[Sorghum TechNote PRF 5-14]

Digestive dynamics of starch and protein
Factors influencing digestive dynamics in sorghum-based broiler diets

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Introduction

As discussed in Technote 4, digestive dynamics of starch and protein embrace the digestion of nutrients in the gut lumen, absorption of end-products into the gut mucosa, and their entry into the systemic circulation. It is a combination of the rate, site and extent of nutrient digestion. In sorghum-based broiler diets, digestive dynamics is more relevant to feed conversion efficiency than individual assessment of apparent digestibility coefficients (Liu *et al.*, 2013b).

This concept was discussed during the early acceptance of synthetic amino acid in 1970s. Initially methionine and subsequently lysine was introduced; however, nutritionists were reluctant to include lysine in diets at more than 0.5 kg per tonne (Kidd and Tillman, 2012). The early research into lysine monohydrochloride provides an invaluable insight as to the gravity with which digestive dynamics can influence pig performance (Batterham, 1974, Batterham and O'Neill, 1978).

Batterham (1974) investigated the effect of frequency of feeding on the utilisation of free lysine in grower pigs and found that in conventional diets, not supplemented with free amino acids, feeding frequency

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did not influence live weight gain. However, in diets containing free lysine, pigs fed six times daily had significantly higher live weight gains than pigs fed on a restricted bais. Subsequently, Batterham and O'Neill (1978) reported that feed conversion efficiency responses to free lysine supplementation were more pronounced with frequent feeding (3.01 versus 2.57) in comparison to once daily feeding (3.09 versus 2.75) in grower pigs. The inferior growth performance was attributed to differential rates of absorption of free lysine and protein-bound amino acids and Batterham and O'Neill (1978) concluded that it is necessary to balance the arrival of free amino acid and protein-bound amino acid at the sites of protein metabolism. Given the importance of digestive dynamics of starch and protein, influential factors, including grain variety, steam-pelleting and exogenous enzyme treatment, are discussed below.

Grain variety

Starch is an important constituent of broiler diets and the majority is derived from cereal grains. The choice of grain type influences starch digestion dynamics in broiler diets, although the choice is largely based on price and availability of cereal grains. The fact that slowly digestible starch may be advantageous to broiler performance provides the opportunity to blend various grains into broiler diet to optimise starch digestion rates.

Liu *et al.* (2013c) compared digestive dynamics of starch and protein in red (Buster) and white (Liberty) sorghums (Table 1) and reported that white sorghum had significantly higher starch digestion rates (4.83 versus 3.42×10^{-2} min^{-1}, $P < 0.05$) and potential digestible starch (0.892 versus 0.851 g/g, $P < 0.05$) than red sorghum; however, there was no significant differences in protein digestion rate and potential digestible protein. The authors concluded that inconsistent broiler performance associated with sorghum under Australian conditions is likely due to variations in starch digestive dynamics relative to protein culminating in sub-standard utilisation of sorghum starch/energy.

Table 1 digestive dynamics of starch and protein (N) in two mediumly-ground (3.2 mm) sorghum-based broiler diets (Liu *et al.*, 2013c)

Sorghum variety	Potential digestible starch (g/100g)	Starch digestion rate ($\times 10^{-2}$ min^{-1})	Potential digestible nitrogen (g/100g)	Nitrogen digestible rate ($\times 10^{-2}$ min^{-1})
Liberty	89.2	4.83	78.9	2.78
Buster	85.1	3.42	78.1	2.81
SEM	1.11	0.448	0.92	0.389
P-value	0.024	0.045	0.519	0.960

It is also possible that sorghum starch digestion is influenced by grain particle size even in steam-pelleted diets. Table 2 showed that in finely-ground sorghum-based diets, there was no significant difference between digestion rates of starch and protein, and also potential digestible fraction of starch and protein.

