Asian-Aust. J. Anim. Sci.
Vol. 22, No. 8 : 1209 - 1223
August 2009
www.ajas.info

The Concept of Standardized Ileal Amino Acid Digestibilities: Principles and Application in Feed Ingredients for Piglets

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ABSTRACT : In this review, the terminology that is used to describe ileal amino acid (AA) digestibilities in piglet feed ingredients is defined. If one accepts that the determination of AA digestibilities should be based on the ileal analysis method, one should consider that ileal digesta contains variable amounts of endogenous crude protein (CP), which originates mainly from digestive secretions, sloughed-off epithelial cells and mucins. The ileal endogenous CP and AA losses are separated into basal ileal endogenous CP and AA losses ($IAAL_B$), which are not influenced by the feed ingredient composition, and specific ileal endogenous CP and AA losses ($IAAL_S$), which are induced by feed ingredient characteristics such as level and type of fiber and anti-nutritional factors (ANF). Depending how ileal endogenous CP and AA losses are considered in the measurement of CP and AA digestibilities, digestibility values are expressed as apparent (AID), standardized (SID), or true (TID) ileal digestibilities of CP and AA. The main concern associated with the use of AID values in diet formulation for pigs is that they are not additive in mixtures of feed ingredients. Consequently, the concept of standardized ileal CP and AA digestibilities was introduced by correcting AID values for basal ileal endogenous CP and AA losses ($IAAL_B$). The correction for both $IAAL_B$ and $IAAL_S$ yields TID values, however, routine procedures to measure $IAAL_S$ are not yet available. In principle, SID values should be preferred, because they represent the fundamental properties of the feed ingredient. There exist only few reports on SID of CP and AA in feedstuffs frequently used in piglet nutrition. These include soybeans (SB), soybean meal (SBM), soy proteins (SP), soy protein concentrate (SPC), soy protein isolate (SPI), corn gluten (CG), wheat gluten (WG), pea protein (PeaP), potato protein (PotP), fish meal (FM) and whey proteins (WP), but the results obtained are inconsistent. Differences in SID values within feed ingredients may, at least in part, be attributed to different processing conditions or inherent differences of the assay feed ingredients. Moreover, there is some evidence that the determination of SID values and $IAAL_B$ in piglets may be confounded by the dietary CP level of the assay diet, age and (or) body weight (BW), the level of feed intake or the methodological approach used to determine $IAAL_B$.

(**Key Words :** Amino Acids, Piglets, Standardized Ileal Digestibility, Protein Supplement)

INTRODUCTION

Feed costs represent at least 55 to 65% of the variable costs in swine production, and play a major role in determining the profitability of a swine enterprise, especially in view of recent increases in feed costs (Yacentiuk, 2001; FAO, 2008). Diets which accurately match the piglet's protein requirement rely, firstly, on the exact knowledge of the animal's requirement for indispensable amino acids (AA) and, secondly, on a precise description of feed ingredients in terms of their capacity to supply these AA for maintenance and growth (Williams, 1995).

The protein quality among feed ingredients varies considerably (Knabe et al., 1989; Yin et al., 1993), and is governed by the AA composition and ratios of indispensable AA, as well as the susceptibility of the protein to be hydrolyzed during digestion (Friedman, 1996). Feed processing is considered to be a major factor which may influence protein quality including digestibility and bioavailability of AA (Camire et al., 1990; Singh et al., 2007). Since measurements of AA availabilities are considered to be time-consuming, labor-intensive and expensive, the determination of AA digestibilities at the ileal level has proven to be a more suitable approach (Mosenthin et al., 2000). Moreover, there is a general agreement that the expression of standardized ileal digestibilities (SID) of crude protein (CP) and AA has advantage over apparent (AID) and true (TID) ileal CP and AA digestibilities, because SID represent the fundamental properties of the individual feed ingredient (Mosenthin and Rademacher, 2003). In this context, a careful assessment of

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Received August 25, 2008; Accepted January 26, 2009

SID of CP and AA is critical for evaluating the protein value of feed ingredients for piglets (Stein et al., 2007).

The SID of CP and AA can be obtained by correcting AID values for basal ileal endogenous CP and AA losses ($IAAL_B$) (Stein et al., 2007). As a result, measurements of SID, in contrast to AID, have proven to be nearly independent of the dietary CP and AA contents in assay diets fed either to grower-finisher pigs (Fan et al., 1995a) or piglets (Eklund et al., 2008b). Thus, SID values have been shown to be additive in mixed diets for grower-finisher pigs (Stein et al., 2005).

Estimates of SID have been generated for most feed ingredients in grower-finisher pigs (NRC, 1998; AmiPig, 2000; Rademacher et al., 2001; Pedersen and Boisen, 2002; CVB, 2003; GfE, 2008), whereas corresponding SID values for piglets hardly exist. Piglets are assumed to have a limited capacity for CP digestion and AA absorption (Pluske et al., 1997; Hedemann and Jensen, 2004). In addition, factors such as body weight (BW) and (or) age (Caine et al., 1997a,b), and the level of feed intake (Moter and Stein, 2004; Diebold et al., 2005) may affect AID, SID and $IAAL_B$ in pigs. Therefore, it remains open, whether SID of CP and AA determined in feed ingredients for grower-finisher pigs can be used in diet formulation for piglets as well.

This review aims to summarize the principles of the concept of SID of CP and AA and its impact on protein evaluation in feed ingredients for piglets.

EXPRESSION OF CRUDE PROTEIN AND AMINO ACID DIGESTIBILITIES

Total tract digestibilities

The digestion of AA in the large intestine is the result of microbial activity (Sauer and Ozimek, 1986; Mosenthin and Rademacher, 2003). The disappearance of AA from this part of the digestive tract would not be necessarily a problem if disappearance represented absorption of AA (Mosenthin and Rademacher, 2003). However, CP digestion through microbial activity does not contribute to maintenance or tissue accretion, because the absorbed end-products of microbial fermentation are ultimately excreted in the urine (Mosenthin and Sauer, 1992). Since AA are only absorbed proximal to the distal ileum, ileal digestibility measurements represent more accurate estimates of AA bioavailabilities than fecal AA digestibilities (Sauer and Ozimek, 1986).

Ileal digestibilities

Apparent ileal digestibilities : The AID of CP and AA are defined as the net disappearance of ingested dietary CP and AA from the digestive tract proximal to the distal ileum (Tanksley et al., 1981; Sauer and Ozimek, 1986). AID values are calculated from the flow and composition of digesta at the distal ileum of pigs by determining the difference between the total ileal outflow of AA and the dietary intake according to the following equation:

$$\text{AID (\%)} = ((\text{CP or AA intake-ileal CP or AA recoveries}) / \text{CP or AA intake}) \times 100\%$$

The expression ‘apparent’ is used to emphasize that both, non-digested dietary CP and AA, and CP and AA of endogenous origin that are secreted into the gastrointestinal tract without being re-absorbed, contribute to the total ileal outflow (Stein et al., 2007). A primary concern with the use of AID values in diet formulation and feed evaluation is the lack of additivity of AID values in the formulation of complex diets (Stein et al., 2005).

