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True Ileal Amino Acid Digestibility of Human Foods Classified According to Food Type as Determined in the Growing Pig

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ABSTRACT

Background: A Food and Agriculture Organization Expert Consultation recommended the use of digestible indispensable amino acid score (DIAAS) to evaluate protein quality of foods for humans. Calculation of DIAAS requires true ileal digestibility (TID) of amino acid (AA) values but currently insufficient data are available.

Objectives: This study aims to generate in pigs TID of AA for a wide range of foods commonly consumed by humans and determine the range of differences in TID of AA among food types.

Methods: A standardized protocol was followed to determine TID of AA in 97 foods across 3 laboratories. Female pigs (25–100 kg during study, $n \geq 6$) received foods for 7 d following a Youden Square design with ileal digesta collected via T-cannula on days 6–7. Endogenous AA losses were determined by feeding a protein-free diet. Foods, diets, and digesta were analyzed for nitrogen, AA, reactive lysine, titanium and dry matter. Foods were categorized into food types with the degree of variation within each food type evaluated using descriptive statistics.

Results: The TID (mean of AA) ranged from 0.247 (apples) to 0.988 (beef tenderloin). The median TID of AA was high (mean of AA $>$ 0.90) for foods categorized as dairy products, eggs, fish and seafood, isolates and concentrates, meat, nuts, plant-based burgers, soy products and wheat products. Food categories with median TID $<$ 0.80 were baked products, fruit, pulses and seeds, and wheat bran cereal, yeast, and zein. Food categories with low variations between foods were fish and seafood (1% units), dairy products (3% units), and eggs (5% units), whereas categories with the greatest variation were grains (18% units), vegetables (16% units), seeds (14% units), and fruit (12% units). There was considerable variation in TID for individual AA both within and among foods.

Conclusions: The database with TID of AA of 97 foods generated by 3 laboratories using a standardized methodology can be utilized for protein quality evaluation.

Keywords: pig, true ileal amino acid digestibility, amino acids, protein quality, protein digestibility

Introduction

The nutritive values of protein in foods and ingredients is of high importance, especially for groups that can be at risk of protein malnutrition. For example, for children, sufficient high-quality protein is needed to support growth [1] and in elderly adults an adequate protein intake is vital to prevent or decelerate sarcopenia [2]. Thus, it is important to consider protein quality in addition to protein content.

Protein quality is assessed according to the amount and availability of indispensable amino acids (AAs) that are consumed from different foods. To determine AA availability, the digestibility of each AA is determined, and it is assumed that digestibility equates to the amount of each AA that is absorbed. The digestibility is usually derived from ileal AA digestibility; that is, digestibility measured at the terminal ileum after ingestion of a protein. It is assumed that AA are absorbed exclusively in the small intestine and that the fraction entering

Abbreviations: AA, amino acids; DIAAS, digestible indispensable amino acid score; DM, dry matter; TID, true ileal digestibility.

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the large intestine is not absorbed in nutritionally relevant quantities [3,4].

An Expert Consultation convoked by the FAO in 2012 [5] regarding protein quality, that had their findings affirmed by 2 subsequent Working Groups [6,7], had 2 primary findings. First, each AA should be treated as a nutrient in its own right thus necessitating having true ileal digestibility (TID) of AA data for a range of foods. Second, when stand-alone estimates of protein quality are required, digestible indispensable amino acid score (DIAAS) should be used, the calculation of which is dependent on TID of AA data. A further recommendation was the use of values of digestible reactive lysine (available lysine) for foods undergoing lysine damage during processing and/or storage. The report noted that as it is difficult to determine TID in humans, an animal model of protein digestibility is needed. The report concluded that currently there is insufficient published TID of AA data, and the call was made for more work to be undertaken.

The gastrointestinal tract of the growing pig, at least to the end of the small intestine, is very similar to that of the adult human [8–10] and direct comparisons of TID of AA in several proteins between the human and pig have demonstrated that the cannulated growing pig is a valid model for the adult human [11–13]. A standardized method to determine TID of AA in proteins consumed by humans using the pig as a model has been published [14].

In the present study, TID of AA for 97 foods and food ingredients were determined using ileal cannulated pigs. The foods were grouped into food categories and median digestibility values are presented as well as the variation of AA digestibility within each food group. It was hypothesized that there would be considerable variation in TID data both within and between foods and food types. The objective was to generate TID of AA values and reactive lysine digestibility data for a wide range of foods commonly consumed by humans to ascertain the range of differences in TID of AA among foods and food types. The study provides a baseline TID dataset from work conducted concurrently in 3 laboratories using 1 method.

Methods

Foods

A total of 97 foods or food ingredients were selected to be evaluated. For the selection of the foods or ingredients, the amount of protein consumed from different foods (g/capita/d) was obtained from FAO (http://www.fao.org/faostat/en/#data/FBS). Foods that were reported to be consumed in quantities that significantly contribute to overall protein intake were identified in both "low protein intake" countries and "high protein intake" countries. Low protein intake countries were defined as those with a protein consumption of <70 g/capita/d. These countries included Indonesia, Pakistan, India, Bangladesh, Thailand, Nigeria, Zimbabwe, Liberia, Angola, Congo, Kenya, and Ethiopia. Countries with a protein consumption of >90 g/capita/d were considered high protein intake and the "representative" countries included United States, Canada, China, England, France, Italy, Australia, and New Zealand.

Categorization of the foods began using FAO examples of food groups [15] but some were further subdivided to allow for better definition of the foods. The final categories used were: algae and fungi, baked products, dairy products, eggs, fish and seafood, fruit, grains, meat, nuts, protein isolates and concentrates, pulses, roots and tubers, seeds, soy products, vegetables, and wheat products. One food was also evaluated in each of the categories: plant-based burger, wheat bran cereal, yeast, and zein. Some foods were placed into >1 food group. As an example, soybean isolate was categorized both with the soy group and in the isolates and concentrates group. Casein, micellar casein, whey protein concentrate and whey protein isolate were all categorized within the dairy group as well as with isolates and concentrates. The full list of foods that were evaluated and details regarding their preparation for the study are provided in Table 1 and their dry matter, protein and AA compositions are given in Supplemental Table 1. In all cases, the foods were supplied to the pigs in as close as possible to the format they would be normally be consumed or swallowed by humans. When necessary, the foods were broken up to ensure even mixing with the indigestible marker (titanium dioxide).

Diets and food allowance

Diets included the basal diet, protein-free diet and test diets. The basal diet (Supplemental Table 2) was formulated to be structurally similar to a human diet and was fed to the animals during the presurgery acclimatization period, during the recovery period between surgery and the assay period and for 7 d following the feeding of the protein-free diet (see below). The protein-free diet (Supplemental Table 2) was used to determine basal endogenous losses of AA at the distal ileum. Test diets, in which the test food was the only source of protein, were also formulated, and where possible, the final diets contained 100 g/kg crude protein. The test diets also contained purified maize starch, sucrose, vitamins and minerals, refined vegetable oil (human food quality), purified cellulose and titanium dioxide (indigestible marker) with the ingredients included as described in Hodgkinson et al. [14] (Supplemental Table 3).

Pig studies

Animal Research: Reporting of In Vivo Experiments (ARRIVE) Reporting Guidelines [16] have been followed. Pig studies were carried out at the Riddet Institute, New Zealand (45 foods), Wageningen UR, The Netherlands (25 foods) and the University of Illinois (20 foods). The results from 7 foods from earlier work using the same methodology [11] and part of the same overall study were also included in the analysis to give 97 foods in total.

At each site, approval from the appropriate animal ethics committee was obtained as follows: Riddet Institute, Massey University Animal Ethics Committee, protocol number 20/85; University of Illinois, Institutional Animal Care and Use Committee, protocol number 19131; Wageningen University, Dutch Council on Animal Experiments and Animal Welfare Body of Wageningen University, AVD104002015326.

The same protocol for the pig studies was followed at each experimental site according to previously published procedures [14]. In short, healthy female pigs of a commercial maternal line [Landrace or Large White (Yorkshire) breed type or their crosses] were used. A minimum bodyweight at surgery was 25 kg and maximum bodyweight at the end of the study was 100 kg. Animals were housed individually in smooth-sided pens (minimum 1.2 × 1.5 m) with slatted floors. The room temperature was kept at 21–24°C (thermoneutral zone), with a 12-h

TABLE 1
Foods and food ingredients included in the studies and their designated classification and preparation.

