Protein Quality in Consumer Products and Diets

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Abstract

Although dietary recommendations focus primarily on quantitative protein intake, protein quality is critical to consider as well. Large differences in dietary protein intake are observed globally, with diets dominated by plant protein sources typically being poorer in quality. This can be related to the less favorable amino acid composition and lower digestibility of plant proteins. The latter is related both to protein structure, but also to the presence of anti-nutritional compounds, such as trypsin inhibitors and tannins and phytates in some products. Food processing can also notably affect protein quality. Glycation of lysine residues in proteins, as a result of the Maillard reaction with reducing carbohydrates, can reduce protein quality notably, whereas processing-induced denaturation and aggregation of proteins can both improve and reduce protein quality. Processing-induced inactivation of trypsin inhibitors and removal of tannins and phytates can improve protein quality, but can should be taken that such processing does not cause negative impact via e.g., protein glycation. Overall, dietary protein quality is in intricate balance which should be considered on a consumer product, and not raw material or protein ingredient level. Dietary consideration at a meal level is essential to not ignore complementarity of protein sources.

Keywords: dietary protein, animal protein, plant protein, protein quality, digestibility, amino acids, food processing, anti-nutritional compounds; trypsin inhibitors; tannins; glycation; Maillard reaction.

Abbreviations

ANFs	Anti-nutritional factors
Arg	Arginine
DAAs	Dispensable amino acids
DIAAS	Digestible indispensable amino acid score
EAR	Estimated average requirement
EFSA	European Food Safety Authority
FAO	Food and Agriculture Organization
IAAs	Indispensable amino acids
Lys	Lysine
PDCAAS	Protein digestibility corrected amino acid score
RDA	Recommended dietary allowance

1. Introduction

1.1. The importance of protein

Proteins are a critical component of the human diet as they play a key role in growth and other essential functions of the human body (Grigg and Sheffield 1995; Qin, Wang, and Luo 2022; Hoffman and Falvo 2004). The primary role of protein in human growth was exemplified by Grasgruber and colleagues (2016), who found that males consuming a low protein diet were shorter in stature compared to those consuming a high-protein diet. Proteins are composed of amino acids linked together by peptide bonds (Wu 2016). There is a global variation in protein consumption, with regions and countries with higher and lower consumption (Reedy et al. 2019). Dietary proteins can be derived from animals or from plants sources (Hoffman and Falvo 2004). As the world's population increases, there is also a continuous increase in the demand for protein supplies (Henchion et al. 2017; Sá, Moreno, and Carciofi 2019).

Because the human body does not keep supplies of proteins or amino acids and is subject to daily losses of nitrogen as a result of protein turnover, a daily supply of dietary protein is required. Dietary protein serves as a source of indispensable amino acids (IAAs), but also as a nitrogen source for the synthesis of dispensable amino acids (DAAs). While recommended intake values for proteins have been established, e.g., 0.83 g of protein per kg of bodyweight per day for adults, it is not only the quantity of protein but also the quality of protein that is a critical factor in determining whether protein intake is sufficient to meet human requirements.

1.2. Protein quality

Within the context of protein quality, two key aspects play a role, i.e., amino acid composition and digestibility. In terms of amino acid composition, dietary proteins are a source of IAAs, i.e., those that the body cannot synthesize, for all of which specific requirements, based on age, exist. Furthermore, dietary proteins do not only contain IAAs, but also DAAs, which are essential sources of nitrogen in the amino acid synthesis in the body (Tessari 2018). In addition, digestibility of proteins is critical and may vary between different dietary protein sources. Such variability may arise from factors intrinsic to the protein, as well as extrinsic factors (Bos, Gaudichon, and Tomé 2000). Intrinsic factors in protein digestibility include both the amino acid sequence, as well as the folding of the protein. Long sequences in proteins without peptide bonds susceptible to hydrolysis by gastrointestinal proteases and peptidases can lead to peptides too large for the brush border peptidases and hence prevent uptake. Furthermore, specific folding of proteins may lead to peptide bonds being inaccessible to gastrointestinal proteases and peptidases. Inaccessibility may also be linked to extrinsic factors, e.g., the inaccessibility of peptide bonds due to interactions with other molecules, or even inaccessibility in the food matrix. Furthermore, the food matrix may also contain anti-nutritional factors (ANFs) which complex with the digestive enzymes which should either hydrolyze the proteins or break down other aspects of the food matrix to make the proteins accessible to proteases and peptidases (Adhikari et al. 2022).

When considering protein quality in the context of the human diet, it is important to consider, of course, that most foods consumed by humans have undergone one or more processing and preparation steps prior to consumption. While some of these steps are mild, and can, e.g., include the washing or removal of inedible parts, in other cases it can include extensive heat treatments or mechanical treatments, which can have a notable effect on the protein structure but also can result in amino acid modifications (Sá, Moreno, and Carciofi 2019). Product processing and preparation varies widely, not only based on the type of product, but also geographically as a result of availability, societal context and economic status. As such, generic proxies for protein quality in human diets are difficult to take, and a detailed look is required, as e.g., protein quality in boiled peas will vary from those of pea proteins in a pea protein concentrate or isolate which is subsequently applied in e.g., an extruded meat replacer or a sterilized beverage.