Table 2 digestive dynamics of starch and protein (N) in two finely-ground (2.0 mm) sorghum-based broiler diets (Liu *et al.*, 2014a)

Sorghum variety	Potential digestible starch (g/100g)	Starch digestion rate ($\times 10^{-2}$ min^{-1})	Potential digestible nitrogen (g/100g)	Nitrogen digestible rate ($\times 10^{-2}$ min^{-1})
Liberty	87.5	5.47	78.1	4.44
Buster	86.8	5.99	79.8	5.09
P-value	0.553	0.468	0.176	0.313

Hydrothermal processes

Presently, steam-pelleted diets are commonly used in chicken-meat production and because of short exposure times, moderate temperatures and low moistures during steam-pelleting, the extent of starch gelatinisation is usually less than 20% in steam-pelleted feed (Svihus *et al.*, 2005). It is well established that pelleted diets generate better growth performance than mash diets; however, it is not clear whether these improvements are from the physical form (mash versus pellet) or from enhanced nutrient utilisation following steam-pelleting. Liu *et al.* (2013c) offered broiler chickens either reground, pre-pelleted mash or raw, unprocessed mash diets to investigate the influence of the hydrothermal component of the steam-pelleting process on starch and protein digestive dynamics. As shown in Table 3, the hydrothermal component significantly increased starch digestion rates (4.11 versus 6.32 $\times 10^{-2}$ min^{-1}); however, given the limited exposure to heat and moisture during steam-pelleting, the increase in starch digestion rate may not be attributed to increased starch gelatinisation entirely. This is further discussed in the following section.

Table 3 digestive dynamics of starch and protein (N) in raw mash and reground mash sorghum-based broiler diets (Liu *et al.*, 2013c)

Hydrothermal treatment	Potential digestible starch (g/100g)	Starch digestion rate ($\times 10^{-2}$ min^{-1})	Potential digestible nitrogen (g/100g)	Nitrogen digestible rate ($\times 10^{-2}$ min^{-1})
Without	87.2	4.11	78.8	3.12
With	85.8	6.32	77.8	2.88
SEM	1.32	0.585	1.46	0.254
P-value	0.445	0.021	0.646	0.503

Conditioning temperatures

Liu *et al.* (2013d) reported that increasing conditioning temperatures from 65 to 80 and 95°C did not influence dynamics of starch and protein digestion (Table 4). The lack of significance in sorghum-based diets steam-pelleted at different conditioning temperatures confirms that starch gelatinisation during hydrothermal treatment is not the major cause of increased starch digestion rate. Moreover, decreased grain particle sizes have been shown to accelerate *in vitro* starch digestion rates (Al-Rabadi *et al.*, 2009). In the Liu *et al.* (2013c) comparison sorghum grain was initially ground through a 3.2 mm hammer-mill screen. However, the secondary particle size reduction from steam-pelleting coupled with physical attrition, rather than starch gelatinisation, probably accounted the substantial increase in starch digestion rates observed in the reground mash diets. This finding has obvious implications for whole grain feeding and may be the prime factor in the generation of slowly digestible starch that appears to be associated with this approach.

Table 4 The influence of conditioning temperatures in digestive dynamics of starch and protein in sorghum-based broiler diets (Liu *et al.*, 2013d)

Conditioning temperatures	Potential digestible starch (g/100g)	Starch digestion rate ($\times 10^{-2}$ min^{-1})	Potential digestible nitrogen (g/100g)	Nitrogen digestible rate ($\times 10^{-2}$ min^{-1})
65°C	85.3	3.64	75.8	3.08
80°C	84.4	3.44	78.1	2.06
95°C	85.1	3.42	78.1	3.81
SEM	1.97	0.498	2.23	0.481
P-value	0.946	0.943	0.720	0.321

Exogenous enzymes

Exogenous enzymes were introduced to the poultry industry in the mid 1980s, initially to improve productivity of birds offered diets based on so-called viscous grains, especially wheat and barley, and now exogenous enzymes are almost routinely included in pig and poultry diets. Amylase and protease; by definition, may directly influence starch and protein digestive dynamics. Liu *et al.* (2013a) showed that in sorghum-based broiler diet, exogenous protease significantly increased the digestion rates of 12 ex 16 amino acids, including leucine (2.07 versus 3.05×10^{-2} min^{-1}) and histidine (2.57 versus 3.45×10^{-2} min^{-1}), tended to increase protein digestion rates ($P < 0.07$), but did not influence starch digestion rates ($P > 0.125$).