Ileal endogenous losses: Ileal endogenous losses of AA represent AA that are present in endogenously synthesized CP (nitrogen×6.25) secreted into the intestinal lumen, and which have not been digested and re-absorbed before reaching the distal ileum (Tamminga et al., 1995; Hodgkinson and Moughan, 2000). Mucoproteins, sloughed cells, serum albumin, digestive enzymes, amides, and ingested hair as well as microbial CP contribute to endogenous CP losses (Souffrant, 1991; Nyachoti et al., 1997). The ileal endogenous losses of CP and AA can be divided into basal (non-specific) ileal endogenous CP and AA losses ($IAAL_B$) and specific ileal endogenous CP and AA losses ($IAAL_S$) (Jansman et al., 2002).

The $IAAL_B$ represent the minimum quantities of AA inevitably lost by the animal (Stein et al., 2007). These losses are considered to be related to the physical flow of feed dry matter (DM) through the digestive tract and (or) the animal’s metabolic state, but are not influenced by diet composition (Stein et al., 2007). The $IAAL_B$ can be measured by feeding i) a CP-free diet, ii) a diet supplemented with a highly digestible CP source such as casein or wheat gluten, iii) a diet based on enzyme-hydrolyzed casein plus ultra-filtration of the digesta, or iv) can be estimated by using different regression analysis methods (Jansman et al., 2002). For piglets, values for $IAAL_B$ are summarized in Table 1 (Eklund et al., 2008a,b).

The $IAAL_S$ are influenced by diet ingredients composition such as content and type of fiber and anti-nutritional factors (ANF) including trypsin inhibitors (TI), lectins or tannins (Jansman et al., 1995; Schulze et al., 1995). There are no routine procedures available to measure $IAAL_S$ in pigs. However, it is possible to calculate $IAAL_S$ by estimating total (basal plus specific) ileal endogenous CP and AA losses ($IAAL_T$) and then subtracting the $IAAL_B$ from $IAAL_T$. Procedures used to estimate $IAAL_T$ include the homoarginine method (Rutherfurd and Moughan, 1990) and isotope tracer dilution techniques (de Lange et al.,

Table 1. Basal ileal endogenous losses of crude protein and amino acids (g/kg DMI) and dietary threshold levels of crude protein and amino acids (g/kg DM) in piglets

Item	Basal ileal endogenous losses (g/kg DMI)		Threshold level[3] (g/kg DM)
	Regression analysis[1]	Casein[2]	
CP	9.3	16.3	176.3
Indispensable AA			
Arginine (Arg)	0.4	0.5	6.6
Histidine (His)	0.2	0.3	5.1
Isoleucine (Ile)	0.2	0.5	8.4
Leucine (Leu)	0.5	0.8	15.9
Lysine (Lys)	0.4	0.7	12.3
Methionine (Met)	0.1	0.2	4.8
Phenylalanine (Phe)	0.4	0.6	9.5
Threonine (Thr)	0.6	0.9	8.5
Tryptophan (Trp)	0.1	0.2	1.9
Valine (Val)	0.4	0.7	10.9
Dispensable AA			
Alanine (Ala)	0.5	0.7	5.4
Aspartic acid (Asp)	0.7	1.1	12.4
Glutamic acid (Glu)	0.9	1.8	35.0
Glycine (Gly)	0.8	0.8	3.9
Proline (Pro)	0.6	0.9	22.0
Serine (Ser)	0.6	0.8	9.3

[1] Eklund et al., 2008b; [2] Eklund et al., 2008a; [3] Eklund, 2007.

1990; Leterme et al., 1998).

True ileal digestibilities: The TID, also referred to as real ileal digestibilities (de Lange et al., 1990; Souffrant, 1991), reflect the proportion of the dietary AA that disappears from the digestive tract proximal to the distal ileum (Stein et al., 2007). In this case, only the undigested dietary AA present in ileal outflow are related to the AA intake, whereas the proportion of $IAAL_T$ in ileal AA outflow is not accounted for (Furuya and Kaji, 1989; de Lange et al., 1990). The TID values are calculated the same way as AID values, except that the $IAAL_T$ are subtracted from the ileal recoveries of CP and AA according to the following equation:

$$\text{TID (\%)} = ((\text{CP or AA intake} - (\text{ileal CP or AA recoveries} - IAAL_T)) / \text{CP or AA intake}) \times 100\%$$

This approach allows the metabolic costs associated with synthesis and recycling of endogenous gut AA losses to be represented explicitly (Stein et al., 2007). There are only few reports on TID values of nitrogen and AA in skim milk powder, soybean meal, soy protein isolate and fish meal in weaned pigs (Caine et al., 1997b; Makkink et al., 1997). A major limitation to the use of TID values in piglet diet formulation is the lack of routine measurements for $IAAL_T$ which are additionally time consuming and expensive. Furthermore, TID values do not include the $IAAL_S$, and therefore require that those unknown costs of protein digestion are included in the estimates of AA requirements. Consequently, the actual requirements for AA would depend on the ingested feed ingredients (Mosenthin, 2002).

Standardized ileal digestibilities : As an alternative to TID values, SID values have been introduced in diet formulation for pigs (Jondreville et al., 1995; Mosenthin et al., 2000). Using this approach, only $IAAL_B$ are subtracted from ileal outflow of CP and AA according to the following equation:

$$\text{SID (\%)} = ((\text{CP or AA intake} - (\text{ileal CP or AA recoveries} - IAAL_B)) / \text{CP or AA intake}) \times 100\%$$

If AID values have been already determined, these values can be transformed into corresponding SID values according to the following equation:

$$\text{SID (\%)} = \text{AID (\%)} + (IAAL_B / \text{CP or AA diet}) \times 100\%$$

The term ‘true ileal digestibilities’ describing the correction of AID values for $IAAL_B$ has been used to represent SID values (Furuya and Kaji, 1989; NRC, 1998). Moreover, different methods to obtain estimates of $IAAL_B$ have been applied. When a protein-free diet is fed, all protein containing compounds in ileal digesta are assumed to be of endogenous origin (Jansman et al., 2002; Pedersen and Boisen, 2002). The main criticism of this method is that animals are in negative nitrogen balance *per se*. The protein free diet may lack the stimulatory effect on endogenous gut secretions, which can lead to underestimation of $IAAL_B$. As an alternative to the protein-free diet method, diets containing protein sources with assumed 100% CP digestibility, such as casein, wheat gluten or crystalline AA have been used to determine $IAAL_B$ as reviewed by Jansman et al. (2002) and Pedersen and Boisen (2002). However, the validity of this method may be questioned until it is proven that these protein sources are indeed 100% digestible (Nyachoti et al., 1997). In various studies, $IAAL_B$ measured in different ways have been applied to calculate SID values in feed ingredients for piglets. For example, Walker et al. (1986) considered ileal CP and AA recoveries from piglets fed enzyme-hydrolyzed casein to represent $IAAL_B$, whereas Yun et al. (2005b) and Yang et al. (2007) determined $IAAL_B$ in piglets fed protein-free diets.

