negative, but to a lesser extent than the values observed for the maltodextrin diet. The low concentration of analyzed TDF in the SCF 70 diet may contribute to this negative value, but the possible presence of non-dietary sources of undigestible carbohydrate in the ileal digesta and feces from pigs fed this diet makes the interpretation of this result difficult. However, relative to the HGD of analyzed TDF in the maltodextrin diet, the lesser negative value for the HGD of analyzed TDF in the SCF 70 diet indicates that the TDF in the SCF 70 diet was not fermented, because more undigested carbohydrate was excreted in the feces of pigs fed the SCF 70 diet compared with pigs fed the maltodextrin diet. The interpretation of this result is not consistent with results of other experiments that indicated that TDF from SCF 70 is fermented in the hindgut.<sup>28,35,36</sup> Therefore, the ileal endogenous loss of TDF and total tract endogenous loss of analyzed TDF were calculated to remove the influence of endogenously synthesized metabolites and microbial matter that were analyzed as TDF. The STTD of analyzed TDF in the SCF 70 diet is more than 1000 g kg<sup>-1</sup>. This indicates that the fiber in SCF 70 is completely fermentable and confirms the results of previous experiments.<sup>28,35,36</sup> Therefore a better estimate of TDF digestibility is obtained by correcting the AID of analyzed TDF for endogenous substrates that are analyzed as TDF.

The assumptions used for calculating basal endogenous losses of analyzed TDF are based on the concept used to calculate the

**Table 4.** Water-binding capacity, apparent ileal digestibility (AID), apparent total tract digestibility (ATTD), and hindgut digestibility (HGD) of gross energy, dry matter, crude protein, and total dietary fiber in pigs fed diets containing maltodextrin (MD), cellulose, resistant starch 60 (RS 60), resistant starch 75 (RS 75), soluble corn fiber 70 (SCF 70) and pullulan, as-fed basis

Item	Diet						SEM	P value
	MD	Cellulose	RS 60	RS 75	SCF 70	Pullulan		
Water-binding capacity (g g <sup>-1</sup> dry weight)	0.38d	0.67a	0.43c	0.41cd	0.40cd	0.48b	0.01	0.001
Gross energy (%)								
AID	96.8a	85.7d	90.5b	88.6c	92.0b	92.2b	0.66	0.001
ATTD	94.4	91.9	94.4	93.6	95.5	92.6	0.98	0.111
HGD	-2.5b	6.0a	3.8a	5.1a	3.8a	0.3b	1.04	0.001
Dry matter (%)								
AID	95.4a	84.8c	89.6b	86.6c	91.1b	90.7b	0.69	0.001
ATTD	94.2a	90.6b	93.4a	92.7ab	94.7a	92.4ab	0.90	0.027
HGD	-1.1c	5.8a	4.0ab	6.1a	3.6ab	1.7bc	1.01	0.001
Crude protein (%)								
AID	90.7a	82.4c	90.0a	90.5a	90.3ab	87.1b	1.09	0.001
ATTD	91.3	92.8	92.9	92.9	94.4	89.8	1.14	0.119
HGD	0.6b	10.4a	-2.8b	2.3b	4.2ab	2.6b	2.52	0.014
Total dietary fiber (%)								
AID	-10.9d	15.7bc	44.4a	28.2ab	-4.3cd	49.5a	7.68	0.001
ATTD	-88.2c	35.1a	56.2a	59.5a	-36.9b	48.6a	12.34	0.001
HGD	-77.4c	25.7a	11.7a	31.3a	-32.6b	-0.9ab	13.28	0.001

Data are least squares means of nine observations per treatment, except for diets containing SCF 70 and pullulan, which have eight and seven observations respectively. Values within a row lacking a common letter differ ( $P \leq 0.05$ ). SEM, standard error of mean.

**Table 5.** Standardized ileal digestibility (SID), standardized total tract digestibility (STTD), and hindgut digestibility (HGD) of total dietary fiber in pigs fed diets containing cellulose, resistant starch 60 (RS 60), resistant starch 75 (RS 75), soluble corn fiber 70 (SCF 70), and pullulan

Item (%)	Diet					SEM	P value
	Cellulose	RS 60	RS 75	SCF 70	Pullulan		
SID	35.8c	66.6ab	47.8bc	85.7a	71.7a	7.55	0.001
STTD	68.8b	93.4ab	93.0ab	114.9a	83.6b	10.49	0.045
HGD	31.7	27.9	44.9	29.0	10.7	9.76	0.129

Data are least squares means of nine observations per treatment, except for diets containing SCF 70 and pullulan, which have eight and seven observations, respectively. Values within a row lacking a common letter differ significantly ( $P \leq 0.05$ ). SEM, standard error of mean.

SID of CP and amino acids.<sup>22</sup> The ileal endogenous loss of TDF and total tract endogenous loss of TDF obtained from a fiber-free diet (maltodextrin diet) are assumed to be associated with the normal physiological and metabolic functions of the gut and are assumed not to be affected by the components of the diet.<sup>22</sup> Therefore this is referred to as basal endogenous loss. The average ileal endogenous loss and average total tract endogenous loss of analyzed TDF obtained from this experiment were 25.25 and 42.87 g kg<sup>-1</sup> DM intake respectively. To our knowledge, this is the first time an estimate of ileal endogenous substrates and total tract endogenous substrates that are analyzed as TDF has been reported. It is possible that microbial biomass may have contributed to the ileal or fecal output of analyzed TDF, and therefore, to the calculated basal endogenous loss of TDF. However, because no fiber was included in the maltodextrin diet, it is likely that the output of microbial biomass in the

ileal and fecal output from pigs fed this diet was minimal and at a level that will always be present in the output from pigs. It is, therefore, appropriate to include this fraction in the basal endogenous loss of analyzed TDF. However, it is likely that the majority of the basal endogenous loss originated from intestinal secretions, including mucin. It is likely that the analyzed concentrations of TDF in the ileal and fecal output from pigs fed the maltodextrin diet are at the lowest possible levels, and these quantities of TDF may, therefore, be categorized as basal endogenous losses.