Table 5 The influence of an exogenous protease on digestion rates (× 10^{-2} min^{-1}) of 12 ex 16 amino acids and their percentage of increase (Liu *et al.*, 2013a)

Protease	His	Ile	Leu	Phe	Val	Ala	Asp	Glu	Gly	Pro	Ser	Tyr
Nil	**2.57**	**2.05**	**2.07**	**2.39**	**2.04**	**2.18**	**2.52**	**2.96**	**2.11**	**2.28**	**2.27**	**1.85**
Plus	**3.45**	**2.89**	**3.05**	**3.44**	**2.95**	**3.16**	**3.51**	**4.15**	**2.90**	**3.55**	**3.21**	**2.88**
P-value	**0.034**	**0.040**	**0.029**	**0.013**	**0.049**	**0.035**	**0.012**	**0.002**	**0.041**	**0.004**	**0.016**	**0.024**
%	***34.2***	***41.0***	***47.3***	***43.9***	***44.6***	***45.0***	***39.3***	***40.2***	***37.4***	***55.7***	***41.4***	***55.7***

Other enzymes, including phytase and non-starch polysaccharide degrading enzymes may influence starch and protein digestion indirectly through the interactions of targeted anti-nutritional factors with starch and protein. For example, phytate may bind protein through binary or ternary complexes depending on its isoelectric point and gut pH, and phytate may bind starch directly via hydrogen bonds and phosphate linkages or indirectly via interactions with starch granule-associated proteins (Selle *et al.*, 2000, Selle *et al.*, 2012). Therefore, phytase has the potential to influence both starch and protein digestion in broiler chickens.

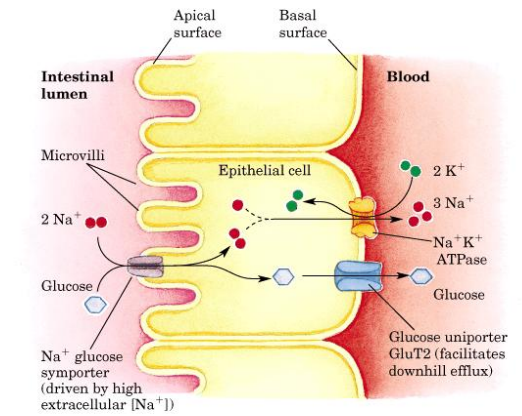

Figure 1 Sodium pump and sorghum-dependent transport system in gut mucosa
Source: http://www.purdue.edu/

There is also the possibility that phytate impedes the absorption of glucose and amino acids. Initially, Cowieson *et al.* (2004) showed that phytate increased sodium excretion in broiler chickens. Subsequently, Selle *et al.* (2009) reported profound impacts of phytase on apparent sodium ileal digestibility, which was restored to parity (-0.043) from a deficit of -0.516 by phytase. This suggests that phytate could impede absorption of amino acids and glucose by dragging sodium to the intestinal lumen thereby compromising Na^+-dependent transport systems and the activity of Na^+-K^+-ATPase or the Na pump (Selle *et al.*, 2012). Instructively, Demjen and Thompson (1991) showed that phytate can influence glucose absorption *per se* in addition to impeding starch digestion. Therefore, phytase has the potential to modify both the dynamics of starch and protein digestion and glucose and amino acid absorption by attenuating the probable negative influence of phytate on Na^+-dependent transport systems and Na pump activity, perhaps particularly the latter.

Sodium metabisulphite

Notionally, sodium metabisulphite (SMBS) has the potential to enhance protein digestion in sorghum by reducing disulphide bonds especially in the β- and γ-kafirin fractions (Oria *et al.*, 1995) and starch digestion via the oxidative-reductive depolymerisation of starch polysaccharides (Paterson *et al.*, 1996). Liu *et al.* (2014b) reported that graded sodium metabisulphite inclusion levels in sorghum-based diets from 0 to 5.25 g/kg linearly decreased starch disappearance rates from the proximal jejunum (abruptly digestible starch) but increased starch disappearance from the three caudal small intestinal segments (gradually digestible starch).

This could be due to the fact that chemically modified or depolymerised starch is less readily digested (Wolf *et al.*, 1999); however, other mechanisms by which this shift in the site of starch digestion occurred may be involved. Nevertheless, Whistler and Belfort (1961) reported that a extensively oxidised maize starch depressed weight gains in rats, which implies that it was refractory to digestion. Subsequently, Chung *et al.* (2008) reported that the glycaemic index of native starch was significantly reduced (71.9 versus 75.3) by oxidation and the proportion of resistant starch was increased by oxidation from 11.7 to 35.1%. Thus oxidative-reductive depolymerisation by sodium metabisulphite may have rendered starch more resistant to digestion, which was reflected in increased amounts of gradually digestible starch in broilers.