In this chapter we will consider the effects of transferring raw materials to consumer products on protein quality. First, we will briefly review assessment of protein quality in dietary protein sources. Next, we will provide an overview of global differences in dietary protein sources. Finally, we will describe the effects of food processing and preparation on protein quality.

2. Assessment of protein quality

With the aforementioned importance of protein quality in human diets, accurate assessment of protein quality parameters is critical. In this respect, a large body of work has focused on methodology for protein quality assessment. The area has been reviewed extensively by several groups (Adhikari et al. 2022; Wolfe et al. 2016). In general, assessment of both amino acid composition and digestibility is preferred. The digestible indispensable amino acid score (DIAAS) method, based on determination of ileal digestible levels of individual amino acids is the most favored methodology in this respect, whereas the protein digestibility corrected amino acid score (PDCAAS) method, based on fecal digestibility of total nitrogen is less favored but also provides useful insights. In vitro methods have been widely researched as well and recent methodology optimizations by Sousa et al. (2023) yield values comparable to DIAAS.

Previous methodologies, may not provide direct links to DIAAS or PDCAAS values, but, at least, often still offer relevant for studying for quantitatively assessing if treatments have an impact on protein digestibility. In this chapter, we will consider studies from all aforementioned techniques, i.e., DIAAS, PDCAAS as well as in vitro, for considering protein quality in global diets, as well as the impact of processing and preparation thereof.

3. Main sources of dietary protein: a global perspective

3.1. Total protein intake

According to the European Food Safety Authority (EFSA), the estimated average requirement (EAR) for healthy adults is 0.66 g protein/kg body weight per day and the recommended dietary allowance (RDA) is 0.83 g protein/kg body weight per day (EFSA 2012). Considering an average global body weight of ~62 kg, the RDA would be just over 50 g of protein per person per day. It has been shown that many people in the world consume more protein than required, particularly in some richer regions (Ranganathan et al. 2016). Beyond that, there are also others that consume less protein. An inadequate dietary protein intake has been associated with various health problems including anemia, physical weakness, edema, vascular dysfunction, and impaired growth and immunity (Wu 2016). Figure 1 shows protein intake, obtained from FAO food balance sheets, in 2020 for 220 countries and regions across the globe, indicating that protein intake varies widely; i.e., from < 30 to > 100 g per person per day, i.e., more than a 3-fold difference. Only 10 countries (9 African plus Haiti) did meet 50 g protein intake per person per day, whereas in all other countries, based on these estimates, average protein consumption did meet requirements. However, it should be noted that this are of course estimates for average intake, and do not account for e.g., inequal distribution of available protein between people within a population.

<insert Figure 1 here>

The main dietary protein suppliers are animal and plant food sources (Hoffman and Falvo 2004). In a study by Reddy et al. (2019) it was reported that the global animal protein intake was higher than plant protein intake, which is in line with trends shown in Figure 1. Furthermore, it has been shown that in 2015, the total protein intake worldwide was 78.2 g/day, with values between 61.0 g for the Middle East and North Africa and 92.5 g/day for Asia (Reedy et al. 2019), comparable to trends in Figure 1. Moreover, besides carbohydrates and fat also protein can serve as a source of energy for our body, although they are not the primary choice (Carreiro et al. 2016; Adhikari et al. 2022; Hoffman and Falvo 2004).

3.2. Main protein sources

The main sources of dietary proteins can derive from both animal or plant sources, but they vary in the protein content and in the amino acid composition as well (Grigg and Sheffield 1995; Hoffman and Falvo 2004). Animal proteins are those contained in foods of animal origin such as meat, poultry, fish, eggs and milk (Hoffman and Falvo 2004), while plant proteins are those contained in foods of plant origin including whole grain, legumes and nuts (Qin, Wang, and Luo 2022). The data in Figure 1 and 2 refer to the proportional protein intake from animal and plant plant-based protein sources, as well as, in the case of Figure 2, some unclassified foods (e.g., mixed foods) sources, in different countries. Figure 2 shows a variability in both animal and plant protein intake across the countries. For instance, the United States, Latin America and Europe (except of the general population in the United Kingdom) showed the highest animal protein intake (ranging from 57-70 % of total protein) (Hoy, Murayi, and Moshfegh 2022; Halkjær et al. 2009; Herrera-Cuenca et al. 2023). Instead in Malaysia the animal protein intake was similar with that of plant protein (50 *versus* 50 %) (Drewnowski et al. 2020).In Indonesia 65_% of dietary protein comes from plant sources, particularly from cereals and the rest from animal sources (35 %) (Figure 2) (Khusun et al. 2022). In a study by Reedy and colleagues (2019) it was reported that global animal protein intake was highest in Latin American and the Caribbean (42.8 g/day) and lowest in Sub-Saharan Africa (38.3 g/day). While Bangladesh and Nepal were the countries with the lowest mean national animal protein intake (7.2 g/day *versus* 10.1 g/day). Instead, global plant protein intake was highest inthe Middle East and North Africa (32.1 g/day) and lowest in the Former Soviet Union (25.5 g/day) (Reedy et al. 2019). However, it has been reported that the choice of a specific protein may depend on several factors such as education, ethnicity and religion (Drewnowski et al. 2020).