Classification	Food or ingredient	Source	Country of origin	Preparation
Algae and fungi	Quorn	Gluten-free quorn pieces	The Netherlands	Simmered in water and cut to 0.25 cm pieces
	Seaweed	YakiNori roasted, Yama products BV	The Netherlands	Cut up and ground
	Spirulina	Organic powder, Eco Mundo	The Netherlands	Fed as received
Baked products	Biscuits	Oreo cookies, Nabisco	United States	Broken up
	Breakfast cereal	Cheerios, Uncle Tobys	Australia	Mixed with warm water
	Cornflakes	Kellogg's	Australia	Cut into 0.2 cm pieces
	Corn tortillas	La Morena yellow corn tortillas	Mexico	Cut into 0.5 cm pieces
	Corn chips	Doritos chips, Bluebird Foods Ltd	New Zealand	Compressed to break up
	Rice crackers	Original rice toast, van der Meulen	The Netherlands	Broken into 0.2 cm pieces
	Wheat crackers	Wheat Thins 100% whole grain, Nabisco	United States	Broken into 1–2 cm pieces
Dairy products	Casein	Lactic Casein 720, Fonterra	New Zealand	Fed as received
	Casein (micellar)	Bulk Powders	Australia	Fed as received
	Cheddar cheese	Albert Heijn Cheddar	The Netherlands	Grated
	Feta cheese	Dodoni Feta Cheese	Greece	Cut into 0.2 cm pieces
	Liquid (bovine) milk	Campina semiskimmed milk, pasteurized	The Netherlands	Fed as received
	Sheep milk powder	Whole sheep milk, Spring Sheep NZ, Blue River Dairy and Maui Milk	New Zealand and Australia	Fed as received
	Ricotta cheese	From whole milk, Galbani	United States	Fed as received
	Skim milk powder	1% fat, Fonterra	New Zealand	Fed as received
	Whey protein concentrate	80% protein	Germany	Fed as received
	Whey protein isolate	WPI 894, New Zealand Milk Powders	New Zealand	Fed as received
	Yogurt	All Natural Plain Unsweetened Yogurt, De Winkel	New Zealand	Unflavored. Fed as received
Eggs	Egg (whole)	Free range medium sized eggs	The Netherlands	Boiled in water, peeled then cut to 0.2 cm pieces
	Egg white	Desugared and spray dried pasteurized egg white powder, supplier: Davis Trading	Italy	Spray dried and pasteurized; fed as received
Fish and seafood	Fish—salmon	Fillets, King Salmon	New Zealand	Oven cooked to 52°C internal temp then flaked
	Fish—sardines	Boneless, skinless, wild caught *Sardina pilchardus*, Season	Morocco	Tinned in olive oil
	Fish—tilapia fillets	*Oreochromis niloticus*	Indonesia	Boiled for 10 min then cut to 0.25 cm pieces
	Mussels	Greenshell mussel meat, deshelled	New Zealand	Simmered with water then diced 1 cm
	Shrimps	Precooked and peeled	China/Vietnam/Thailand	Cut to 0.5–1.0 pieces
Fruit	Apple	Fresh Gala variety	New Zealand	Fresh, cored and grated
	Avocado	Mixture of different varieties	New Zealand	Fresh, lightly mashed
	Banana	Bonita	Ecuador	Fresh, lightly mashed
	Coconut	Dessicated long thread with SO2 Primex	Philippines	Fed as received
	Cooked plantain	Dole plantains	Guatamala	Diced 1–2 cm then boiled with water
	Dates	Dried Medjool dates, van Wijck	The Netherlands	Cut to 0.2 cm pieces
	Pear	Beurre bose cultivar	New Zealand	Fresh, cored and grated
Grains	Amaranth	Supplied by de Notenshop	The Netherlands	Simmered with water 25 min
	Barley	Dry pearled barley grains, Harraways	New Zealand	Cooked in rice cooker with water
	Brown rice	Long grain Jasmine rice	Thailand	Cooked in rice cooker with water
	Buckwheat	Smaakt Buckwheat biologic	The Netherlands	Simmered with water 25 min
	Millet	Smaakt millet by Albert Heijn	The Netherlands	Simmered with water
	Oatmeal	Quaker oatmeal	The Netherlands	Simmered with water 15 min
	Polenta	Medium cornmeal (320) supplier: Davis Trading	New Zealand	Simmered with water 15 min then oven baked 45 mins
	Quinoa	White grain, supplier: Davis Trading	New Zealand	Soaked 10 mins then cooked in rice cooker
	Rye bread (wholeseed)	Fresian style bread baked at WUR	The Netherlands	Cut to 1 cm pieces
	Sorghum	Sorghum flour	United States	Simmered with water
	White rice		Thailand	Cooked in rice cooker with water

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TABLE 1 (*continued*)

Classification	Food or ingredient	Source	Country of origin	Preparation
		Thai Hom Mali rice, Royal Umbrella		
Isolates and concentrates	Bovine collagen	CiPro HBC, DC Ingredients	Denmark	Fed as received
	Casein	Lactic Casein 720, Fonterra	New Zealand	Fed as received
	Micellular casein	Bulk Powders	Australia	Fed as received
	Pea protein isolate	Isolated pea protein powder from yellow peas supplier: Nuts.com	China	Fed as received
	Potato protein isolate	Coagulated potato protein, Avebe	The Netherlands	Fed as received
	Soybean isolate	Isolated soy protein powder with <0.1% lecithin, supplier: Nuts.com	China	Fed as received
	Whey protein concentrate	80% protein	Germany	Fed as received
	Whey protein isolate	WPI 894, New Zealand Milk Powders	New Zealand	Fed as received
Meat	Beef tenderloin	Choice grain-fed beef, boneless, barrel cut, Halperns	United States	Roasted to 63°C internal temperature, diced 1–2 cm
	Chicken	Chicken breast	The Netherlands	Boiled then diced 0.25 cm
	Chicken-based luncheon	Tegel	New Zealand	Diced to 0.5 cm
	Turkey breast	Skin on, boneless, Gordon	United States	Roasted to 74°C internal temperature then diced 1 cm
Nuts	Almonds	Carmel Supreme almonds, processed with hammer mill	United States	Raw
	Cashews	Cashew kernels, processed with hammer mill	Vietnam	Raw
	Peanuts	Blanched, deshelled, dehusked, processed with hammer mill	Argentina	Blanched and dehusked
	Peanut butter	Smooth peanut butter, Brooks Fine Foods	India	Fed as received
Plant-based burger	Plant-based burger	Soya protein based, Harvest Gourmet Sensational Burger, Nestle	Malaysia	Baked in oven 200°C for 14 min then diced 1 cm
Pulses	Black beans	Dried, supplier: Davis Trading	Canada	Soaked then pressure cooked in water then lightly mashed
	Yellow chickpeas	Canned in brine, Sofia	Italy	Drained
	Black chickpeas	Dried, supplier: Davis Trading	India	Soaked, pressure cooked in water then lightly mashed
	Haricot beans	Dry navy beans, Gordon	United States	Soaked, pressure cooked in water then lightly mashed
	Kidney beans	Canned, Albert Hejn	The Netherlands	Drained, cut to 0.2 cm
	Mung bean	Green mung beans	Australia	Pressure cooked in water
	Pigeon peas	Dhal Toor	Canada	Soaked then pressure cooked in water
	Pinto beans	Whole dry pinto beans	United States	Soaked then pressure cooked in water
Seeds	Chia seeds	Black, non-GM, nonirradiated, supplier: Nuts.com	Bolivia	Soaked in water overnight
	Linseed	Broken biologic by Albert Heijn	The Netherlands	Raw
	Pumpkin seeds	"Shine skin" heat treated, Brooks Fine Foods	China	Kernels pulsed 15 times in food processor
	Sunflower seeds	Raw, supplier: Nuts.com	United States	Broken in food processor
Roots and tubers	Cassava	Fresh, Le Fe	Costa Rica	Simmered with water, diced 1–2 cm
	French fries	Potato (96%) and cannola with dextrose, supplier: Davis Trading	New Zealand	Oven cooked, cut to 2 cm lengths
	Potato (boiled)	Agria cultivar	The Netherlands	Pressure cooked and diced 0.2 cm
	Sweet potatoes (boiled)	Kumara	New Zealand	Diced 1 cm, simmered with water then mashed
	Yam	Red yams	New Zealand	Diced to 1 cm then roasted in oven
Soy products	Edamame (soybeans)	Shelled, blanched, grade A, by Simplot	China	Simmered with water
	Soy milk	Original flavor, shelf stable by Silk, Danone	United States	Fed as received
	Soyabean isolate	Isolated soy protein powder with <0.1% lecithin, supplier: Nuts.com	China	Fed as received
	Tofu	Firm tofu by Hing	New Zealand	Diced to 2 cm
Vegetables	Cabbage	White, jumbo, by Michael Farms	United States	Fresh, diced to 1–2 cm
	Carrots	Markon from Grimmway Farms	United States	Simmered with water, diced to 1–2 cm
	Corn kernels	Frozen kernels by Watties	New Zealand	Immersed in hot water briefly twice

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TABLE 1 (*continued*)

Classification	Food or ingredient	Source	Country of origin	Preparation
	Edamame (soybeans)	Shelled, blanched, grade A, by Simplot	China	Simmered with water
	Green beans	Grade A whole green beans by Gordon	United States	Simmered with water, diced 1–2 cm
	Mushrooms	White mushroom, *Agaricus bisporus*	The Netherlands	Cut to 1–2 mm slices, steamed, diced 0.2 cm
	Peas	Green peas, frozen by Watties	New Zealand	Simmered with water
	Pumpkin	Crown (gray) Whangaparoa pumpkin	New Zealand	Cubed then simmered with water, mashed
Wheat products	Bagel	Wheat kettle boiled by Just Bagels	United States	Baked to golden brown, diced 1–2 cm
	Couscous	Medium Dari Coucous	Morocco	Soaked with boiling water
	Multigrain bread	Lower Carb 5 seed bread with 21% seeds by Freyas	New Zealand	Diced 1–2 cm
	Unleavened (flat) bread	Made in house with wheat flour and water	New Zealand	Diced 1–2 cm
	Wheat bread	Baked at Illinois University	United States	Toasted lightly, diced 1–2 cm
	Wheat flour	Commercial wheat flour	The Netherlands	Fed as received
	Wheat noodles (pasta)	Dry fettucine made from Durum wheat	Italy	Simmered in water, cut to 3 cm lengths
	Whole wheat bread	Whole wheat bread, by Aunt Millie's	United States	Diced 1–2 cm
Wheat bran cereal	Wheat bran cereal	All Bran cereal by Kelloggs	New Zealand	Soaked in water
Yeast	Yeast	Inactive yeast from Speerstra	The Netherlands	Fed as received
Zein	Zein	Sigma product Z3625, food grade	United States	Fed as received

Abbreviations: GM : genetically modified; WUR : Wageningen University and Research.

light/dark cycle. Fresh water was freely available to all animals at all times.

Throughout the study, the daily dietary ration for each pig was 0.08 × metabolic bodyweight ($kg^{0.75}$) calculated on a DM basis. The daily ration was given in 2 equal meals 9 h apart (08:00 and 17:00). Individual pig weights were recorded weekly and the daily ration for each pig was then adjusted according to the bodyweight of the pig.