Cellulose or each of the novel fiber ingredients added to the diets was the only source of TDF in each of the diets. By definition, dietary fiber is resistant to digestion by mammalian enzymes in the small intestine, but the positive values for AID and SID of analyzed TDF in the fiber-containing diets indicate that some of the components analyzed as TDF disappeared in the small intestine. Future research should be directed at quantifying the amounts of microbial mass and mucin in the analyzed ileal output to obtain values for the true fiber digestibility. The presence of a microbial population in the ileum has been recognized<sup>37</sup> and the digestibility of TDF in the small intestine is likely due to the fermentative capability of the microbial population in the stomach and small intestine.

The greater STTD of analyzed TDF in the RS 60 and RS 75 diets than in diets containing cellulose and pullulan confirms results from other studies indicating that the dietary fiber in resistant starch is fermentable<sup>38</sup> whereas the dietary fiber in cellulose is poorly fermentable.<sup>39</sup>

The reduced AID of DM in diets that contained cellulose or the novel fiber ingredients was also reflected in a low AID of GE in these diets. Because these diets were mainly composed of carbohydrates, the reduced AID of GE is likely a result of reduced carbohydrate digestibility in the small intestine of pigs fed diets containing cellulose or the novel fiber ingredients. Addition of

dietary fibers to a starch-containing diet increased the recovery of starch at the end of the ileum<sup>40</sup> and depressed the AID of starch in pigs.<sup>41</sup> The reduced AID of GE in diets containing cellulose or the novel fiber ingredients may, therefore, indicate a reduction in the amount of glucose that was digested and absorbed in the small intestine of pigs fed these diets compared with pigs fed the maltodextrin diet. However, the ATTD of DM and GE in diets containing the different novel fiber ingredients was not reduced. The reason for this observation is that nutrients that were not digested in the small intestine may be fermented in the hindgut, and the products of carbohydrate fermentation can also be a source of energy for the pig.<sup>42</sup> However, the energetic efficiency of absorbed short-chain fatty acids is less than that of glucose.<sup>43</sup> Therefore, although the concentration of GE in all diets used in this experiment was similar and the ATTD of GE in diets containing cellulose or novel fiber ingredients is not different from that of the maltodextrin diet, the bioavailable energy of the fiber-containing diets is expected to be less than that of the maltodextrin diet.

Addition of dietary fiber to the diet may reduce the AID of CP,<sup>44</sup> although this is not always the case.<sup>39,40</sup> In the present experiment the addition of cellulose or pullulan, but not RS 60, RS 75 or SCF 70, to a maltodextrin-based diet reduced the AID of CP. Pullulan also reduced the AID of CP when added to diets for dogs.<sup>45</sup> These observations indicate that the effect of dietary fiber on CP digestibility depends on the type of dietary fiber in the diet. Soluble corn fiber and pullulan are both soluble fibers, but the pullulan diet has a greater capacity to bind water than the SCF 70 diet. Increasing water-binding capacity also increases the endogenous loss of N that is induced by dietary fiber.<sup>30</sup> Therefore, the water-binding capacity of the diet is likely one of the reasons for the reduced AID of CP in the diet containing pullulan compared with diets containing maltodextrin or the other novel fibers.

The absence of a reduction in the AID of CP when RS 60 or RS 75 was added to the maltodextrin diet is consistent with data from other experiments.<sup>40,41</sup> However, the reduction in the AID of CP in the diet containing cellulose is not consistent with data indicating that the addition of cellulose has no effect on the AID of CP.<sup>39,46</sup> The cellulose (Solka floc 100) used in the present experiment has a fiber length of approximately 40  $\mu\text{m}$  and the water-binding capacity of cellulose increases with increasing fiber length up to 100  $\mu\text{m}$ .<sup>47</sup> The fiber length of the cellulose used in previous studies was not reported.<sup>39,46</sup> However, the cellulose diet used in this experiment had a water-binding capacity that was greater than that of the other diets. Water-binding capacity is directly proportional to the swelling capacity<sup>48</sup> or the ability of the diet to form 'bulk'.<sup>49</sup> Pea fibers with high water-binding capacity increase ileal endogenous flow of N, although the mechanism is unclear.<sup>30</sup> Therefore, the reduction in the AID of CP in diets containing cellulose may be a result of the capacity of cellulose to bind water.

## CONCLUSIONS

Addition of cellulose or novel fiber ingredients to a maltodextrin-based diet reduced the AID of DM with a concomitant reduction in the AID of GE, but the ATTD of GE was not reduced in the fiber-containing diets. RS 60, RS 75 and SCF 70 did not affect the AID of CP, but the addition of cellulose and pullulan reduced the AID of CP. A proportion of the analyzed TDF in RS 60, RS 75 and pullulan disappeared in the small intestine. The negative AID and ATTD of analyzed TDF in diets containing maltodextrin and SCF 70 indicate that some of the endogenous compounds that are secreted into the intestinal tract may be analyzed as TDF. This observation

indicates that the TDF procedure has limitations when used to analyze data for digestibility. As a consequence, measurement of endogenous losses of analyzed TDF and calculation of the SID and STTD of analyzed TDF are better indicators of TDF fermentability than measurements of AID and ATTD of TDF.

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