<insert Figure 2 here>

Tables 1 and 2 indicate that the meat and cereals are the main protein contributors in many diets. From Table 1 it can be observed that dairy products are considered the second source to animal protein after meat for the most part of countries, whereas for Indonesia and for some parts of Spain fish is considered the second contributor to animal protein. Furthermore, it has been shown that in some Eastern Africa countries, such as Burundi, Rwanda, Tanzania, and Uganda, the percentage of fish in animal protein intake was notably higher than the world average (Table 1) (Obiero et al. 2019). Instead, Table 2 shows that, vegetables are the most important plant protein suppliers after cereals in most countries followed by fruits, legumes and potatoes. Moreover, cakes and non-alcoholic beverages also contributed to plant protein in several countries, even if in a small percentage (cakes 2-7 % and non-alcoholic beverages 1-12 %; Table 2) (Halkjær et al. 2009). Instead, in the Philippines, 19 % of protein comes from plant sources such as rice (Table 2), followed by animal sources like 17 % from pork, 17 % from fish, and 5 % from egg and egg dishes (Table 1) (Angeles-Agdeppa and Custodio 2020).

<insert Table 1 here>

<insert Table 2 here>

3.3. Protein quality: differences between sources

When choosing a dietary protein, in addition to the quantity, it is very important to consider the quality as well. As discussed in Section 2 the quality of any protein can be determined by its amino acid composition and by its digestibility. Protein digestibility refers to the fraction of ingested protein that is hydrolyzed into amino acids, dipeptides and tripeptides that can be readily absorbed by the organism (Adhikari et al. 2022). In general, animal proteins have a higher nutritional quality than plant proteins due to their amino acid profile and to the higher digestibility (Qin, Wang, and Luo 2022; Vieux et al. 2022). It has been reported that animal proteins have a DIAAS (Digestible Indispensable Amino Acid Score) value higher than 90 % or even higher than 100 %, while most of plant proteins have a low quality with DIAAS value lower than 90 % with the exception of soy-based products and mung beans with DIAAS value higher than 90 % (Adhikari et al. 2022). Animal products like meat, poultry, eggs, milk and fish provide the highest-protein quality as they have complete protein with all essential amino acids that human body need (Hoffman and Falvo 2004). Furthermore, among these animal products, fish is an important source of protein for different countries. In particular, in Africa around 200 million people consume high-quality protein derived from fish (Obiero et al. 2019). Instead, plant products generally provide the lowest-protein quality as they often contain incomplete proteins, thus deficient in one or more essential amino acid (Hoffman and Falvo 2004). Hence, it has been suggested that to get all the essential amino acids from plant-based products is necessary to consume a variety of plant products.

3.4. Protein quality: differences between diets

The impact of different protein sources in diets is also reflected in the overall protein quality of diets. It has, for instance, been reported that true fecal digestibility of protein from diets in different parts of the world could vary from > 90 % to only just above 50 % (Table 3), even without considering amino acid composition as well (Gilani, Cockell, and Sepehr 2005). Similar variation was reported by Moughan (2021) who estimated DIAAS values for mixed diets in different countries in Asia and Africa. As shown in Figure 3, a wide variety was observed, with DIAAS values > 90 % observed for some developing countries (e.g., Thailand and Pakistan), whereas Nigeria and Ethiopia had estimated values < 70 %. This reflects large differences worldwide. In all cases, lysine was the first limiting amino acid in diets, which is typically a reflection of high levels of plant-based protein sources in diets. The differences in protein quality in global diets are important to consider. While data in Figure 1 indicate that protein intake in most countries could potentially be adequate, it is important to keep in mind that RDA's of 0.83 g protein per person per day are based on proteins with an ideal amino acid composition and complete digestibility, i.e., a DIAAS value of 100. Lower estimated DIAAS values for diets could thus mean even though protein intake looks adequate, digestible amino acid requirements are not met.

<insert Figure 3 here>

<insert Table 3 here>

The differences in protein quality between diets illustrated in Table 3 and Figure 3 highlight the key importance of not only considering protein quantity, but also quality. While excess indispensable amino acids in some protein sources can compensate for shortfalls in others, it is clear that in many diets, shortfalls will remain. While in some cases recommended daily intake values may be met, if protein quality is suboptimal, then issues will still arise. Furthermore, it has been argued by Adhikari et al. (2022) that complementarity of protein sources should be considered on a meal basis, and not a diet basis, which could lead to even lower values for protein quality on a diet basis if considered. Similar arguments were put forward recently in the consideration of nutrient-based frameworks for protein quality (Forester et al. 2023). In addition, it is important to consider that many protein quality data are derived from studies on protein ingredients and after not final consumer products. Further processing can impact protein quality, which is described further in Section 4.