After the pigs were adapted to the environment and basal diet for a period of ≥8 d, a titanium T-cannula was surgically inserted into the end of the small intestine (terminal ileum) of each pig. The pigs were then given a minimum of 7 d to recover from surgery prior to starting the assay phase with the basal diet provided during this period as well.

The black bean, collagen, chickpea, wheat bread, wheat bran and zein diets were received by 18 pigs (6 pigs in each laboratory; $n = 18$), the whey protein isolate diet and pigeon pea diets were received by 36 pigs (12 pigs in each laboratory; $n = 36$) and the sorghum diet was received by 35 pigs (12 pigs in 2 laboratories and 11 pigs in 1 laboratory; $n = 35$) as detailed by Hodgkinson et al. [17]. The remaining diets were each administered to 6 pigs in the same laboratory with the individual pig serving as the experimental unit ($n = 6$) in each case. Pigs were randomly allotted to their diets according to a Latin Square or incomplete Latin Square design (Youden Squares) with animal and period comprising the rows and the columns of the squares, respectively. Thus, the order that the pigs received the diets differed within each Youden Square but no pig received the same diet for >1 experimental period. Individual pigs received ≤10 different test diets plus the protein-free diet as described below. As the diets were visually distinguishable and most required different preparation protocols, they were not blinded to the researchers.

Test cycles for each test food had a 7-d duration with the initial 5 d being the adaptation period to the diet. Digesta were collected from the opened cannula for 9 h on days 6 and 7 starting immediately after the first meal of the day was provided. Small plastic bags were attached to the cannula barrel using a zip tie or elastic. Bags were replaced whenever filled with digesta or at least once every 30 min and the digesta were immediately frozen (–20°C).

Each pig also received a protein-free diet for 7 d, which allowed for the calculation of endogenous AA from each pig as a control for the correction for ileal endogenous (nondietary) AA excretions on an individual basis. Thus, the pig was its own control for the correction of endogenous AAs. Feeding the protein-free diet and subsequent collection of ileal digesta were carried out in the same manner as for the test diets. To minimize possible carry over effects from the protein-free diet to subsequent diets, the basal diet was fed to the pigs for a period of 7 d after feeding the protein-free diet, before additional test diets were provided.

Chemical analyses

Digesta were thawed, but maintained at <4°C. After pooling and mixing the digesta, a subsample of the digesta from each pig and diet was collected and freeze-dried. All samples were ground through a 1 mm sieve. Ingredients, test diets and digesta samples were subsampled using standard sampling procedures. Samples were analyzed for dry matter according to the method described by Association of Official Analytical Collaboration (AOAC) [18]; titanium following the method of Short et al. [19] or using inductively coupled plasma optical emission spectrometry [20].

The AA contents including methionine and cysteine of the test foods, test diets, and ileal digesta samples were determined using methods described by Rutherfurd et al. [21] involving a 24-h acid hydrolysis period. Performic acid oxidation was used in the case of the sulfur AAs and tryptophan content was determined using the method described by AOAC [18] involving a 20-h alkaline hydrolysis. The weight of each AA was calculated using free AA molecular weights and no correction was made for potential destruction/further release of AAs during the 24-h hydrolysis. Values for proline are not reported as when the pigs consume the protein-free diet; there are high losses of proline related to muscle breakdown [22], which results in inaccuracies when TID values of proline are determined in foods.

The reactive lysine content of the foods was determined as described by Moughan and Rutherfurd [23]. When the reactive lysine of a test food was found to be less than the total lysine, it was assumed that lysine damage may have occurred in that food and the digesta samples corresponding to that food were also analyzed for reactive lysine content. The chemical analyses, except for reactive lysine, were conducted at each laboratory where the samples were generated. All reactive lysine analyses were conducted at the Riddet Institute or Wageningen University.

Calculations

The ileal AA concentrations (AA, normalized to the ingestion of 1 g of dry matter intake; DMI) were determined with reference to the marker titanium, using the following equation:

$$\text{Ileal AA}(\mu\text{g}/\text{gDMI}) = \frac{\text{Concentration of AA in digesta }(\mu\text{g/g DM}) \times \text{Diet titanium }(\mu\text{g/g DM})}{\text{Digesta titanium }(\mu\text{g/g DM})}$$

True ileal AA digestibilities were calculated:

$$\text{True digestibility }(\%) = \frac{\text{Dietary AA }(\mu\text{g/gDMI}) - (\text{IlealAA}(\mu g/\text{gDMI}) - \text{Endogenous AA }(\mu\text{g/gDMI}))}{\text{Dietary AA }(\mu\text{g/gDMI})} \times 100$$

Values for gut endogenous AA were those determined for each pig fed the protein-free diet.

Results

The TID of AA in each food/ingredient is reported in Table 2 and the SEM for the TID of each AA in each food is given in Supplemental Table 4. Due to unevenly distributed data and means, median values for TID of AA for each food group are presented in Table 3, along with the number of foods that were analyzed in each food group. TID of AA was high (mean of AAs >0.90) for dairy products, eggs, fish, and seafood, isolates and concentrates, meat, nuts, plant-based burgers, soy products, and wheat products. The food groups with mean TID of AA (Table 3) lower than 0.80 were baked products, fruit, pulses, seeds, wheat bran cereal, yeast, and zein. Overall, the mean of the median TID values for AA ranged from a low of 62% for fruit to a high of 97% for meat.

The SDs of TID of AA within each category are shown in Table 4. The food categories with the lowest SDs, thus the lowest variations between foods within the category, were fish and seafood (1% units), dairy products (3% units), and eggs (5% units) whereas those with the greatest variation within the categories were grains (18% units), vegetables (16% units), seeds (14% units), and fruit (12% units).

Table 5 provides the range in TID of AA for each category, expressed as mean values ± SD. The ranges were relatively small for the food categories fish and seafood, dairy products and eggs, with more variation for the food groups vegetables, grains, seeds and fruit.

Discussion

The TID of AA values for foods are required to provide bioavailability data for foods and to allow an assessment of protein quality. This necessitates the collection of digesta from the end of the small intestine. There are methods that have been developed to measure TID of AA in humans such as naso-ileal intubation [24] or with the participation of ileostomates [25]. However, neither method is straightforward and such approaches cannot be applied routinely to evaluate the quantity of foods that require evaluation [26]. In view of this, the growing pig has been recommended as an animal model for protein digestion in the adult human [7]. The true ileal AA digestibility of 7 of the same foods (from the same batch) evaluated in the present study have also been evaluated with human ileostomates [11]. The foods evaluated included foods from a range of categories (dairy product, isolates and concentrates, pulses, wheat product, wheat bran, zein) and spanned the range of digestibilities (true ileal mean AA digestibilities from 60% to 98%). The pig and human digestibility values were very similar, with a linear regression equation for digestibility coefficients for the mean of all AA of (y = human, x = pig) $y = 1.00x - 0.010$. This supports the use of TID values determined in pigs (such as in the present study) to accurately predict digestibility for human nutrition. Ideally, in vitro digestibility methods such as the INFOGEST method [27] would be used to routinely predict TID of AA. However, more validation is required to ensure that the results obtained with the current in vitro digestion methods accurately predict in vivo values.

The protein quality of chickpeas and mung beans has been determined using the dual isotope method in humans [28] with mean digestibilities for the indispensable AA of 77 and 63% for chickpeas and mung beans, respectively. These values are lower

TABLE 2

Mean true ileal digestibility of nitrogen and amino acids for foods and food ingredients determined in the growing pig, and number of observations (n).

	Almonds	Amaranth	Apple[1]	Avocado	Bagel	Banana	Barley	Beef tenderloin	Black beans	Black chickpeas	Buckwheat
n[2]	6	6	6	6	6	6	6	6	18	6	6
Nitrogen	0.723	0.398	0.247	0.727	0.885	0.607	0.788	1.000	0.660	0.718	0.827
Histidine	0.882	0.437	0.000	0.728	0.954	0.718	0.766	0.987	0.748	0.860	0.819
Isoleucine	0.840	0.416	0.288	0.786	0.968	0.721	0.771	0.990	0.790	0.799	0.841
Leucine	0.867	0.396	0.235	0.772	0.968	0.708	0.801	0.995	0.801	0.781	0.842
Reactive lysine	0.876	0.671	0.607	0.904	0.720	0.350	0.765	0.991	0.860	0.869	0.960
Methionine	0.895	0.519	0.779	0.792	0.963	0.730	0.834	0.990	0.777	0.721	0.883
Phenylalanine	0.879	0.447	0.429	0.677	0.982	0.661	0.811	0.987	0.800	0.813	0.867
Threonine	0.790	0.403	0.176	0.589	0.960	0.638	0.730	0.984	0.712	0.736	0.825
Tryptophan	0.846	0.494	—	0.840	1.000	0.453	0.711	0.995	0.733	0.703	0.832
Valine	0.833	0.370	0.123	0.708	0.959	0.658	0.760	0.996	0.750	0.762	0.827
Total lysine	0.890	0.514	0.607	0.904	0.715	0.350	0.765	0.991	0.824	0.870	0.878
Alanine	0.788	0.307	0.100	0.745	0.802	0.628	0.655	1.000	0.743	0.751	0.810
Arginine	0.846	0.600	—	0.910	0.844	0.454	0.846	1.000	0.877	0.911	0.935
Aspartic acid	0.874	0.376	0.278	0.608	0.912	0.595	0.612	0.988	0.685	0.661	0.846
Cysteine	0.910	0.592	—	0.504	0.942	0.190	0.805	0.910	0.346	0.754	0.861
Glutamine	0.917	0.532	0.266	0.795	0.980	0.758	0.895	0.991	0.825	0.815	0.885
Glycine	0.714	0.363	—	0.753	0.786	0.111	0.582	1.000	0.614	0.643	0.770
Serine	0.823	0.419	—	0.663	0.956	0.558	0.756	1.000	0.757	0.755	0.868
Tyrosine	0.782	0.454	0.556	0.780	0.983	0.728	0.800	0.975	0.799	0.783	0.846