Due to the fact that only the $IAAL_B$ but not the $IAAL_S$ are subtracted from the total ileal AA recoveries, values for SID are intermediate between values for AID and TID (Stein et al., 2007). By correcting AID values for $IAAL_B$ to calculate SID values, some of the variations observed in AID values among different samples of the same feed ingredient are reduced, largely because potential effects of the CP and AA levels on the measurements of AID of CP and AA are eliminated (Fan et al., 1995a; Stein et al., 2007; Eklund et al., 2008b). The SID values reflect the effects of TID and feed ingredient on $IAAL_S$. In other words, a reduction in SID may be due to a reduction in TID of CP and AA or to an increase in $IAAL_S$ (Stein et al., 2007). The SID have the advantage over AID and TID that they represent the fundamental property of the individual feed ingredients, i.e. SID values include any variation of the endogenous fraction related to the feed ingredient itself (Mosenthin, 2002). The main advantage of using SID in comparison to AID is that values for SID of CP and AA are more likely to be additive in mixed diets (Stein et al., 2005). There are, however, only few reports on SID values in feed ingredients for piglets.

FACTORS AFFECTING BASAL ILEAL ENDOGENOUS CRUDE PROTEIN AND AMINO ACID LOSSES AND ILEAL CRUDE PROTEIN AND AMINO ACID DIGESTIBILITIES

Dietary crude protein level

Apparent ileal digestibilities : Similar to reports in grower-finisher pigs, AID of CP and AA in piglets follow so called ‘segmented quadratic with plateau relationships’ with increasing dietary CP and AA contents because $IAAL_B$, as percentage of total ileal CP and AA recoveries, decrease proportionally (Fan et al., 1994; Eklund, 2007). Above individual break points for CP and each individual AA, AID reach individual plateau values (Eklund, 2007). The dietary CP and AA contents, corresponding to the initial plateau AID, represent the dietary threshold levels (Fan et al., 1994). The plateau AID are rarely affected by the dietary CP or AA content or variations in $IAAL_B$. To obtain the plateau AID, the CP and AA contents in the assay diets should meet or exceed the corresponding dietary threshold levels (Fan et al., 1994; Eklund, 2007). Dietary threshold levels for CP and AA determined in piglets are presented in Table 1.

Basal ileal endogenous losses : The $IAAL_B$ have originally been defined as the CP and AA recoveries in digesta of animals fed a nitrogen-free diet (Mitchell, 1924). However, similar to reports in grower-finisher pigs (Hodgkinson and Moughan, 2000), Eklund et al. (2008a) observed in piglets a linear increase in $IAAL_B$ with increasing dietary CP contents. Whether or not this effect should be included in the calculation of SID values remains a rather theoretical discussion and warrants further investigations (Jansman et al., 2002).

Standardized ileal digestibilities : Similar to observations in grower-finisher pigs (Fan and Sauer, 1997), small but significant effects of the dietary CP level on SID values were observed in piglets (Eklund et al., 2008a). These effects resulted mainly from variations in SID values, which were determined in assay diets with CP and AA contents below the corresponding threshold levels. Therefore, SID values should be determined from the AID values measured at higher dietary CP and AA levels, ideally from the plateau AID (Fan and Sauer, 1997; Eklund et al., 2008a). Moreover, Eklund et al. (2008a) showed in piglets that SID of AA in casein were not affected by dietary CP levels up to 415 g/kg (as fed), provided that the increases in $IAAL_B$ with increasing dietary CP levels were taken into account in the calculation. In contrast, Zhang et al. (2005) observed for grower pigs linear decreases in SID values with increasing CP levels originating from soy protein.

Age or body weight

Apparent ileal digestibilities : In piglets, considerable increases in AID of CP and AA have been reported during the first weeks after birth (Li et al., 1993; Chae et al., 1999). Notably, according to some reports (Kim and Easter, 2001; Diebold et al., 2005), AID of CP and AA may also decline during the last experimental period. For example, Diebold et al. (2005) reported that AID of CP decreased from 83.8 in period 1 (approximately 34 days of age) to 75.7% in period 2 (approximately 44 days of age) in piglets fed a diet based on wheat and soy protein. According to Kim and Easter (2001), average AID of all AA was lower in the fourth (6 weeks of age) compared to the third experimental period (5 weeks of age) with values decreasing from 64.9 to 56.1% in piglets fed a diet consisting mainly of cornstarch and fish meal. In contrast, Eklund (2007) did not find any differences in AID of CP and AA when feeding casein as sole protein source to piglets from 34 to 55 days of age.

Basal ileal endogenous losses : Based on a literature review, Stein and Nyachoti (2003) concluded that $IAAL_B$ are higher in younger compared to mature pigs, and that the effect of BW on $IAAL_B$ decreases rapidly with increasing BW. According to currently available data, $IAAL_B$ are proportional to BW when the DM intake (DMI) is lower than 70 $g/kg^{0.75}$ (Mariscal-Landin et al., 1995; Hess and Seve, 1999). This hypothesis is supported in the study of Caine et al. (1997b) where higher $IAAL_T$ in 29- compared to 38-day old piglets were determined. In contrast, Eklund et al. (2008a,b) showed that $IAAL_B$ in piglets were similar to values for grower-finisher pigs (Jorgensen and Gabert, 2001; Jansman et al., 2002), and there was no difference in $IAAL_B$ between 34 to 55 days of age.

Standardized ileal digestibilities : In grower-finisher pigs fed *ad libitum*, SID of CP and AA were not different from those of lactating sows fed *ad libitum*, indicating that the BW *per se* may not affect the measurement of SID (Stein et al., 2001). In agreement with this report, there was no effect of age on SID values in 34 to 55-day old piglets fed a casein-based diet (Eklund et al., 2008b).