4. Impact of food processing and preparation on protein quality: from raw material to consumer product

In the perspective of consumption of dietary protein, it is important to consider that virtually all the major dietary protein sources consumed worldwide will undergo various processing and preparation steps prior to consumption. E.g., while raw milk is consumed by some people, by far most milk produced worldwide is subjected to different treatments (e.g., heat treatment) or the milk is even converted into different products, like cheese or yoghurt (Walstra et al. 2005). Likewise, wheat is not consumed as such, but is typically first milled into a flour and subsequently forms the basis of a wide range of food products, including e.g., bread, which undergoes a substantial thermal processing during preparation (Shewry 2009). As such, while understanding protein quantities and quality parameters in raw materials is important, understanding the transitions of the proteins throughout the different stage from raw material to final product is also critical, as well as in other factors affecting their digestibility. Within this field of process-induced protein modifications, the following four aspects are considered most important:

(1) Process-induced changes in amino acids
(2) Process-induced changes in protein structure
(3) Process-induced changes in anti-nutritional compounds

4.1. Process-induced changes in amino acids

During processing of food, some process-induced changes in amino acids can occur. The most notable example is probably the glycation of Lys and Arg residues, which can occur as a first step in the Maillard reaction, between the amino group on the side chain of these amino acids and reducing sugars, such as glucose, fructose, maltose and lactose (Martins et al. 2001). The reaction is promoted by the application of heat, occurs at a higher rate at elevated pH (due to the fact that the reaction required the non-protonated amino groups) and has a strong dependence on water activity, with maximum rates often found in the water activity area 0.5 – 0.7 (Ames 1990). Examples of where these reactions happen include the baking or toasting of bread, processing of cereals, frying and grilling of meat products. Protein glycation can lead to substantial losses in (bio)available lysine. For cereal products, > 50 % of lysine may be unavailable (Rutherfurd and Moughan 2007). However, common at home preparation methods for meat (e.g., grilling, frying, etc) had only limited effect on bioavailable lysine in beef products (Hodgkinson et al. 2018). For dairy products, process-induced losses in available lysine are generally limited in most common dairy products, not exceeding 10 % of total lysine; for some products, e.g., evaporated milk products, which typically undergo sterilization treatments, higher losses in available lysine have been reported (Mehta and Deeth 2016). Overall, process-induced changes of amino acids, should be carefully considered, particularly given the importance of lysine as one of the most-limiting IAAs globally.

4.2. Processing-induced changes in protein structure

Proteins can be characterized by a primary, secondary, tertiary and sometimes even quaternary structure. These structures are subject to change based on changes in environmental conditions, including e.g., temperature, pH and ionic strength. Such changes may be reversible or irreversible. Irreversible changes often occur as a result of e.g., heat treatment, when denaturation of the protein occurs. As a result of denaturation, peptide bonds previously inaccessible to digestive proteases become accessible, which can lead to enhanced digestion. This has, for instance, been shown for the heat-induced denaturation of whey proteins (Peram et al. 2013) but also for pressure-induced denaturation of whey proteins (Zeece, Huppertz, and Kelly 2008), both of whey improved whey protein digestion in vitro. However, protein denaturation can also lead to (extensive) aggregation of proteins, which, in turn, can make parts of protein poorly accessible and reduce digestibility. This, for instance, has been observed in the case of proso millet protein (Gulati et al. 2017) and sorghum protein

(Duodu et al. 2003), where intermolecular formation of hydrophobic bonds and disulphide bonds. Overall, processing-induced changes protein conformation and its impact on protein digestibility is a topic that requires careful consideration. While e.g., heat treatments are often necessary in food processing to inactivate undesirable micro-organisms and enzymes, they will also affect digestibility.

4.3. Processing-induced changes in anti-nutritional compounds

In addition to proteins and other nutrients, food products can also contain compounds that can negatively affect the digestion and absorption of nutrients, including those that affect protein digestion. Herein, two different categories of effects can be considered, i.e., components that interact with the proteins and therewith affect digestibility, and components that affect protein digestibility via interactions with or effects on the digestive enzymes.

4.3.1. – Trypsin inhibitors

Enzyme inhibitors can impact digestibility of proteins foods. The most common inhibitor class in this respect are the so-called trypsin inhibitors, which not only affect trypsin, but also enzymes such as chymotrypsin and elastase. Of the most common protein sources in the human diet, soybeans contain the highest levels of trypsin inhibitors. Defatting of soybeans to create a soy flour does not change protein: trypsin inhibitor ratio. However, due to their proteinaceous nature, trypsin inhibitors are susceptible to heat-induced inactivation, which can occur e.g., during the toasting of soy flour, extrusion or heat treatments, such as sterilization, applied to extracts of soy proteins or products in which they are used. Typically, in e.g., soy protein concentrate, soy protein isolate, tofu or soy drink, trypsin inhibitor levels approximately 5-10-fold lower than in soybeans are reported (Anderson and Wolf 1995).

Autoclaving raw soybean flour has been shown to increase ileal digestibility of amino acids approximately 2-fold (Li, Sauer, and Caine 1998). Next to in soybeans, trypsin inhibitors are also present in other legumes, including e.g., many types of peas and beans, as well as cereals (Gilani, Cockell, and Sepehr 2005). Also here, reducing trypsin inhibitor activity is warranted to improve protein digestibility.

4.3.2 - Tannins

Tannins are water-soluble polyphenolic compounds which occur naturally in a range of foods important for human consumption, including sorghum, millet, barley and various beans and peas. Levels may reach tens of grams per kg of (dry) product. Their ability to interact with proteins and precipitate them from aqueous solutions, but also to interact with digestive enzymes, can lead to reduced digestibility of food proteins. An example is shown in Figure 4, showing the effect of the inclusion of a tannin-rich fraction of faba bean hull material on the digestion of casein in rats, where a linear decrease in digestibility was observed. Likewise, for faba bean protein, reduced digestibility has also been observed in high-tannin variants compared to low-tannin variants (Jansman et al. 1995). Next to concentrations in products, tannin levels in meals, and interaction between products should also be considered. This was illustrated nicely by Kashyap et al. (2019)who showed that the co-ingestion with tea reduced the digestibility of egg protein, compared to co-ingestion with water, presumably due to the tannins present in the tea. Common practices like dehulling, soaking and cooking can reduce tannin content in e.g., legumes.