	Cabbage[1]	Carrots	Casein	Casein, micellular	Cashew nuts	Cassava	Cheerios	Cheese feta	Cheese ricotta	Cheese, cheddar	Chia seeds	Chicken
n[2]	6	6	6	6	6	6	6	6	6	6	6	6
Nitrogen	0.758	1.000	0.943	0.952	0.877	0.934	0.879	0.976	1.000	0.992	0.286	0.979
Histidine	0.855	0.697	0.968	0.967	0.921	0.795	0.500	0.990	0.979	0.990	0.449	0.973
Isoleucine	0.793	0.807	0.905	0.902	0.905	0.933	0.843	0.974	0.950	0.962	0.429	0.963
Leucine	1.000	0.766	0.971	0.974	0.917	0.834	0.899	0.987	0.972	0.988	0.428	0.969
Reactive lysine	—	0.870	0.972	0.965	0.955	1.000	0.850	0.987	1.032	0.986	0.545	0.986
Methionine	0.730	0.944	0.962	0.957	0.750	0.943	0.875	0.984	0.992	0.980	0.455	0.974
Phenylalanine	0.971	0.803	0.981	0.992	0.918	0.854	0.880	0.989	0.971	0.989	0.418	0.963
Threonine	0.797	0.446	0.930	0.963	0.864	0.672	0.499	0.973	0.889	0.982	0.339	0.956
Tryptophan	1.000	1.000	0.978	0.987	0.974	0.984	0.837	0.981	0.985	0.981	0.496	0.940
Valine	0.953	0.822	0.932	0.930	0.906	0.912	0.810	0.978	0.956	0.976	0.374	0.960
Total lysine	—	0.806	0.972	0.965	0.955	0.540	0.847	0.983	0.941	0.982	0.331	0.971
Alanine	1.000	1.000	0.921	0.934	0.870	0.918	0.851	0.954	1.000	0.960	0.352	0.974
Arginine	0.988	1.000	0.971	0.977	0.930	0.971	0.909	0.978	1.000	0.980	0.517	0.990
Aspartic acid	0.772	0.879	0.922	0.937	0.919	0.922	0.562	0.970	0.940	0.972	0.451	0.954
Cysteine	0.757	0.177	0.781	0.918	0.851	0.765	0.778	0.955	0.945	0.985	0.359	0.909
Glutamine	0.918	0.847	0.918	0.906	0.946	0.904	0.915	0.974	0.938	0.970	0.491	0.971
Glycine	1.000	1.000	0.964	1.000	0.945	0.480	0.876	0.951	1.000	0.969	0.310	0.994
Serine	0.809	0.727	0.777	0.773	0.899	0.834	0.832	0.937	0.883	0.941	0.438	0.967
Tyrosine	0.813	0.874	0.980	1.000	0.895	0.900	0.828	0.988	0.984	0.989	0.472	0.963

(continued on next page)

TABLE 2 (*continued*)

	Chickpeas, yellow	Coconut	Collagen[1]	Corn Tortillas	Cornflakes	Couscous	Dates[1]	Dorito corn chips	Edamame	Egg white powder	Egg, boiled	Fish, white
n[2]	18	6	18	6	6	6	6	6	18	6	6	6
Nitrogen	0.640	0.842	0.790	0.466	0.702	0.930	—	0.839	0.955	0.820	0.904	0.949
Histidine	0.844	0.928	0.841	0.597	0.698	0.973	—	0.893	0.893	0.833	0.851	0.927
Isoleucine	0.834	0.869	0.897	0.680	0.751	0.997	—	0.892	0.881	0.829	0.920	0.951
Leucine	0.853	0.901	0.883	0.843	0.902	0.993	—	0.944	0.881	0.856	0.928	0.959
Reactive lysine	0.921	1.000	0.899	0.020	0.239	1.000	—	0.918	0.908	0.870	0.949	0.983
Methionine	0.869	0.818	0.903	0.737	0.873	0.906	0.341	0.973	0.891	0.883	0.952	0.968
Phenylalanine	0.884	0.916	0.876	0.802	0.854	0.995	—	0.923	0.903	0.860	0.931	0.952
Threonine	0.761	0.671	0.822	0.493	0.677	0.921	—	0.782	0.833	0.779	0.874	0.937
Tryptophan	0.813	0.992	0.478	0.398	0.397	0.921	—	0.906	0.816	0.814	0.875	0.922
Valine	0.820	0.865	0.894	0.661	0.767	1.000	—	0.873	0.880	0.837	0.914	0.946
Total lysine	0.887	1.000	0.898	0.120	0.051	1.000	—	0.873	0.908	0.870	0.910	0.965
Alanine	0.810	0.875	0.921	0.651	0.824	0.906	—	0.895	0.927	0.844	0.914	0.955
Arginine	0.943	0.943	0.944	0.251	0.571	0.873	—	0.854	0.987	0.887	0.940	0.976
Aspartic acid	0.734	0.902	0.677	0.278	0.588	0.951	0.349	0.832	0.880	0.795	0.822	0.913
Cysteine	0.683	0.804	—	0.577	0.728	0.966	0.180	0.891	0.745	0.746	0.858	0.886
Glutamine	0.874	0.963	0.892	0.654	0.847	0.987	0.409	0.923	0.911	0.866	0.910	0.962
Glycine	0.657	0.976	0.867	0.141	0.426	0.772	—	0.793	0.935	0.817	0.908	0.970
Serine	0.826	0.834	0.809	0.494	0.760	0.957	—	0.834	0.872	0.817	0.811	0.940
Tyrosine	0.869	0.851	0.821	0.779	0.872	0.965	—	0.849	0.890	0.849	0.919	0.948

	Green beans	Haricot beans	Kidney beans	Kumara	Linseed	Luncheon	Milk liquid	Millet	Mung beans	Mushrooms	Mussel, green lipped	Oatmeal
n[2]	6	6	6	6	6	6	6	6	18	6	6	6
Nitrogen	0.858	0.966	0.741	0.897	0.603	0.992	0.917	0.688	0.786	0.775	0.959	0.828
Histidine	0.810	0.862	0.723	0.934	0.610	0.982	0.953	0.686	0.814	0.554	0.931	0.814
Isoleucine	0.829	0.855	0.780	0.891	0.622	0.989	0.855	0.699	0.807	0.873	0.963	0.825
Leucine	0.820	0.873	0.795	0.885	0.637	0.991	0.942	0.711	0.836	0.875	0.959	0.847
Reactive lysine	1.000	0.881	0.928	0.939	0.821	0.999	0.965	0.857	0.818	0.956	0.972	0.941
Methionine	0.879	0.848	0.767	0.971	0.654	0.965	0.940	0.769	0.815	0.852	0.931	0.871
Phenylalanine	0.824	0.876	0.824	0.890	0.638	0.983	0.954	0.707	0.860	0.887	0.950	0.858
Threonine	0.725	0.816	0.700	0.931	0.580	1.000	0.870	0.705	0.774	0.835	0.957	0.767
Tryptophan	0.845	0.911	0.655	0.814	0.662	1.000	0.917	0.695	0.798	0.862	0.965	0.813
Valine	0.820	0.852	0.737	0.874	0.609	0.994	0.885	0.707	0.804	0.856	0.948	0.821
Total lysine	0.856	0.881	0.810	0.939	0.682	0.999	0.965	0.703	0.818	0.895	0.972	0.799
Alanine	0.849	0.916	0.718	0.914	0.591	0.990	0.879	0.692	0.703	0.893	0.951	0.799
Arginine	1.000	1.000	0.864	1.000	0.709	1.000	0.957	0.792	0.823	0.946	0.951	0.892
Aspartic acid	0.836	0.761	0.668	0.917	0.621	0.971	0.896	0.683	0.736	0.863	0.936	0.790
Cysteine	0.643	0.608	0.327	0.823	0.708	0.942	0.909	0.797	0.473	0.585	0.850	0.855
Glutamine	0.832	0.868	0.835	0.905	0.692	0.976	0.883	0.712	0.856	0.900	0.958	0.897
Glycine	0.795	1.000	0.634	0.873	0.661	1.000	0.916	0.658	0.445	0.752	0.993	0.792
Serine	0.796	0.872	0.783	0.875	0.623	0.994	0.750	0.731	0.796	0.860	0.915	0.835
Tyrosine	0.750	0.845	0.771	0.926	0.607	0.953	0.949	0.723	0.787	0.885	0.942	0.844

(*continued on next page*)

TABLE 2 (*continued*)