Feed intake level

Apparent ileal digestibilities : According to Moter and Stein (2004), AID of CP and AA increase linearly with higher levels of feed intake or follow a quadratic function. There are no detailed studies in piglets so far on the effect of feed intake level on AID of CP and AA. However, there is evidence that at higher feed intake levels up to 60 g/kg BW considerably lower AID of CP and AA in piglets can be obtained (Diebold et al., 2005).

Basal ileal endogenous losses : There is a general agreement that an increase in feed intake level is associated with a reduction in $IAAL_B$ (g/kg DMI) in grower-finisher pigs (e.g. Furuya and Kaji, 1992; Moter and Stein, 2004). According to Leterme and Thewis (2004), a part of higher $IAAL_B$ in piglets can be attributed to a lower DMI level. In piglets, the feed intake level is highly variable during the first weeks after weaning. If piglets are weaned at 21 days of age, their feed intake level usually does not exceed 35 g/kg of BW during the first week after weaning. In the following 2 weeks, however, their feed intake level may reach more than 60 g/kg of BW (NRC, 1998; Brooks and Tsourgiannis, 2003). Further studies are warranted to determine the effect of feed intake level on $IAAL_B$ in piglets.

Standardized ileal digestibilities : According to Moter and Stein (2004), SID of CP and AA decrease linearly with increasing feed intake levels in grower-finisher pigs. The authors speculated that the higher CP consumption due to the higher feed intake may limit the maximum capacity for CP digestion and AA absorption at certain levels. However, there are no reports so far on the effect of feed intake level on SID of CP and AA in piglets.

Choice of method for determination of ileal digestibilities

Direct, difference or different types of regression methods have been described to obtain estimates of ileal digestibilities in pigs (e.g. Fan and Sauer, 1995a,b; Mosenthin et al., 2000). Most of theses methods have in common that SID values are obtained by correcting AID values in the assay diets for estimates of $IAAL_B$.

Using the direct method, an assay diet is formulated in such a manner that the assay feed ingredient provides the sole dietary nutrient to be assessed. Therefore, the nutrient digestibility in the assay feed ingredient corresponds to the digestibility coefficient obtained for the assay diet (Mosenthin et al., 2000).

The difference method involves the formulation of both a basal and an assay diet. In this approach, the basal diet contains the basal feed ingredient, whereas the assay diet consists of a mixture of the basal and assay feed ingredient. Provided that there is no interaction in nutrient digestibility between the basal and the assay feed ingredient, the digestibility of nutrients can be calculated by difference (Mosenthin et al., 2000).

Moreover, there are two types of regression approaches to obtain estimates of SID in pigs. In one approach, the basal and assay feed ingredient are evaluated simultaneously (Fan and Sauer, 1995a,b). The basal and assay feed ingredient are mixed at graded levels in a series of assay diets provided that there is no interaction between the basal and assay feed ingredients. The digestibility of each feed ingredient can be obtained by extrapolating their respective dietary contents to 100% (Mosenthin et al., 2000). In another approach, various graded inclusion levels of the assay feed ingredient can be formulated in such a manner that the assay feed ingredient provides the sole dietary nutrient to be assessed. Under this condition, the slope of the linear regression equation between apparent ileal digestible and total dietary contents of CP and AA provides direct estimates of SID (Fan et al., 1995a; Eklund et al., 2008b).

There are some comparative studies (e.g. Fan and Sauer, 1995a,b) in which the effects of the direct, difference and regression methods on AID values were compared. In general, the selection of the method had no major impact on the determination of AID values. Similarly, Fan et al. (1995a) and Eklund et al. (2008b) observed no differences between SID values, either determined according to the direct or the regression analysis method between apparent ileal digestible and total dietary AA contents.

Table 2. Range in nutrient composition of feed ingredients (g/kg, as fed)

Item	SB (2,5,11, 17,19,36)	SBM (1,2,4, 5,8,14, 18,19, 28, 34,36,40, 42,43)	SP (17,18,36, 42,43)	SPC (8,10,30, 34, 36,40, 42)	SPI (1,10,30, 34, 36,40)	CG (13,19,36, 41)	WG (1,20,32, 36,39)	PeaPC (12,21,29)	PeaPI (21,22,29)	PotP (15,23,31, 36)	FM (6,7,16, 19,25,36, 43)	WP (3,24,27, 36)	WPC (7,9,26, 33,35,36, 43)	WPI (26)
DM	876-906	872-917	929-961	911-953	917	893-902	927-972	914-920	-	899-947	902-924	930-979	947-979	-
CP	345-392	360-562	530-577	631-719	812-886	546-604	704-841	534-593	883-919	761-855	592-927	70-132	350-802	916-927
CF	41-50	26-151	321-540	20-46	0.7	7-30	<0.4	24-32	-	3-24	3-18	0.4	<1	-
EE	188-210	2-54	19-38	3-30	1-22	20-51	38-57	32-34	-	3-40	20-93	5-16	17-197	4-6
CA	50	60-218	698-712	48-69	20-47	11-17	9-12	56-57	-	5-22	68-181	12-150	22-61	14-22
TIA*	1.0-8.5	0.2-5.4	1.0-1.7	0.8-3.0	1.0-1.9	-	-	2.1-2.8	0.6-1.4	-	-	-	-	-
Lactose	-	-	-	-	-	-	-	-	-	-	-	610-805	21-500	4-5
Arg	23.1-29.0	28.0-38.5	36.7-41.6	45.4-57.9	55.3-66.5	16.3-19.8	23.0-32.6	-	85.0-86.0	40.6-42.9	35.1-54.7	2.3-2.4	8.0-24.8	-
His	8.7-10.2	0.5-16.4	13.6-16.8	16.0-18.9	20.5-23.4	10.4-13.0	14.0-26.2	-	25.0-26.0	16.8-18.7	10.6-30.9	1.8	6.9-15.6	-
Ile	14.8-17.2	5.5-23.9	23.6-26.7	27.2-33.8	35.4-41.6	21.1-26.1	22.0-29.3	-	47.0-48.0	38.1-46.3	25.1-34.2	5.6-5.9	20.0-51.5	-
Leu	23.1-29.5	28.1-46.9	38.8-52.8	49.2-56.1	64.7-73.1	87.2-108.0	47.0-56.0	-	81.0-84.0	77.8-84.7	43.7-58.8	9.8-9.9	36.0-104.0	-
Lys	19.9-23.9	25.0-31.6	29.9-62.0	39.0-44.5	47.6-55.1	8.6-10.4	12.0-18.0	-	51.0-62.0	57.7-62.7	44.1-61.3	8.1-8.4	24.0-74.9	-
Met	4.8-5.5	4.8-7.6	6.4-8.0	7.5-9.8	9.1-16.1	10.8-13.8	7.1-25.0	-	29.0-46.0	17.5-18.0	17.7-23.2	1.7	5.0-21.8	-
Phe	17.0-19.7	20.0-25.7	25.8-27.9	31.4-38.5	42.0-47.1	33.2-36.9	30.0-47.0	-	50.0	48.0-53.5	21.0-31.6	3.2-3.6	10.0-31.1	-
Thr	14.2-15.0	17.3-23.8	20.6-22.5	24.0-28.5	27.2-35.6	18.0-21.2	13.4-23.0	-	43.0-50.0	43.3-45.6	25.4-34.6	6.6-6.7	23.0-52.8	-
Trp	4.5-5.2	5.1-7.7	6.9-7.4	3.9-9.2	11.2	2.7-3.4	6.0-7.0	-	11.0-14.0	10.1-11.2	4.8-9.1	1.8-2.0	6.9-17.2	-
Val	16.5-17.9	16.3-24.8	23.7-27.7	28.3-33.5	37.2-39.0	9.4-28.2	17.0-31.2	-	52.0-61.0	52.0-56.3	27.8-39.3	5.4-5.8	20.0-48.2	-