<insert Figure 4 here>

4.3.3. Phytate

Another common antinutritional factor in food products is phytate, which can affect protein digestibility in two ways, i.e., through chelation of metal ions required in the active site of digestive enzymes or via direct complexation with the proteins. Phytate is found in e.g., nuts, seeds, legumes and grains. Phytate levels in cereals can be reduced through milling and refining, because more of the phytate is present in the bran of wheat, the germ of corn or the pericarp of rice, which are typically removed during refining processes. In legumes, however, most phytate is found in the cotyledon, together with the protein, so this is largely retained during fractionation and refinement. Phytase is heat-stable, but can be broken down by enzymes (phytase) and fermentation. Breakdown or removal of phytate has been shown to improve protein digestibility (Elliott et al. 2022), though overall effects of phytate on protein digestibility are smaller than those of trypsin inhibitors and tannins.

Mini dictionary of terms

Amino acid digestibility: fraction of amino acids that can be absorbed in the gastro-intestinal tracts after protein digestion.

Animal-based protein: dietary protein derived from animal-based sources, such as meat, fish, dairy and eggs.

Dispensable amino acids: amino acids that can be synthesized by the human body.

Indispensable amino acids: amino acids that cannot be synthesized by the human body.

Phytate: a phosphate ester present in plant-based foods and food ingredients that can impair protein digestion.

Plant-based protein: dietary protein derived from plant-based sources, such as grains, cereals, legumes, nuts and vegetables

Protein digestion: breakdown of proteins by gastro-intestinal enzymes

Protein glycation: non-enzymatic covalent bond formation between amines in proteins (mainly lysine residues) and reducing carbohydrates.

Protein quality: the extent to which a protein is able to provide indispensable amino acids in digestible form relative to a reference pattern.

Tannins: class of water-soluble polyphenols present in plant-based foods and food ingredients that can impair protein digestion

Summary points:

- Dietary protein quality strongly differs between countries and regions
- Higher animal protein intake is often related to higher dietary protein quality
- The presence of anti-nutritional factors can strongly reduce protein quality
- Protein glycation reduces protein digestibility and amino acid bioavailability
- Tannins and phytates can reduce protein digestibility via complexation with proteins and digestive enzymes
- Processing can reduce antinutritional factors but can also impair protein digestibility via glycation and protein aggregation
- Consideration of protein quality at a consumer product level rather than raw material level is critical

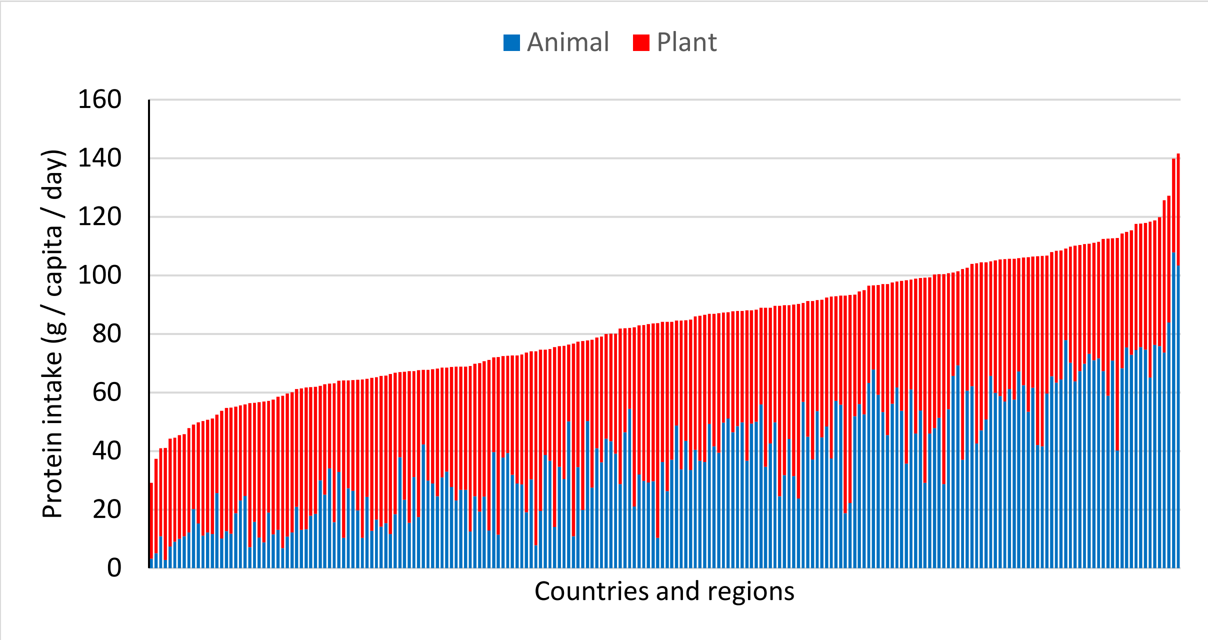

Figure 1: protein intake across countries and regions

Legend to Figure 1: Estimated protein intake (in g per capita per day) from animal-based and plant-based food sources for 220 countries and regions in 2020 (data from FAO food balance sheets).