Sodium metabisulphite has been shown to enhance efficiency of energy utilisation via modification of starch digestion dynamics. In sorghum-casein diets, Selle *et al.* (2013) showed that inclusion of 5 g/kg SMBS significantly decreased abruptly digestible starch by 16.3% and abruptly digestible starch was negatively correlated with AME ($r = -0.668$; $P<0.05$) and AMEn ($r = -0.689$; $P<0.05$). Subsequently, Liu *et al.* (2014b) reported 1.5 g/kg SMBS in sorghum-soybean-based broiler diets increased AME from 13.45 to 13.81 MJ/kg (Figure 2), which was associated with decreased (508 versus 410 g/bird) abruptly digestible starch but increased (155 versus 217 g/bird) gradually digestible starch. That the unequivocal improvements in AME, AMEn and FCR generated by SMBS were associated with the increased provision of gradually digestible starch is a very instructive outcome.

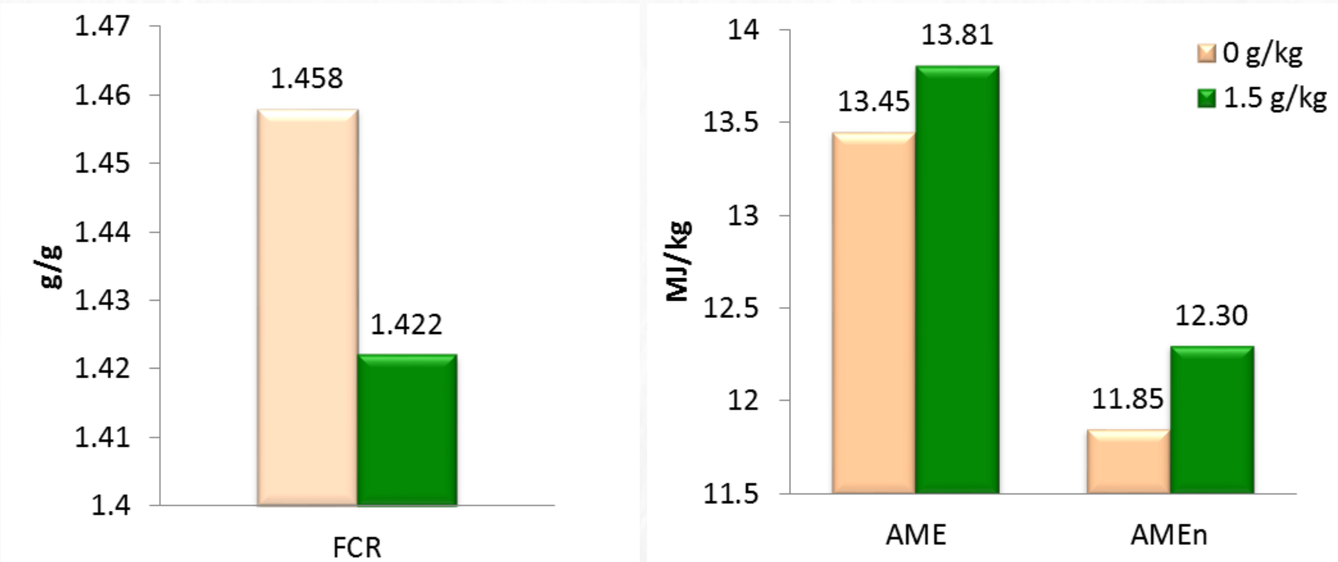

Figure 2 The influence of 1.5 g/kg sodium metabisulphite on FCR, AME and AMEn in sorghum-based broiler diets

Conclusions and implications

Digestive dynamics of starch and protein along the small intestine are more relevant to efficiency of energy utilisation and feed conversion than static ileal digestibility coefficients of individual nutrients. There are limited numbers of studies have investigated the influence of digestive dynamics in broiler chickens and the possible strategies to enhance performance via synchronising starch and protein digestive dynamics. For practical nutritionists to have the capacity of embracing the concept of digestive dynamics in the formulation of their diets, the generation of a considerable amount of data on digestion rates of feed ingredients are required. It is only with this database that nutritionists will be able to adopt digestive dynamic concepts where recognition is given to rates as well as extents of digestion and nutritionists will be better equipped to predict the performance of broiler chickens as a consequence.

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