* Trypsin inhibitor activity (mg/g product, as fed).

SB = Heat treated soybeans; SBM = Soybean meal; SP = Soy protein; SPC = Soy protein concentrate; SPI = Soy protein isolate; CG = Corn gluten; WG = Wheat gluten; PeaPC = Pea protein concentrate; PeaPI = Pea protein isolate; PotP = Potato protein; FM = Fish meal; WP = Whey powder; WPC = Whey protein concentrate; WPI = Whey protein isolate.

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CHARACTERIZATION AND EVALUATION OF PROTEIN INGREDIENTS FOR PIGLETS BASED ON STANDARDIZED ILEAL CRUDE PROTEIN AND AMINO ACID DIGESTIBILITIES

Oilseeds and their by-products

Oilseed cakes and meals are the residues remaining after removal of the main part of oil from oilseeds. These residues are rich in CP. Therefore, oilseed by-products are considered as valuable protein supplements for livestock (Kellems and Church, 2001).

Soybeans : Soybeans (SB) may contain 345 to 392 g/kg (as fed) CP and up to 210 g/kg (as fed) ether extract (EE) (Table 2). The SB storage protein consists of a mixture of differently composed proteins (conglycinin, glycinin and globulins) (Wolf, 1970). The seeds contain also bioactive proteins such as α-amylase, cytochrome, lectin, lipoxygenase, urease, TI, secondary metabolites including isoflavones, saponins, phytic acid, oligosaccharides and goitrogens (Friedman and Brandon, 2001). The major protein fraction in SB is made of globulins (60 to 90%) which are storage proteins rich in Lys, Arg, Glu, Asp and their amides, and poor in the sulfur containing AA, such as Met and Cys (Friedman and Brandon, 2001). Soybeans contain also 10 to 20% albumins, which are richer in Thr and Trp than globulins (Friedman and Brandon, 2001). With regard to the Ideal Protein pattern for piglets, SB are rich in Arg and Lys but relatively poor in Met and Cys (NRC, 1998) (Table 2).

Raw SB contain antigens (glycinin, β-conglycinin) and several ANF (Kunitz and Bowman-Birk TI families, haemagglutinins, raffinose, stachyose) that may cause intestinal immune responses and gut wall damage, possibly resulting in reduced growth performance in piglets (Li et al., 1991). The growth depression due to ANF may result from a reduced activity of (chymo-)trypsin, resulting in poor digestibility, delayed absorption of AA (Huisman and Jansman, 1991; Nitsan, 1991), and increased $IAAL_S$, which are mainly sulfur containing AA (Walker et al., 1986; Fan et al., 1995b). The nutritional quality of raw SB can be improved by inactivating heat labile ANF (TI, lectins) through thermal or hydro-thermal treatments such as autoclaving, expanding, extrusion, toasting and micronizing as well (Marty et al., 1994; Marty and Chavez, 1995). According to some reports, TI activity (TIA) in raw SB may range from 20.1 to 32.6 mg TIA/g (as fed) product (Huisman and Jansman, 1991; Qin et al., 1996), whereas in heat treated SB, TIA is considerably lower ranging from 1.0 to 8.5 mg TIA/g (as fed) product (Huisman and Jansman, 1991; Clarke and Wiseman, 2005). Temperature and duration of heat treatment, particle size and moisture of the SB are the main factors involved in the efficient reduction of ANF (TI, lectins) (Qin et al., 1996; Zarkadas and Wiseman, 2005a,b). For example, the TIA in SB, which were micronized with full steam or low steam were reduced to 2.0 and 16.0 mg TIA/g (as fed) product, respectively (Zarkadas and Wiseman, 2005a). Similarly, extrusion of SB at 70 and 150°C reduced the TIA to 24.1 and 2.9 mg TIA/g product (as fed), respectively (Zarkadas and Wiseman, 2005a). Collective terms that are used to describe processed SB include ‘full-fat SB seed’, ‘heat processed SB’, ‘heat treated SB’, and ‘whole SB’.

Soybean meal : Soybean meal (SBM) is obtained after removal of most of the oil from dehulled SB by a solvent extraction process (Kellems and Church, 2001). Thereafter, defatted flakes are subjected to a steam heating process where the residuals of the solvent are removed and ANF (mainly TI, lectins) are partly inactivated (O’Quinn et al., 1997). High-protein SBM may contain 450 to 562 g/kg (as fed) CP and not more than 30 g/kg (as fed) crude fiber (CF) (van Eys et al., 2004). Low protein SBM may contain 360 to 440 g/kg (as fed) CP (Table 2). The CF content in SBM depends on the amount of soy hulls that are added to the product after the extraction process has been completed (Peisker, 2001). Performance responses and ileal CP and AA digestibilities in SBM are influenced by the content of ANF (TI, lectins) and oligosaccharides present in SBM after processing (Huisman and Jansman, 1991; Smiricky et al., 2002). After toasting, the TIA in SBM may range from 0.2 to 5.4 mg TIA/g (as fed) product (van Kempen et al., 2006). Accordingly, levels of oligosaccharides, mainly raffinose and stachyose, may range from 0.6 to 4.0% (as fed) (van Kempen et al., 2006), and from 5.2 to 6.0% (Smiricky et al., 2002; van Kempen et al., 2006), respectively. According to the results of a study by Smiricky et al. (2002), there are only minor effects of oligosaccharides in SBM diets on SID of CP and AA in grower-finisher pigs. However, in the study by Kim et al. (2003) with weaned pigs, the dietary supplementation with a mixture of carbohydrases to a corn-soybean meal diet reduced the amount of stachyose and raffinose in the small intestine, thereby improving gain:feed ratio, energy and AA digestibility.