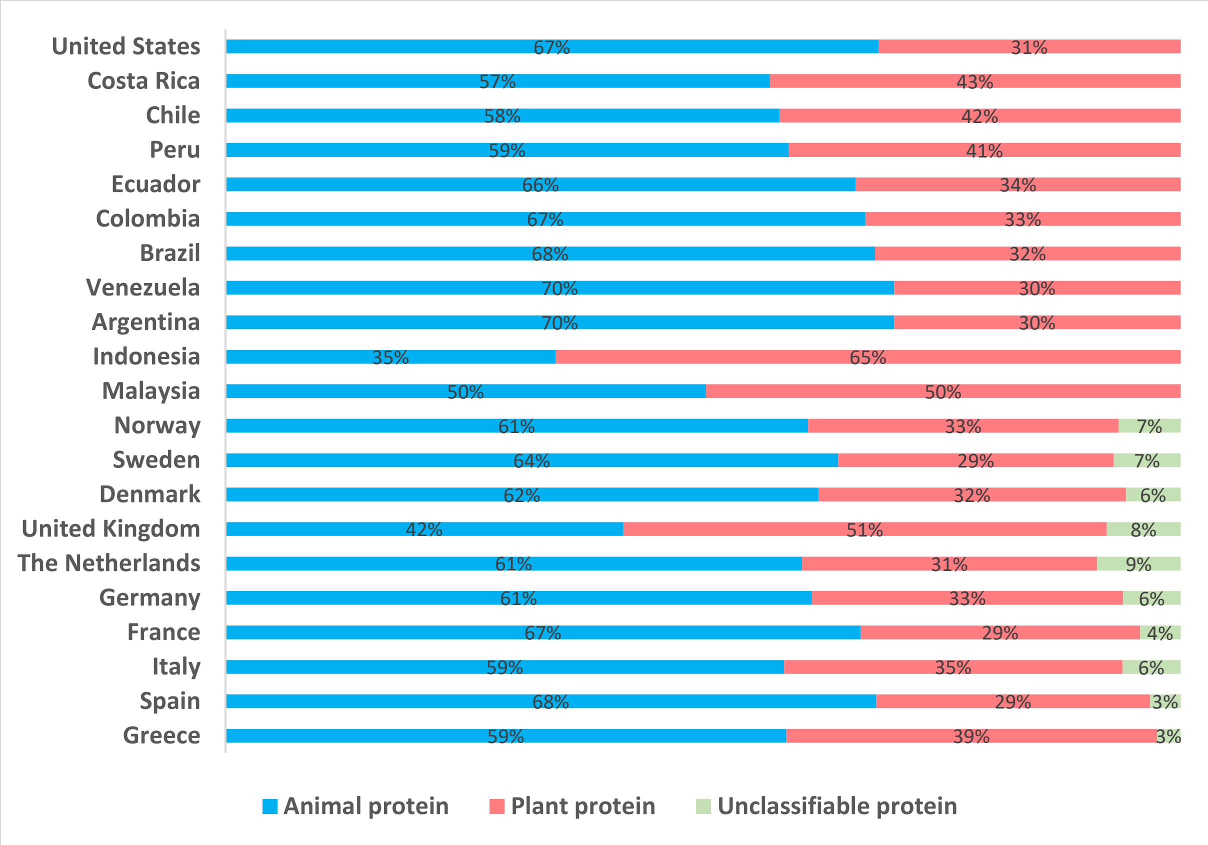

Figure 2: Global differences in protein intake from different sources

Legend to Figure 2: Calculated gender-averaged of total protein intake percentage (%) from animal, plant and unclassifiable food sources among different countries. Data for European countries from Halkjaer et al. (2009), for South American countries from Herrera-Cuenca et al. (2023), for United States from Hoy et al. (2022), for Indonesia from Khusun et al. (2022) and for Malaysia from Drewnowski et al. (2020).