	Oreo biscuits	Pasta	Pea protein isolate	Peas, green	Peanut	Peanut Butter	Pear[1]	Pigeon peas	Pinto beans	Plant-based burger	Plantain	Polenta
n[2]	6	6	6	6	6	6	6	36	18	6	6	6
Nitrogen	0.553	0.852	0.924	0.905	0.815	0.926	0.266	0.850	0.677	0.927	0.718	0.877
Histidine	0.625	0.931	0.940	0.899	0.885	0.935	—	0.884	0.699	0.937	0.809	0.959
Isoleucine	0.725	0.952	0.941	0.921	0.883	0.976	0.523	0.886	0.752	0.927	0.688	0.906
Leucine	0.765	0.971	0.942	0.930	0.911	0.978	0.461	0.885	0.767	0.925	0.632	0.952
Reactive lysine	0.731	0.872	0.977	0.950	0.891	0.941	—	0.950	0.810	0.940	1.000	0.963
Methionine	0.702	0.865	0.892	0.903	0.534	0.957	0.500	0.857	0.744	0.967	0.577	0.850
Phenylalanine	0.765	0.974	0.950	0.933	0.924	0.982	0.476	0.890	0.774	0.924	0.662	0.930
Threonine	0.509	0.957	0.887	0.912	0.827	0.932	0.525	0.821	0.652	0.853	0.388	0.978
Tryptophan	0.941	0.701	0.883	0.925	0.553	0.915	0.299	0.800	0.678	0.891	0.932	0.698
Valine	0.685	0.954	0.924	0.920	0.880	0.974	0.398	0.862	0.700	0.897	0.641	0.882
Total lysine	0.236	0.826	0.977	0.950	0.847	0.941	—	0.924	0.810	0.940	0.693	0.882
Alanine	0.638	0.833	0.909	0.890	0.883	0.926	0.249	0.856	0.625	0.896	0.737	0.930
Arginine	0.103	0.784	0.963	0.938	0.941	0.962	—	0.960	0.749	0.998	1.000	0.859
Aspartic acid	0.454	0.854	0.943	0.907	0.918	0.939	0.168	0.868	0.623	0.827	0.653	0.796
Cysteine	0.695	0.913	0.830	0.846	0.551	0.965	—	0.685	0.398	0.866	—	0.891
Glutamine	0.851	0.982	0.966	0.940	0.941	0.967	0.526	0.915	0.798	0.948	0.648	0.931
Glycine	0.049	0.612	0.886	0.745	0.925	0.845	—	0.753	0.405	0.948	0.922	0.637
Serine	0.663	0.932	0.930	0.891	0.875	0.921	0.082	0.868	0.696	0.898	0.448	0.882
Tyrosine	0.717	0.951	0.929	0.934	0.925	0.967	1.000	0.881	0.713	0.950	0.535	0.905

	Potato	Potato fries	Potato protein isolate	Prawns	Pumpkin	Pumpkin seeds	Quinoa	Quorn	Rice cracker	Rice, brown	Rice, white	Rye bread
n[2]	6	6	6	6	6	6	6	6	18	6	6	6
Nitrogen	0.708	0.934	0.940	0.967	0.601	0.668	0.854	0.806	0.616	0.899	0.951	0.456
Histidine	0.682	0.917	0.913	0.957	0.684	0.661	0.967	0.740	0.709	0.908	0.933	0.412
Isoleucine	0.733	0.914	0.931	0.967	0.386	0.615	0.921	0.901	0.655	0.873	0.917	0.476
Leucine	0.774	0.937	0.948	0.969	0.454	0.644	0.925	0.910	0.637	0.848	0.898	0.499
Reactive lysine	0.844	0.972	0.959	1.001	0.878	0.708	0.943	0.973	0.855	0.978	1.000	0.166
Methionine	0.820	0.923	0.953	0.990	0.453	0.645	0.946	0.927	0.577	0.779	0.797	0.468
Phenylalanine	0.806	0.939	0.944	0.949	0.486	0.631	0.918	0.907	0.672	0.863	0.907	0.607
Threonine	0.701	0.892	0.933	0.941	0.240	0.574	0.916	0.813	0.606	0.859	0.941	0.396
Tryptophan	0.600	0.912	0.907	0.922	0.485	0.752	0.942	0.865	0.675	0.903	0.940	0.293
Valine	0.756	0.916	0.933	0.948	0.371	0.609	0.897	0.883	0.676	0.876	0.915	0.443
Total lysine	0.820	0.972	0.934	0.978	0.585	0.708	0.919	0.899	0.754	0.978	1.000	0.149
Alanine	0.636	0.914	0.943	0.978	0.434	0.618	0.889	0.882	0.625	0.854	0.922	0.356
Arginine	0.843	0.984	0.969	1.000	0.819	0.671	0.952	0.944	0.773	0.931	0.963	0.510
Aspartic acid	0.875	0.940	0.913	0.925	0.561	0.690	0.883	0.840	0.633	0.879	0.920	0.254
Cysteine	0.638	0.720	0.892	0.772	0.814	0.650	0.939	0.710	0.577	0.825	0.845	0.512
Glutamine	0.822	0.969	0.940	0.973	0.629	0.682	0.927	0.886	0.635	0.828	0.860	0.735
Glycine	0.268	0.781	0.968	1.000	0.141	0.645	0.800	0.773	0.488	0.976	1.000	0.190
Serine	0.645	0.891	0.924	0.939	0.241	0.545	0.933	0.864	0.595	0.845	0.903	0.515
Tyrosine	0.787	0.925	0.951	0.968	0.487	0.627	0.880	0.892	0.659	0.818	0.889	0.490

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TABLE 2 (*continued*)

	Salmon	Sardines	Seaweed	Seed bread	Sheep milk powder	Skim milk powder	Sorghum	Soy milk	Soybean isolate	Spirulina	Sunflower seeds	Sweet corn
n[2]	6	6	6	6	6	6	35	6	18	6	6	6
Nitrogen	0.964	0.889	0.822	0.675	0.952	0.959	0.840	0.776	0.897	0.768	0.657	0.848
Histidine	0.967	0.901	0.818	0.742	0.986	0.976	0.876	0.760	0.954	0.758	0.785	0.848
Isoleucine	0.968	0.885	0.843	0.729	0.946	0.914	0.889	0.766	0.934	0.780	0.772	0.839
Leucine	0.971	0.890	0.888	0.766	0.983	0.981	0.902	0.769	0.936	0.784	0.774	0.887
Reactive lysine	0.980	0.993	0.968	0.731	0.972	0.969	0.909	0.796	1.000	0.867	0.939	0.884
Methionine	0.959	0.889	0.912	0.655	0.973	0.981	0.933	0.662	0.942	0.863	0.810	0.868
Phenylalanine	0.968	0.871	0.841	0.773	0.994	0.982	0.887	0.796	0.946	0.811	0.775	0.869
Threonine	0.965	0.844	0.784	0.635	0.934	0.941	0.818	0.697	0.918	0.798	0.687	0.699
Tryptophan	0.974	0.882	0.802	0.610	0.945	0.986	0.880	0.880	0.949	0.702	0.895	0.762
Valine	0.970	0.878	0.853	0.698	0.946	0.941	0.876	0.750	0.934	0.747	0.746	0.823
Total lysine	0.980	0.873	0.865	0.770	0.972	0.969	0.879	0.796	0.897	0.802	0.675	0.884
Alanine	0.969	0.881	0.893	0.681	0.925	0.972	0.886	0.744	0.834	0.769	0.631	0.875
Arginine	0.986	0.951	0.921	0.684	0.949	1.000	0.937	0.874	0.891	0.847	0.792	0.794
Aspartic acid	0.957	0.725	0.842	0.628	0.960	0.926	0.889	0.741	0.946	0.781	0.737	0.805
Cysteine	0.860	0.667	0.582	0.680	0.949	0.840	0.819	0.539	0.846	0.725	0.797	0.788
Glutamine	0.972	0.874	0.874	0.844	0.943	0.931	0.887	0.826	0.967	0.803	0.826	0.890
Glycine	1.000	0.850	0.703	0.722	0.935	1.000	0.894	0.674	0.886	0.856	0.535	0.620
Serine	0.964	0.862	0.852	0.713	0.830	0.823	0.838	0.717	0.938	0.758	0.684	0.806
Tyrosine	0.964	0.880	0.901	0.762	0.932	0.995	0.882	0.736	0.931	0.811	0.709	0.821

	Tofu	Turkey breast	Unleavened bread	Wheat bran cereal	Wheat crackers[1]	Wheat flour	Whey protein concentrate	Whey protein isolate	White bread
n[2]	6	6	6	18	6	6	6	36	18
Nitrogen	0.933	0.985	0.928	0.610	0.489	0.941	0.942	0.960	0.940
Histidine	0.959	0.939	0.943	0.700	0.768	0.903	0.938	0.960	0.928
Isoleucine	0.942	0.956	0.835	0.716	0.849	0.945	0.955	0.970	0.921
Leucine	0.946	0.958	0.939	0.738	0.878	0.952	0.972	0.980	0.936
Reactive lysine	0.962	0.948	0.931	0.670	0.110	0.941	0.959	0.970	0.730
Methionine	0.939	0.967	0.855	0.759	0.824	0.961	0.917	0.980	0.946
Phenylalanine	0.951	0.943	0.948	0.761	0.884	0.963	0.959	0.950	0.944
Threonine	0.915	0.913	0.881	0.593	0.716	0.863	0.882	0.880	0.862
Tryptophan	0.939	0.941	0.914	0.671	0.866	0.891	0.961	0.970	0.912
Valine	0.930	0.950	0.955	0.680	0.834	0.936	0.927	0.930	0.913
Total lysine	0.951	0.948	0.914	0.497	0.095	0.882	0.959	0.970	0.823
Alanine	0.912	0.995	0.882	0.648	0.397	0.906	0.914	0.930	0.864
Arginine	0.955	0.995	0.922	0.799	0.380	0.982	0.916	0.970	0.917
Aspartic acid	0.938	0.907	0.776	0.484	0.657	0.895	0.943	0.960	0.824
Cysteine	0.848	0.785	0.972	0.533	0.778	0.906	0.969	0.970	0.910
Glutamine	0.955	0.954	0.965	0.853	0.898	0.983	0.939	0.950	0.971
Glycine	0.854	1.000	0.880	0.546	—	0.966	1.000	0.980	0.832
Serine	0.932	0.925	0.888	0.676	0.745	0.939	0.864	0.880	0.909
Tyrosine	0.927	0.952	0.917	0.730	0.838	0.952	0.942	0.960	0.947

(*continued on next page*)

TABLE 2 (*continued*)

	Whole wheat bread	Yams	Yeast	Yogurt	Zein
n	6	6	6	6	18
Nitrogen	0.707	0.759	0.726	0.933	0.690
Histidine	0.837	0.802	0.772	0.955	0.780
Isoleucine	0.862	0.821	0.803	0.932	0.750
Leucine	0.890	0.761	0.812	0.973	0.780
Reactive lysine	0.510	0.961	0.875	0.935	0.000
Methionine	0.859	0.939	0.753	0.935	0.780
Phenylalanine	0.906	0.761	0.825	0.977	0.760
Threonine	0.779	0.699	0.674	0.940	0.740
Tryptophan	0.964	0.682	0.738	0.930	0.000
Valine	0.856	0.758	0.789	0.947	0.770
Total lysine	0.513	0.894	0.842	0.935	0.000
Alanine	0.688	0.705	0.679	0.916	0.780
Arginine	0.675	1.002	0.848	0.923	0.760
Aspartic acid	0.745	0.675	0.775	0.937	0.770
Cysteine	0.852	0.366	0.613	0.891	0.730
Glutamine	0.946	0.923	0.837	0.938	0.780
Glycine	0.470	0.203	0.553	0.878	0.780
Serine	0.845	0.645	0.607	0.872	0.770
Tyrosine	0.909	0.818	0.797	0.970	0.780

[1] When true ileal digestibility of an amino acid is below detection limits, a dash (—) is given in the table.
[2] Number of observations.