Purified soybean products : Further processing of soy flakes or SBM leads to products referred to as soy protein (SP) (Zhang et al., 2005; Kim et al., 2006; Yang et al., 2007), soy protein concentrate (SPC) and soy protein isolate (SPI) (Lusas and Riaz, 1995; Peisker, 2001).

Soy proteins : Soy proteins (SP) are relatively new products. In principle, they are produced by enzymatic or microbial fermentation of dehulled SBM (Kim et al., 2006). For the fermentation process, microorganisms such as *Aspergillus oryzae* and (or) *Bacillus subtilis* may be used (Yang et al., 2007). The methodology is based on the principle that microorganisms degrade carbohydrates during fermentation, resulting in an enrichment of CP in SP ranging from 530 to 577 g/kg (as fed) CP. Due to the fungal and (or) bacterial fermentation, the levels of TI and oligosaccharides, such as raffinose and stachyose, may decrease in SP (Min et al., 2004; Kim et al., 2006). Moreover, SP may contain high proportions of small peptides due to enzymatic or microbial degradation of soy protein during the fermentation process (Hong et al., 2004; Min et al., 2004).

Soy protein concentrate : Soy protein concentrate (SPC) is made from white soy flakes (Lusas and Riaz, 1995). Three processing techniques including aqueous alcohol extraction (70 to 90% ethyl alcohol), water extraction at isoelectric pH (4.5), or denaturation of the protein fraction with heat followed by water extraction are used to produce SPC (Lusas and Riaz, 1995). The majority of SPC are produced by aqueous ethyl alcohol extraction (Peisker, 2001). The main objective in producing SPC is to remove ANF (TI, lectins) and oligosaccharides (stachyose, raffinose) (Peisker, 2001; Smiricky et al., 2002). The CP contents in SPC may range from 631 to 719 g/kg (as fed) (Table 2).

Soy protein isolate : Soy protein isolate (SPI) is obtained by extraction of the soluble soy constituents from white soy flakes with water at alkaline pH 8.0 to 9.0, followed by centrifugation to remove the remaining insoluble carbohydrates (Lakemond and Vereijken, 2003; Yang et al., 2007). Thereafter, soluble carbohydrates are removed by isoelectric precipitation of the protein, and the precipitated SPI may be hydrolyzed enzymatically. In this case, peptide bonds are broken into shorter chain units by means of proteolytic enzymes such as pepsin, papain, ficin and trypsin or by microbial proteases (Lusas and Riaz, 1995). The CP content in SPI may range from 812 to 886 g/kg (as fed) (Table 2). Soy protein concentrate and SPI represent highly purified feed ingredients which can be used as components in milk replacers and starter diets for piglets, but the use of SPI in animal nutrition might not be cost efficient (Peisker, 2001; Lakemond and Vereijken, 2003).

Standardized ileal CP and AA digestibilities in soybean products : So far, there are only few reports on SID of CP and AA in soybean products for piglets (Table 3). According

Table 3. Standardized ileal crude protein and amino acid digestibilities (%) in feed ingredients for piglets

Item	SB[1]	SBM[1-3]	SP[1,3]	SPC[1-4]	SPI[1,2]	CG[1]	PeaP[1]	WG[1]	PotP[1]	FM[1]	WPC[1]
CP	73	80-94	74-86	86-99	86-94	90	87	87-90	83-87	79-87	80-94
Arg	82	86-92	86-94	87-98	94-97	89	93	85-90	90-92	89-93	85-98
His	78	81-98	77-89	89-100	89-97	87	87	85-89	85-89	83-89	82-96
Ile	72	76-88	77-88	85-96	88-94	90	86	84-89	85-88	82-89	82-98
Leu	73	81-86	77-89	85-94	87-93	95	87	86-92	87-90	85-91	84-98
Lys	78	83-95	71-88	85-100	90-96	68	90	58-63	86-89	86-92	90-97
Met	76	83-87	84-91	84-96	89-95	94	81	87-90	89-91	89-94	87-98
Phe	69	80-89	72-88	83-96	87-94	89	87	88-92	80-83	76-86	77-90
Thr	67	76-92	66-84	78-95	81-92	84	81	74-80	82-86	81-87	81-89
Trp	71	82	71-84	83-85	83	63	79	77-82	75-80	74-86	83-97
Val	71	80-89	74-88	81-95	86-93	90	87	84-88	86-89	81-89	91-96

SB = Heat treated soybeans; SBM = Soybean meal; SP = Soy protein; SPC = Soy protein concentrate; SPI = Soy protein isolate; CG = Corn gluten; PeaP = Pea protein; WG = Wheat gluten; PotP = Potato protein; FM = Fish meal; WPC = Whey protein concentrate.

[1] Urbaityte (2008); [2] Walker et al. (1986); [3] Yang et al. (2007); [4] Yun et al. (2005b).

to Urbaityte (2008), SID of CP and indispensable AA in SB range from 67 to 82% (Table 3). Reports on SID of CP and indispensable AA in SBM for piglets are inconsistent among the studies. According to Walker et al. (1986), SID of indispensable AA in SBM range from 86 to 98%, whereas Urbaityte (2008) and Yang et al. (2007) obtained SID values which range from 76 to 89%. The SID values for SP are inconsistent in piglets as well. In a study by Yang et al. (2007), SID of indispensable AA in SP fermented by *A. oryzae* range from 80 to 91%. Similarly, SID of indispensable AA in SP, fermented by a combination of *A. oryzae* and *B. subtilis,* range from 80 to 88%. According to Urbaityte (2008), SID values in a microbial fermented SP product range from 66 to 86%, whereas SID values of indispensable AA in an enzymatic fermented SP product range from 74 to 94% in piglets. The SID of indispensable AA in SPC for piglets vary generally from 78 to 95% (Yun et al., 2005b; Yang et al., 2007; Urbaityte, 2008) but higher SID values in the range from 94 to 100% have been reported as well (Walker et al., 1986). According to Walker et al. (1986), SID of indispensable AA in SPI range from 92 to 97% in piglets, whereas Urbaityte (2008) reported lower SID values in the range from 81 to 94%.

By-products of starch production

Wet milling is used to produce starch, sugar, syrup or oil and provides a large variety of by-products such as corn gluten (CG) (Weigel et al., 1997), wheat gluten (WG) (Day et al., 2006), pea proteins (PeaP) (Roquette’s Nutrition Business Unit, 2007) and potato protein (PotP) (Kerr et al., 1998).