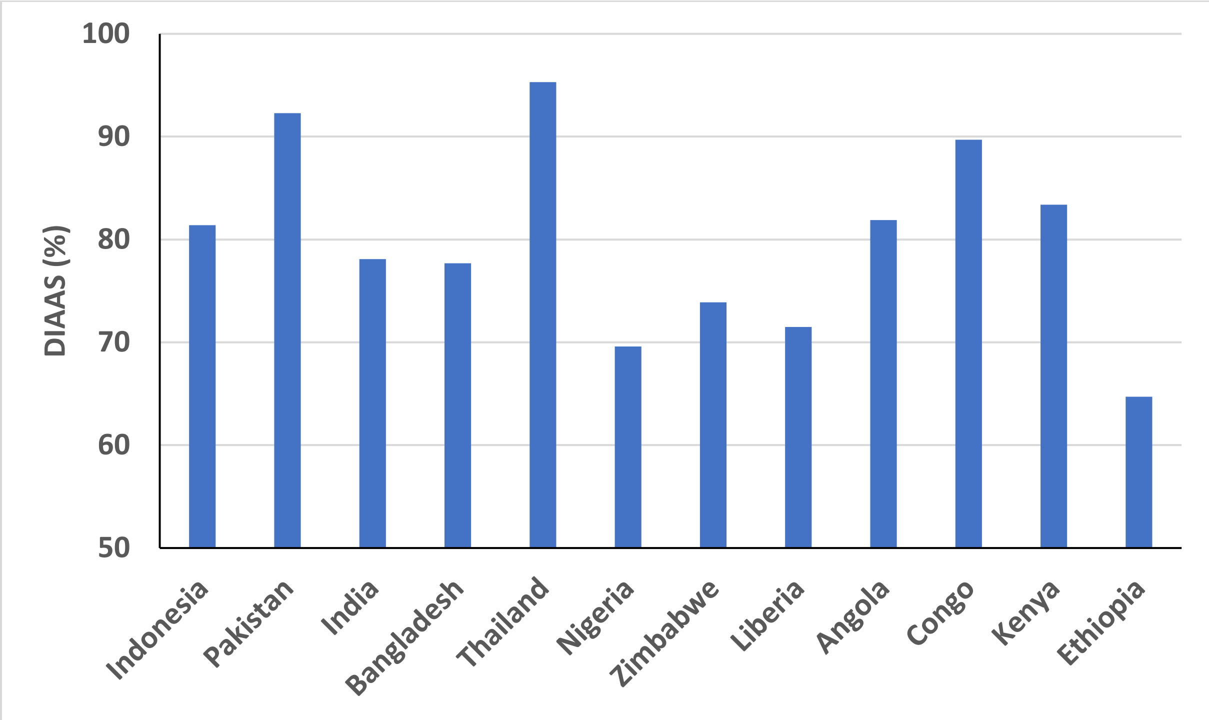

Figure 3: Protein quality in diets in different countries

Legend Figure 3: Estimated DIAAS values of mixed diets from different countries (data from Moughan (2021)).

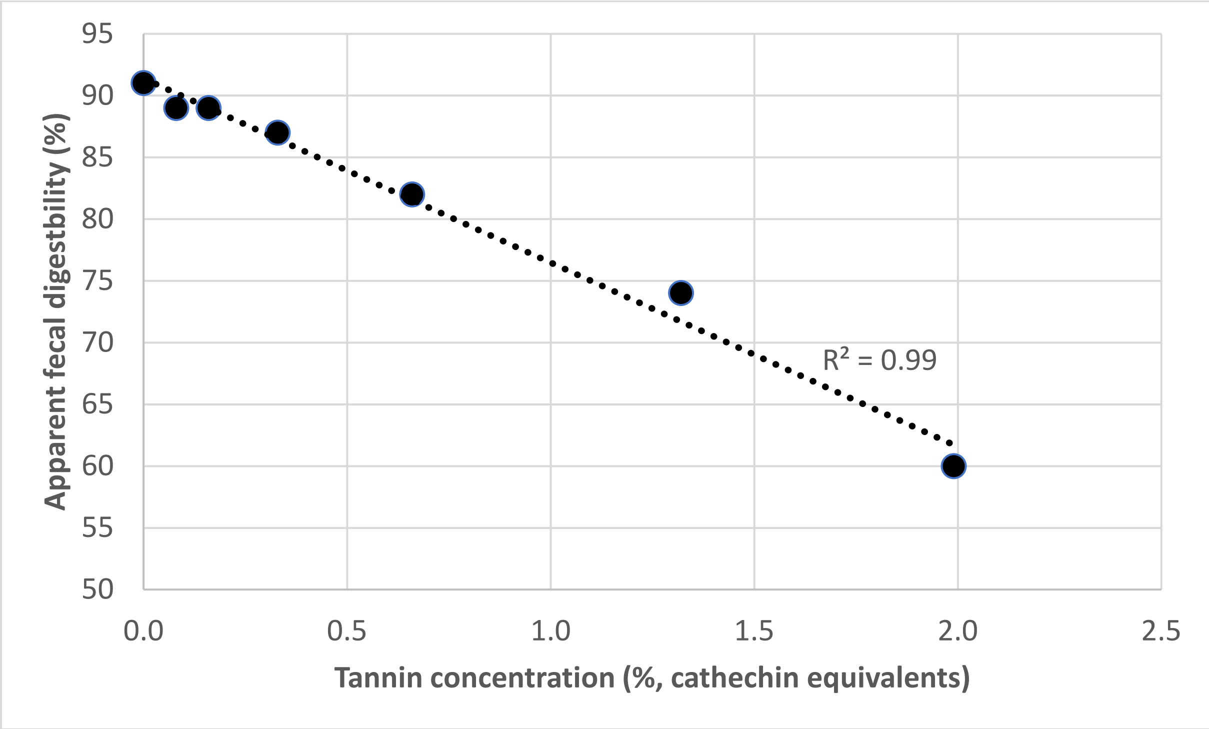

Figure 4: Effect of tannins on protein digestibility

Legend to Figure 4: Effect of tannin, added in the form of tannin-rich faba bean hull material, on the apparent fecal digestibility of caseins in rat (data from Jansman et al. (1994)).