TABLE 3
Median true ileal digestibility of amino acids in the food categories and the number of foods included within each category.

	Algae and fungi	Baked products	Dairy products	Eggs	Fish and seafood	Fruit	Grains	Isolates and concentrates	Meat	Nuts
Histidine	0.76	0.70	0.97	0.94	0.93	0.72	0.82	0.94	0.98	0.90
Isoleucine	0.84	0.75	0.95	0.93	0.96	0.70	0.84	0.93	0.98	0.89
Leucine	0.88	0.88	0.97	0.92	0.96	0.67	0.85	0.95	0.98	0.91
Reactive lysine	0.97	0.73	0.97	0.94	0.98	0.76	0.94	0.97	0.99	0.92
Methionine	0.91	0.82	0.97	0.97	0.96	0.73	0.83	0.94	0.97	0.82
Phenylalanine	0.84	0.85	0.98	0.92	0.95	0.66	0.86	0.95	0.97	0.92
Threonine	0.80	0.61	0.93	0.85	0.94	0.56	0.82	0.89	0.97	0.85
Tryptophan	0.80	0.84	0.98	0.89	0.92	0.65	0.81	0.96	0.97	0.88
Valine	0.85	0.77	0.94	0.90	0.95	0.65	0.83	0.93	0.98	0.89
Mean IAA	0.85	0.77	0.96	0.92	0.95	0.68	0.84	0.94	0.98	0.89
Total lysine	0.86	0.24	0.97	0.94	0.97	0.65	0.88	0.96	0.98	0.92
Alanine	0.88	0.65	0.93	0.90	0.95	0.68	0.81	0.92	0.99	0.88
Arginine	0.92	0.57	0.97	1.00	0.98	0.68	0.89	0.96	1.00	0.94
Aspartic acid	0.84	0.59	0.94	0.83	0.92	0.60	0.80	0.94	0.96	0.92
Cysteine	0.71	0.73	0.95	0.87	0.85	0.18	0.83	0.85	0.91	0.88
Glutamine	0.87	0.85	0.94	0.95	0.96	0.65	0.89	0.94	0.97	0.94
Glycine	0.77	0.43	0.97	0.95	0.99	0.43	0.77	0.96	1.00	0.88
Serine	0.85	0.75	0.86	0.90	0.94	0.50	0.84	0.88	0.98	0.89
Tyrosine	0.89	0.83	0.98	0.95	0.95	0.75	0.84	0.94	0.96	0.91
Overall mean[1]	0.84	0.73	0.95	0.92	0.95	0.62	0.84	0.93	0.97	0.90
Number	3	7	11	2	5	6	11	9	4	4

	Plant-based burger	Pulses	Seeds	Roots and tubers	Soy products	Vegetables	Wheat products	Wheat bran cereal	Yeast	Zein
Histidine	0.94	0.83	0.64	0.80	0.92	0.83	0.93	0.70	0.77	0.78
Isoleucine	0.93	0.80	0.62	0.89	0.91	0.83	0.93	0.72	0.80	0.75
Leucine	0.92	0.82	0.64	0.83	0.91	0.88	0.95	0.74	0.81	0.78
Reactive lysine	0.94	0.87	0.76	0.96	0.93	0.91	0.80	0.67	0.88	—
Methionine	0.97	0.80	0.65	0.94	0.91	0.87	0.89	0.76	0.75	0.78
Phenylalanine	0.92	0.84	0.63	0.85	0.92	0.88	0.96	0.76	0.82	0.76
Threonine	0.85	0.75	0.58	0.70	0.87	0.76	0.87	0.59	0.67	0.74
Tryptophan	0.89	0.77	0.71	0.81	0.91	0.85	0.91	0.67	0.74	—
Valine	0.90	0.78	0.61	0.87	0.90	0.84	0.94	0.68	0.79	0.77
Mean IAA	0.92	0.81	0.65	0.85	0.91	0.85	0.91	0.70	0.78	0.77
Total lysine	0.94	0.85	0.68	0.89	0.90	0.88	0.82	0.50	0.84	0.00
Alanine	0.90	0.75	0.60	0.91	0.87	0.89	0.85	0.65	0.68	0.78
Arginine	1.00	0.89	0.69	0.98	0.92	0.97	0.86	0.80	0.85	0.76
Aspartic acid	0.97	0.80	0.66	0.94	0.91	0.87	0.89	0.76	0.75	0.78
Cysteine	0.83	0.71	0.68	0.92	0.91	0.85	0.84	0.48	0.77	0.77
Glutamine	0.95	0.85	0.69	0.91	0.93	0.90	0.98	0.85	0.84	0.78
Glycine	0.95	0.64	0.59	0.48	0.87	0.77	0.78	0.55	0.55	0.78
Serine	0.90	0.79	0.58	0.83	0.90	0.81	0.92	0.68	0.61	0.77
Tyrosine	0.95	0.79	0.62	0.90	0.91	0.85	0.95	0.73	0.80	0.78
Overall mean[1]	0.92	0.79	0.64	0.85	0.91	0.86	0.89	0.69	0.76	0.77
Number	1	8	4	5	4	8	8	1	1	1

Abbreviation: IAA, indispensable amino acids.
[1] Reactive lysine was included in the mean value, total lysine was not.

than those determined in the present study with the pig (84% and 81%). Although the preparation of the mung beans was similar in both the previous and present study, the chickpeas evaluated in the previous study were pressure cooked, whereas those in the present study were canned. This difference in processing may explain the differences in results for chickpeas. It should be noted, however, that when AA digestibility results obtained using the dual isotope method have been directly compared with those from naso-ileal intubation (considered the reference standard method), quite different results have been reported [29]. The indicator AA oxidation (IAAO) technique has also been used to evaluate chickpeas with a reported metabolic availability for methionine of 63% [30]. The IAAO technique determines metabolic availability which would be expected to be lower than the TID of AA, as was the case when the results are compared with those obtained in the present study (87% for methionine in yellow chickpeas).

A strength of the present study was that reactive (available) lysine was determined for all of the foods. When foods are subjected to heat and pressure, a proportion of lysine will be altered structurally and become nutritionally unavailable [31]. However, some of the altered lysine reverts to lysine under the acid hydrolysis conditions used during AA analysis. Altered lysine molecules may be partly absorbed but are not utilized postabsorption. Other AAs such as methionine and tryptophan may also be damaged during processing [32,33], but other AAs

TABLE 4

SDs and coefficient of variation[1] (CV, %) of true ileal digestibility of amino acids within each food category and the number of foods included in each food category.

Amino acid	Algae and fungi		Baked products		Dairy products		Eggs		Fish and seafood		Fruit	
	SD	CV	SD	CV	SD	CV	SD	CV	SD	CV	SD	CV
Histidine	0.04	4.6	0.13	18.5	0.02	1.7	0.01	1.5	0.01	2.8	0.17	78.7
Isoleucine	0.06	7.2	0.09	11.9	0.04	3.9	0.06	7.4	0.01	3.7	0.09	32.5
Leucine	0.07	7.8	0.11	12.5	0.01	1.3	0.05	5.7	0.01	3.6	0.10	38.5
Reactive lysine	0.06	6.3	0.39	73.6	0.02	2.4	0.06	6.1	0.00	1.2	0.17	63.1
Methionine	0.03	3.7	0.13	16.6	0.02	2.5	0.05	5.3	0.01	4.1	0.07	27.8
Phenylalanine	0.05	5.8	0.09	10.4	0.02	1.6	0.05	5.6	0.01	4.1	0.07	27.2
Threonine	0.02	2.3	0.12	19.1	0.04	4.3	0.07	8.2	0.01	5.2	0.08	37.6
Tryptophan	0.08	10.4	0.23	32.6	0.02	2.5	0.04	5.1	0.01	4.0	0.16	67.9
Valine	0.07	8.6	0.08	11.2	0.03	2.7	0.05	6.2	0.01	3.7	0.11	46.6
Mean IAA	0.05	6.3	0.15	22.9	0.02	2.5	0.05	5.7	0.01	3.6	0.11	46.7
Total lysine	0.05	5.7	0.38	89.3	0.02	1.6	0.03	3.1	0.01	4.8	0.15	62.4
Alanine	0.07	8.0	0.17	24.8	0.03	3.5	0.05	5.6	0.01	4.0	0.13	55.6
Arginine	0.05	5.5	0.31	57.1	0.03	2.8	0.04	4.1	0.00	2.2	0.19	85.1
Aspartic acid	0.03	4.1	0.17	30.2	0.02	2.4	0.02	2.4	0.02	10.6	0.10	50.1
Cysteine	0.08	12.4	0.11	15.8	0.06	6.8	0.08	9.9	0.02	11.1	0.12	128.2
Glutamine	0.04	5.1	0.12	14.9	0.03	2.8	0.03	3.5	0.01	4.4	0.09	38.6
Glycine	0.08	10.8	0.35	88.7	0.04	4.2	0.06	7.4	0.01	6.7	0.19	102.4
Serine	0.06	6.9	0.13	18.0	0.06	7.5	0.00	0.5	0.01	4.2	0.13	76.3
Tyrosine	0.05	5.5	0.08	9.9	0.02	2.4	0.05	5.6	0.01	3.8	0.07	23.9
Overall mean[2]	0.06	7.3	0.17	32.4	0.03	4.1	0.05	4.9	0.01	5.9	0.12	70.0
Number	3	7	11	2	5	6						