Corn gluten : The CG is a by-product of starch extraction through wet milling. It represents the dried residue from corn after removal of larger proportions of starch and germ (Weigel et al., 1997). Principally, CG consists of CP (gluten), along with small amounts of starch and fiber which are not recovered during the separation process (Weigel et al., 1997). The CG may contain approximately 546 to 604 g/kg (as fed) CP, and it is a good source of Leu and Phe, whereas it is deficient in Lys and Trp compared to the Ideal Protein pattern for piglets (NRC, 1998) (Table 2).

Standardized ileal CP and AA digestibilities in corn gluten : So far, there exists only one report in piglets on SID of CP and AA in CG. According to Urbaityte (2008), SID of CP and indispensable AA range from 84 to 95%, except for Lys and Trp, with lower SID values of 68 and 63%, respectively (Table 3).

Wheat gluten : The WG is obtained by removing starch through a wet milling process from wheat flour. Thereafter, the protein rich residues are dried so that the native viscoelastic properties of the WG are retained (Lawrence et al., 2004). Glutenin and gliadin are the two major protein components of WG. Wheat gluten has been originally used in bakery products, meat and cheese analogs (Magnuson, 1985). Recently, WG gets more frequently used as feed ingredient for livestock, particularly in starter diets and milk replacer for piglets (Richert et al., 1994; Blasco et al., 2005). To improve the solubility of WG in milk replacers, deamidation by acid or alkali treatments, sulfuric, phosphoric or chlorosulfonic acids, or enzymatic hydrolysis by papain, bromelain, subtilisin, trypsin or pronase have been introduced (Day et al., 2006). The enzymatic hydrolysis breaks the peptide bonds so that polypeptide chains in WG are reduced. Smaller polypeptides in WG may result in a faster AA absorption during digestion in piglets (Blasco et al., 2005). However, some authors failed to observe differences in growth performance and nitrogen digestibility between hydrolyzed and native WG in piglets (Richert et al., 1994; Vente-Spreeuwenberg et al., 2004). Both hydrolyzed and non hydrolyzed WG contains from 704 to 841 g/kg (as fed) CP which consists mainly of Glu and Pro, amounting to 344 and 106 g/kg (as fed), respectively (Grala et al., 1998; Reeds et al., 2000). Glutamic acid is known as the primary energy source for enterocytes. Glutamic acid renews and protects the intestinal structure and helps to improve the absorption capacity of the intestine (Lai et al., 2004). Moreover, WG is rich in Leu and Phe but poor in Lys and Thr compared to the Ideal Protein pattern for piglets (NRC, 1998) (Table 2).

Standardized ileal CP and AA digestibilities in wheat gluten : The SID of CP and indispensable AA in WG range from 74 to 92%, except for SID of Lys which has a lower SID value of 60% (Urbaityte, 2008).

Pea proteins : The separation of starch from peas through wet milling provides either pea protein concentrate (PeaPC) or pea protein isolate (PeaPI) (Owusu-Ansah and McCurdy, 1991). The PeaPC is produced through an acid leaching procedure (Sumner et al., 1981). The PeaPI may be produced by i) alkaline extraction and precipitation at the isoelectric point, ii) ultra-filtration and reverse osmosis, iii) extraction by a sodium chloride solution and precipitation of the isolate by water dilution (Sumner et al., 1981). Both, PeaPC and PeaPI may contain high CP contents ranging from 534 to 593 g/kg (as fed) and from 883 to 919 g/kg (as fed), respectively (Table 2). The composition of AA in pea proteins depends on the proportion of the three major soluble protein fractions present in pea seeds: legumins, vicilins and albumins. Legumins and vicilins together constitute the main storage protein, globulin, whereas albumins mainly constitute the enzymatic and metabolic proteins (polypeptides, TI, lectins) (Stefanyshyn-Cote et al., 1998). Legumin contains more sulfur containing AA and Arg, whereas vicilin is rich in Ile, Leu, Phe, and Lys content (Owusu-Ansah and McCurdy, 1991). It has been suggested that increasing the proportion of legumin to vicilin could improve the nutritional quality of pea proteins (Casey and Short, 1981). The PeaPC and PeaPI are rich in indispensable AA, except for sulfur containing AA (Met, Cys) and Trp compared to the Ideal Protein pattern for piglets (NRC, 1998) (Table 2).

Peas may contain several ANF such as lipoxygenase, TI and lectins (Owusu-Ansah and McCurdy, 1991). The TI in peas are different from Bowman-Birk and Kunitz soybean TI, and show a 2 to 10 times higher inhibition of proteases in 8-week-old piglets compared to grower-finisher pigs (Arentoft et al., 1991). Various processing methods such as extrusion or micronizing of peas may inactivate TI and increase the nutritional value of pea products (Owusu-Asiedu et al., 2002). The PeaPI is almost devoid of carbohydrates and ANF, whereas PeaPC may still contain small amounts of ANF amounting from 2.1 to 2.8 mg TIA/g (as fed) product and 2.8 mg lectins/g (as fed) product (Owusu-Ansah and McCurdy, 1991; Huisman et al., 1992; le Guen et al., 1995a) (Table 2).

Standardized ileal CP and AA digestibilities in pea proteins : The results of a recent study with piglets revealed SID of CP and indispensable AA in the range of 79 to 93% for PeaP (Urbaityte, 2008) (Table 3).

Potato proteins : Potato protein (PotP) is obtained from the effluents produced during the starch extraction from chopped potatoes (Refstie and Tiekstra, 2003). During potato starch manufacturing, the soluble potato proteins are diluted in a liquid potato juice. To retrieve potato protein, the potato juice is heated to precipitate the protein, centrifuged and dried to PotP (Refstie and Tiekstra, 2003). The proteins in potato juice consist mainly of patatin (the storage protein) and protease inhibitors (Pouvreau et al., 2003). The PotP may contain from 761 to 855 g/kg (as fed) CP with high Lys contents up to 57.7 to 62.7 g/kg (as fed), whereas the contents of sulfur AA (Met, Cys) and Trp are relatively low compared to the Ideal Protein pattern for piglets (NRC, 1998) (Table 2).

The nutritional value of potato protein depends on the level of glycoalkaloids such as solanine and chaconine and their secondary metabolites (Friedman, 1996). Glycoalkaloids are naturally occurring, nitrogen-containing plant steroids with a carbohydrate side chain. Glycoalkaloids may reduce the feed intake in piglets (Friedman and Dao, 1992). New processing methods have been introduced to remove glycoalkaloids from PotP (Kerr et al., 1998; Refstie and Tiekstra, 2003). According to Kerr et al. (1998), processed PotP products may contain less than 16 mg glycoalkaloids/100 g (as fed) product compared to 303 mg/100 g (as fed) product in conventional PotP.

Standardized ileal CP and AA digestibilities in potato proteins : In piglets, SID of indispensable AA in PotP range between 75 and 92% (Urbaityte, 2008) (Table 3). The effects of glycoalkaloids on SID of CP and AA in piglets have not yet been determined.

Fish meal

Fish meal : Fish meal (FM) is defined as clean, dried, ground tissue of undecomposed whole fish or fish cuttings, with or without extraction of part of the oil (Hampton, 1981). Processing of FM involves cooking, pressing, drying, and grinding of the fish (Barlow and Windsor, 1983). Fish is cooked to coagulate the proteins, to remove water and fat from the tissues, and to sterilize the raw material (Hussein and Jordan, 1991). Cooked fish is pressed to remove part of the water and fat. The remaining liquid is evaporated to thick liquor (stick water) and added back to the pressed fish (Hussein and Jordan, 1991). The quality of FM depends on i) the origin of the fish (i.e. species of fish, fat content, whole fish or fish scraps) (Barlow and Windsor, 1983; Kim and Easter, 2001), ii) the freshness of the fish before processing (Johnson and Savage, 1987), iii) the amount of stick water added back to fish meal (Johnson and Savage, 1987), iv) time and temperature used to dry the pressed fish, because heat treatment may destruct heat susceptible AA, such as Cys, His, Lys and Trp (Mason and Weidner, 1964), and v) the storage conditions of the FM (Johnson and Savage, 1987). The CP contents in FM may vary from 592 to 927 g/kg (as fed). In general, FM is rich in indispensable AA, particularly in Lys, sulfur AA (Met, Cys) and Trp compared to the Ideal Protein pattern for piglets (NRC, 1998) (Table 2).

Standardized ileal CP and AA digestibilities in fish meal : In piglets, SID of CP and indispensable AA in FM vary considerably from 74 to 94%, and the digestibility coefficients are consistently low for Cys (Urbaityte, 2008) (Table 3).

Whey products

Whey is a by-product of cheese, quark and casein production (Maswaure and Mandisodza, 1995; Wit, 1998). Whey remains from the precipitation of casein in milk or skimmed milk followed by mechanical separation from casein and fat (Codex Alimentarius, 2006). Whey consists up to 96% of water and contains most of the lactose, minerals, and water-soluble protein, which are left from cheese, quark or casein processing (Cinq-Mars et al., 1986). The different types of whey are classified according to the method of precipitation used. Cheese is made by using rennet-enzyme precipitation. The resulting whey is called sweet whey (Maswaure and Mandisodza, 1995). Curd-cheese and quark products are made by using a precipitation process through lactic acid producing bacteria. The resulting whey is referred to as acid whey (de Wit, 1998). The protein fraction of whey consists of lactoglobulin and lactoalbumin, approximately at a ratio of 70:28 (Mahan, 1992; de Wit, 1998). Lactoglobulin is more easily denaturated during the drying process than lactoalbumin (Mahan, 1992). Therefore, lactoglobulin is generally considered to be a protein fraction with a high biological value (Mahan, 1992).

Whey powder : Whey powder is the remainder of whey after steaming and drying and consists mainly of whey protein, lactose and minerals (Cinq-Mars et al., 1986). Some authors demonstrated the benefits of high lactose inclusions in starter diets for piglets in terms of improved growth performance (Mahan, 1992; Owen et al., 1993; O´Doherty et al., 2004) and increased nutrient digestibilities, particularly of the protein fraction (Sewell and West, 1965; Owsley et al., 1986; Nessmith et al., 1997b). The improved nutrient digestibilities may have to be attributed to the microbial fermentation of lactose to lactic acid in the stomach, which may stimulate gastric proteolytic activity, assisting in the digestion of non-milk proteins (Partridge and Gill, 1993). Sweet whey powder (SWP) with a pH of >6.0 contains at least 110 g/kg (as fed) CP, 650 g/kg (as fed) lactose and a maximum of 85 g/kg (as fed) crude ash (CA). Whey powder from acid whey with a pH of ≥5.1 has a minimum content of 70.0 g/kg (as fed) CP and 610 g/kg (as fed) lactose, and a maximum CA content of 150 g/kg (as fed) (Codex Alimentarius, 2006) (Table 2).

Whey protein concentrate/isolate : Whey protein concentrate (WPC) and whey protein isolate (WPI) are produced from cheese whey by several techniques including gel filtration, ion exchange, ultra-filtration, adsorption, and polyphosphate precipitation (Shimada and Cheftel, 1988; Morr and Foegeding, 1990; Britten et al., 1994). These processes allow for removal of lactose, minerals and other components to concentrate the whey protein. The CP content may range from 350 to 802 g/kg (as fed) in WPC, and from 916 to 927 g/kg (as fed) in WPI (Table 2). Whey proteins are a good source of almost all indispensable AA, except for Arg, His and Phe compared to the Ideal Protein pattern for piglets (NRC, 1998). Moreover, several treatments have been suggested to modify whey proteins to improve their functional attributes, such as solubility, water binding, emulsification and foam development (Britten et al., 1994). Hydrolysis by proteases improves the solubility and surface activity of whey proteins. The properties of the hydrolysate depend mainly on the type of enzyme used, the degree of hydrolysis, the environmental conditions, the substrate pre-treatment (Adler-Nissen, 1986), and the final heat treatment to eliminate the residual enzyme activities (Phillips and Beuchat, 1981).

Standardized ileal CP and AA digestibilities in whey products : SID of indispensable AA in WPC and a hydrolyzed WPC have been obtained in recent studies with piglets (Urbaityte, 2008). The SID of CP and indispensable AA in WPC and hydrolyzed WPC range from 77 to 98% (Table 3).

CONCLUSION

There is a general agreement that the amount of AA absorbed in the small intestine up to the terminal ileum gives a more reliable estimate of the amount available to the animal than does the conventional fecal analysis method. Ileal digestibility values may be expressed as AID, TID or SID depending whether and to which extent ileal endogenous CP and AA losses are taken into account. A major concern with the use of AID values is that they are not additive in mixtures of feed ingredients, because they are affected by the dietary CP and AA levels. This concern may be overcome by using $IAAL_B$ to correct AID which yields in SID values. The SID of CP and AA are frequently used in diet formulation for grower-finisher pigs, however, there are only few reports on SID values for by-products from starch processing, for fish meal and also for whey products in piglets. The SID values in soybean products for piglets are inconsistent among studies. Therefore, further studies are warranted to extend the database for SID of AA in those feed ingredients which are frequently used in piglet nutrition. In this context, the effects of age and (or) BW, feed intake level, but also the methods used to estimate $IAAL_B$ for the determination of SID values warrant further investigations in piglets as well.

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