	Grains		Isolates and concentrates		Meat		Nuts		Pulses	
	SD	CV	SD	CV	SD	CV	SD	CV	SD	CV
Histidine	0.20	25.0	0.04	4.3	0.02	2.2	0.03	2.9	0.07	8.8
Isoleucine	0.18	22.8	0.02	2.7	0.02	1.8	0.06	6.3	0.04	5.3
Leucine	0.18	22.9	0.03	3.2	0.02	1.8	0.05	5.0	0.04	5.3
Reactive lysine	0.24	29.1	0.03	3.2	0.02	2.3	0.04	4.2	0.05	5.8
Methionine	0.16	19.8	0.03	3.4	0.01	1.2	0.19	23.9	0.06	6.9
Phenylalanine	0.15	19.0	0.03	3.4	0.02	2.1	0.04	4.6	0.04	5.1
Threonine	0.20	25.9	0.04	4.5	0.04	4.0	0.06	7.1	0.06	7.8
Tryptophan	0.20	27.0	0.16	17.9	0.03	3.4	0.19	22.7	0.08	11.2
Valine	0.19	24.5	0.01	1.4	0.02	2.4	0.06	6.5	0.06	7.3
Mean IAA	0.19	24.0	0.04	4.9	0.02	2.3	0.08	9.3	0.06	7.1
Total lysine	0.25	32.1	0.04	3.9	0.02	2.3	0.05	5.5	0.04	5.1
Alanine	0.22	29.7	0.04	3.8	0.01	1.1	0.06	6.7	0.09	12.0
Arginine	0.15	18.0	0.03	3.2	0.00	0.5	0.05	5.6	0.08	9.0
Aspartic acid	0.22	30.9	0.09	9.7	0.03	3.6	0.03	3.0	0.08	10.6
Cysteine	0.13	16.1	0.30	39.0	0.07	7.9	0.18	22.5	0.17	31.6
Glutamine	0.12	14.7	0.03	2.8	0.02	1.6	0.02	2.2	0.04	4.4
Glycine	0.25	35.7	0.06	6.5	0.00	0.3	0.10	12.2	0.18	28.5
Serine	0.16	21.2	0.07	7.7	0.03	3.5	0.04	4.8	0.06	7.5
Tyrosine	0.16	20.4	0.05	5.3	0.01	1.1	0.08	8.9	0.06	6.9
Overall mean[2]	0.18	23.3	0.06	9.7	0.02	2.5	0.07	8.2	0.08	13.8
Number	11	9	4	4	8					

	Seeds		Roots and tubers		Soy products		Vegetables		Wheat products	
	SD	CV	SD	CV	SD	CV	SD	CV	SD	CV
Histidine	0.14	22.2	0.10	12.5	0.09	10.4	0.12	15.7	0.08	8.5
Isoleucine	0.14	23.0	0.08	9.5	0.08	9.2	0.17	21.4	0.09	9.8
Leucine	0.14	23.1	0.07	8.8	0.08	9.2	0.17	20.0	0.07	7.8
Reactive lysine	0.17	22.3	0.06	6.3	0.09	9.7	0.05	5.3	0.16	20.1
Methionine	0.15	22.7	0.06	6.3	0.13	15.5	0.16	19.5	0.10	11.4
Phenylalanine	0.15	24.0	0.07	8.2	0.07	10.5	0.15	18.1	0.07	7.6
Threonine	0.15	26.9	0.12	15.7	0.10	12.3	0.23	33.3	0.11	12.5
Tryptophan	0.17	23.8	0.16	19.9	0.06	6.8	0.17	19.8	0.14	15.7
Valine	0.15	26.4	0.08	9.6	0.09	9.8	0.18	22.6	0.09	10.4
Mean IAA	0.15	23.8	0.09	10.8	0.09	10.4	0.15	19.5	0.10	11.5
Total lysine	0.18	30.0	0.17	20.8	0.07	7.4	0.12	14.4	0.15	18.2
Alanine	0.13	24.0	0.14	16.6	0.08	9.8	0.18	21.0	0.09	11.1
Arginine	0.12	17.1	0.07	6.9	0.05	5.7	0.08	8.8	0.11	13.5
Aspartic acid	0.13	20.0	0.11	12.6	0.09	10.8	0.11	13.7	0.10	12.7
Cysteine	0.19	30.1	0.18	27.0	0.15	19.5	0.22	32.4	0.09	10.5

(continued on next page)

TABLE 4 (*continued*)

Glutamine	0.14	20.5	0.05	5.9	0.06	7.0	0.10	11.6	0.05	5.0
Glycine	0.16	30.1	0.30	57.4	0.11	13.6	0.28	37.4	0.16	20.6
Serine	0.11	18.5	0.12	15.8	0.10	11.9	0.21	28.3	0.08	9.1
Tyrosine	0.10	16.3	0.06	7.4	0.09	10.6	0.14	17.5	0.07	7.5
Overall mean[2]	0.14	23.0	0.11	18.7	0.09	11.1	0.16	21.3	0.10	11.3
Number	4	5	4	8	8					

Abbreviation: IAA, indispensable amino acids.

[1] (SD/mean) ×100.

[2] Reactive lysine was included in the mean value, total lysine was not.

have been less well studied, and assays to detect damage for other AAs have not been developed.

In the present study, foods and food ingredients were evaluated in pig studies carried out at 3 different laboratories. It is important to ensure consistency for AA digestibility of results between the laboratories and this was evaluated in previous work by determining the TID of AA of the same 9 foods in the growing cannulated pig in each of the 3 laboratories. The mean coefficient of variation between laboratories for digestibility of the indispensable AAs was 5.0% with an overall mean for all AAs of 5.5%. This demonstrated that there is little variation between these laboratories for TID of AA determined in the growing pig. A high degree of consistency was found both between and within laboratories [17]. In the present work, all of the laboratories used the same standardized method for the pig study and chemical analyses [14] based on recommendations from an FAO Expert Working Group [7]. The studies reported here were carried out in pigs in the weight range 25–100 kg. Pedersen et al. [34] evaluated the effect of bodyweight on the TID of AA. Although a difference in TID of AA was found in pigs with a body weight of <20 kg compared with larger pigs, no differences were found between pigs in the weight range of 20–50 kg and those >50 kg.

The growing pig was used to determine TID of AA for 97 foods such that the data would give an indication of the variation in TID in human foods. The foods were grouped into categories and median digestibility values determined for each category. The median values for true ileal AA digestibility could potentially be applied to predict digestibility values for other foods within the category.

Although the categorizing of foods in this way will always be to some degree subjective, this was initially done based on the FAO food groups, with some groups divided into several subcategories. For example, "cereal and cereal products" was divided into "grains," "pulses," with some incorporated into the "baked products" category. When dividing the groups, factors such as food category, source, and processing were considered. It is acknowledged that the number of foods in the different categories varied. This was due to the manner in which the foods were chosen, which was dependent on the amount of protein consumed via these foods in different countries as explained in the Methods. There are also foods that are commonly consumed in developing countries that were not included in this study and these need to be tested in future work.

It was decided to present the median values for true ileal AA digestibility in each food category (Table 3). Presenting the median values, as opposed to mean values, ensured that any outliers within the food categories did not unduly affect the results. The variation among foods in a category is indicated by the SD values presented in Table 4. The accuracy of using the median true ileal AA digestibility values presented in Table 3 to predict the digestibility values for other foods of the same type depends on the food category; for foods such as fish and seafood, dairy products and egg products, accurate results can be obtained. For dairy foods, for example, 11 different products were evaluated, and the mean SD between them was only 0.03 units (3% units). The small SD values for these food categories indicate that the median digestibility values can be used with confidence to estimate the digestibility of other foods within these categories.

However, the variation within the categories baked products, fruit, grains, seeds, roots and tubers and vegetables were much greater (>10 percentage units). Grains and seeds are often considered to be "good" protein sources. The results indicate that care must be taken in the use of the median values to predict digestibility values for other foods in these food categories. Similar variation was previously reported when 8 cereal grains were tested for TID of AA, which ranged from 69% to 94% [35].

Statistically, it can be expected that 0.66 of the foods in a category will have digestibility values lying within the mean TID of AA ±1 SD (Table 5). For some food groups (e.g., dairy products, eggs, fish and seafood, isolates and concentrates and meat), there was little variation in TID of AA between foods within the category giving support to the use of median values to predict the TID of AA of other foods that would fall within these categories. Interestingly, the food categories with the lowest degree of variation were predominantly animal source proteins. The foods in these categories have high TID of AA values and relatively high protein contents and contain low concentrations of compounds such as fiber and few, if any, antinutritional factors. For other categories, however, such as baked products, fruit, grains, seeds, roots and tubers, and vegetables, there was a much greater variation in the TID of AA of the foods evaluated, and using the median TID of AA values (Table 3) for other foods in these categories will give an indicative AA availability only, but this indication cannot be expected to be of high accuracy. Within these categories, the foods will vary in terms of their nutritional contents, particularly in terms of carbohydrates such as fiber, which would explain an important part of the variability. Plant-based products may also contain antinutritional factors such as phytates, protease inhibitors (e.g., trypsin inhibitors) and tannins which may affect AA digestion, absorption, and utilization, thus decreasing AA digestibility [36,37]. Adhikari et al. [38] compiled TID of AA values from the literature and categorized them in a similar way to that in the present study and found similar levels of variation within the food categories as in the present study. For example, they reported the range of TID of the limiting AA within the category of 95%–99% for beef,

TABLE 5
Range in variability for true ileal digestibility of amino acids in food categories expressed as mean values ± 1 SD.

Amino acid	Algae and fungi	Baked products	Dairy products	Eggs	Fish and seafood	Fruit
Histidine	0.74–0.80	0.56–0.81	0.95–0.99	0.83–0.86	0.91–0.98	0.36–0.70
Isoleucine	0.78–0.90	0.68–0.86	0.90–0.97	0.81–0.94	0.93–0.94	0.56–0.73
Leucine	0.79–0.93	0.73–0.94	0.96–0.99	0.84–0.95	0.94–0.95	0.52–0.72
Reactive lysine	0.88–0.99	0.14–0.92	0.95–1.00	0.85–0.97	0.98–0.99	0.48–0.81
Methionine	0.87–0.93	0.66–0.93	0.94–0.99	0.87–0.97	0.94–0.96	0.58–0.72
Phenylalanine	0.80–0.90	0.74–0.91	0.96–0.99	0.84–0.95	0.94–0.96	0.57–0.71
Threonine	0.78–0.81	0.50–0.73	0.89–0.97	0.76–0.90	0.93–0.95	0.42–0.57
Tryptophan	0.71–0.87	0.48–0.95	0.94–0.99	0.80–0.89	0.92–0.94	0.42–0.75
Valine	0.76–0.90	0.67–0.84	0.92–0.97	0.82–0.93	0.93–0.94	0.46–0.67
Total lysine	0.81–0.90	0.05–0.80	0.95–0.98	0.86–0.92	0.94–0.96	0.44–0.74
Alanine	0.78–0.92	0.52–0.87	0.91–0.97	0.83–0.93	0.94–0.95	0.43–0.68
Arginine	0.85–0.95	0.24–0.86	0.94–0.99	0.87–0.96	0.97–0.98	0.36–0.74
Aspartic acid	0.79–0.85	0.40–0.74	0.92–0.97	0.79–0.84	0.87–0.91	0.41–0.60
Cysteine	0.59–0.75	0.60–0.83	0.86–0.99	0.72–0.89	0.79–0.82	0.12–0.36
Glutamine	0.81–0.90	0.70–0.94	0.91–0.96	0.86–0.93	0.94–0.96	0.53–0.71
Glycine	0.69–0.86	0.04–0.75	0.93–1.00	0.80–0.94	0.95–0.98	0.27–0.65
Serine	0.77–0.88	0.58–0.83	0.78–0.91	0.81–0.82	0.92–0.93	0.30–0.56
Tyrosine	0.82–0.91	0.71–0.87	0.95–1.00	0.83–0.94	0.93–0.95	0.67–0.81
	Grains	Isolates and concentrates	Meat	Nuts	Pulses	
Histidine	0.58–0.97	0.89–0.97	0.95–0.99	0.88–0.93	0.73–0.88	
Isoleucine	0.60–0.95	0.90–0.95	0.96–0.99	0.84–0.96	0.77–0.86	
Leucine	0.60–0.96	0.92–0.98	0.96–1.00	0.87–0.96	0.78–0.87	
Reactive lysine	0.57–1.07	0.94–1.00	0.96–1.00	0.88–0.95	0.83–0.93	
Methionine	0.63–0.94	0.90–0.97	0.96–0.99	0.60–0.97	0.74–0.86	
Phenylalanine	0.65–0.95	0.92–0.98	0.95–0.99	0.88–0.97	0.80–0.88	
Threonine	0.56–0.95	0.86–0.94	0.93–1.00	0.79–0.91	0.69–0.80	
Tryptophan	0.54–0.95	0.74–1.06	0.94–1.00	0.64–1.01	0.68–0.85	
Valine	0.57–0.95	0.91–0.94	0.95–1.00	0.84–0.96	0.73–0.84	
Total lysine	0.52–1.02	0.90–0.98	0.96–1.00	0.86–0.96	0.81–0.90	
Alanine	0.52–0.96	0.87–0.94	0.98–1.00	0.81–0.92	0.67–0.86	
Arginine	0.69–0.99	0.92–0.98	0.99–1.00	0.87–0.97	0.81–0.97	
Aspartic acid	0.50–0.94	0.82–1.00	0.92–0.99	0.89–0.94	0.64–0.79	
Cysteine	0.67–0.92	0.47–1.07	0.82–0.96	0.63–1.00	0.37–0.70	
Glutamine	0.70–0.95	0.91–0.96	0.96–0.99	0.92–0.96	0.81–0.89	
Glycine	0.45–0.95	0.87–1.00	1.00–1.00	0.75–0.96	0.46–0.83	
Serine	0.61–0.94	0.80–0.94	0.94–1.01	0.84–0.92	0.73–0.85	
Tyrosine	0.62–0.93	0.89–0.99	0.95–0.97	0.81–0.97	0.75–0.86	
	Seeds	Roots and tubers	Soy products	Vegetables	Wheat products	
Histidine	0.49–0.77	0.73–0.93	0.80–0.98	0.66–0.88	0.83–0.98	
Isoleucine	0.47–0.75	0.78–0.94	0.80–0.96	0.60–0.96	0.81–0.99	
Leucine	0.48–0.76	0.77–0.91	0.80–0.96	0.64–1.00	0.86–1.00	
Reactive lysine	0.59–0.92	0.89–1.00	0.83–1.01	0.87–0.98	0.64–0.97	
Methionine	0.50–0.79	0.86–0.98	0.73–0.99	0.64–0.97	0.78–0.98	
Phenylalanine	0.47–0.76	0.78–0.92	0.83–0.97	0.66–0.99	0.87–1.01	
Threonine	0.40–0.69	0.66–0.90	0.74–0.94	0.43–0.91	0.75–0.97	
Tryptophan	0.53–0.87	0.64–0.96	0.83–0.96	0.66–1.02	0.73–1.00	
Valine	0.43–0.74	0.76–0.92	0.79–0.96	0.60–0.99	0.82–1.01	
Total lysine	0.42–0.78	0.66–1.01	0.82–0.95	0.70–0.96	0.66–0.96	
Alanine	0.42–0.68	0.69–0.95	0.77–0.94	0.66–1.04	0.73–0.92	
Arginine	0.56–0.79	0.90–1.03	0.87–0.98	0.84–1.01	0.72–0.95	
Aspartic acid	0.50–0.75	0.76–0.98	0.78–0.97	0.69–0.92	0.72–0.94	
Cysteine	0.44–0.82	0.49–0.84	0.60–0.89	0.43–0.89	0.80–0.99	
Glutamine	0.54–0.81	0.85–0.96	0.85–0.98	0.75–0.96	0.91–1.01	
Glycine	0.38–0.70	0.23–0.82	0.72–0.95	0.42–1.01	0.59–0.93	
Serine	0.47–0.68	0.66–0.90	0.76–0.97	0.51–0.96	0.81–0.98	
Tyrosine	0.51–0.70	0.81–0.94	0.78–0.96	0.65–0.94	0.85–1.00	

94%–101% for dairy, 77%–87% for nuts, and 13%–96% for cereals. Such wide ranges in TID of AA underly the need to have accurate information on AA digestibility in human foods. Previous studies that have determined TID of AA values for specific types of foods using the cannulated pig have reported similar findings in terms of TID of AA and similar degrees of variability for these values among foods to those in the present study. For example, Bailey et al. [39] reported high TID of AA values for a range of meat products with low variability between the products. Han et al. [40] determined TID of AA for 6 pulses and reported similar TID values as those in the present study and also a similar degree of variability between them.

For each of the food categories plant-based burger, wheat bran cereal, yeast and zein, there was only 1 product evaluated.

These products were included to provide indicative values, but it was not possible to provide an indication of variation within the category.

The range in TID for individual AA within foods was particularly notable in the present study (Table 2). For example, the TID values for cysteine in pulses such as black beans, kidney beans and mung beans (0.346, 0.327, and 0.473) were considerably lower than the TID of reactive lysine in the same foods (0.860, 0.928, and 0.818 for black beans, kidney beans and mung beans, respectively). The mean TID of AA for these pulses was 0.742, 0.736 and 0.761 for black beans, kidney beans and mung beans, respectively. It is particularly important to note that in terms of protein quality for these 3 products, the sulfur AA (methionine + cysteine) are first limiting, so if an mean value (e.g., N digestibility) is used to calculate indices such as DIAAS, their protein quality will be overestimated. This highlights the need to account for the TID of individual AA for accuracy in the evaluation of protein quality.

In conclusion, for foods that are within the categories dairy products, eggs, fish and seafood, isolates and concentrates and meat, the median values presented here can be used to estimate TID of AA with a high degree of confidence. However, for foods within the categories baked products, fruit, grains, seeds, roots and tubers and vegetables, use of the median values to estimate TID of AA may not give accurate values.

The study is a milestone for human nutrition. It is the first study to provide a stand-alone database with so many foods tested concomitantly by internationally recognized laboratories using a standardized methodology.

Author contributions

The authors' responsibilities were as follows – PJM, WHW, SMH, SdV, NvdW, HHS: responsible for planning the study; SMH, NS, HHS, NF, SdV, NvdW: conducted the studies; SMH, PJM: interpreted the data; SMH: prepared the first draft of the manuscript which was revised by PJM; and all authors: read and approved the final manuscript.

Conflict of interest

PJM reports financial support was provided by Project Proteos, funded by a consortium of food companies and food sectors, coordinated by Global Dairy Platform, Chicago, United States. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tjnut.2025.08.004.

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