Table 1: Main dietary animal protein sources in different regions

Legend to Table 1: Calculated gender-averaged percentage contribution of different product categories to dietary animal protein intake in different countries and regions.

Country and region	Dairy	Total meat	Beef	Pork	Mutton	Red meat	Poultry	Processed meat	Fish	Eggs	References
Greece	34.7	39.7				24.6	9.9	3.4	21.5	2.7	
Spain											
Granada	27.2	40.9				15.9	12.3	12.1	24.6	4.3	
Murcia	22.6	47.8				17.4	15.6	12.9	22.1	4.8	
Navarra	19.0	50.4				21.6	12.1	14.7	22.4	5.8	
San Sebastian	17.7	51.1				26.2	12.3	10.3	23.9	6.1	
Asturias	22.4	47.5				21.6	10.6	13.4	22.7	5.4	
Italy											
Ragusa	27.5	57.1				33.0	15.6	7.4	11.0	3.1	
Naples	35.6	47.1				28.0	9.6	8.9	10.0	3.0	
Florence	27.1	58.6				27.1	18.4	9.8	9.6	2.8	
Turin	29.0	57.1				26.6	17.1	11.6	8.8	3.2	
Varese	29.6	59.5				27.0	16.0	15.3	6.2	2.1	
France											Halkjær et al., 2009
South coast	35.4	44.7				18.0	13.8	9.3	14.4	3.0	
South	34.0	46.9				22.8	13.2	9.0	12.6	3.3	
North-East	33.3	47.3				22.9	12.2	9.3	13.6	3.2	
North-West	29.8	46.6	NA	NA	NA	20.0	14.5	10.2	17.8	3.3	
Germany											
Heidelberg	27.8	58.3				25.2	10.7	21.4	6.4	3.2	
Potsdam	25.7	57.0				21.8	9.0	25.3	8.4	3.8	
The Netherlands											
Bilthoven	32.8	57.6				30.7	8.1	18.1	5.0	3.8	
Utrecht	41.6	49.0				26.0	8.8	13.9	4.6	3.9	
United Kingdom											
General population	30.3	52.9				20.5	18.3	13.2	11.5	3.2	
Health-conscious	49.8	26.6				7.5	10.8	7.7	10.8	5.1	
Denmark											
Copenhagen	31.3	52.1				31.6	9.4	10.1	11.7	4.1	
Aarhus	34.5	50.4				29.7	9.4	10.1	9.7	4.3	
Sweden											
Malmo	33.7	48.6				26.5	6.7	14.4	11.6	4.0	
Umea*	39.3	43.8				20.3	4.3	14.3	10.1	3.8	
Norway											
South and East	34.7	45.7				16.7	10.2	16.1	12.4	4.5	
North and West	32.7	41.2				18.4	4.6	16.8	18.8	4.1	
Malaysia	18.76 (egg and dairy)	19.43	1.47	1.41	0.30	NA	16.25	NA	12.12	NA	Drewnowski et al., 2020

Indonesia	2.46	NA	3.44	0.13	0.04	NA	8.43	NA	9.81	10.32	Khusun et al., 2022
Philippines	NA	NA	NA	17	NA	NA	NA	NA	17	5 (eggs and egg dishes)	(Angeles-Agdeppa and Custodio 2020)
World									16.9		
Africa									18.4		
Burundi									28.1		
Ethiopia									1.6		Obiero et al., 2019
Kenya	NA	NA	NA	NA	NA	NA	NA	NA	7.3	NA	
Rwanda									25.1		
Tanzania									22.5		
Uganda									30.1		

Table 2: Main dietary plant protein sources in different regions

Legend to Table 2: Calculated gender-averaged percentage contribution of different product categories to dietary plant protein intake in different countries and regions.

Country and region	Potatoes	Vegetables	Legumes	Fruits	Rice	Cereals	Tubers	Cakes	Non-alcoholic drinks	References
Greece	3.1	13.8	7.1	8.1		59.6		3.2	2.1	
Spain										
Granada	5.8	11.2	7.9	12.3		47.6		3.0	2.3	
Murcia	5.8	18.8	7.2	14.8		39.8		6.2	1.3	
Navarra	4.8	11.9	9.7	11.9		47.0		4.1	1.7	
San Sebastian	6.5	12.7	13.7	11.3		42.3		3.1	1.4	
Asturias	8.0	7.0	14.3	11.4		43.9		4.8	2.0	
Italy										
Ragusa	2.8	9.3	4.3	7.9		64.0		3.1	1.3	
Naples	2.9	13.0	3.7	7.4		60.7		3.5	2.7	
Florence	2.9	12.3	3.8	6.9		62.0		2.7	2.3	
Turin	3.1	15.2	1.6	8.0		60.5		3.2	2.2	
Varese	3.3	12.0	2.2	8.2		62.6		3.2	2.8	
France										Halkjær et al., 2009
South coast	2.5	15.5	2.9	10.4		52.8		3.8	3.1	
South	4.1	13.1	1.9	9.1	NA	56.2	NA	3.9	2.9	
North-East	4.7	13.1	1.8	9.6		53.1		4.4	3.5	
North-West	5.7	12.8	1.6	10.0		54.6		3.4	3.6	
Germany										
Heidelberg	7.4	11.0	1.4	7.5		42.3		5.4	12.1	
Potsdam	8.8	11.0	1.2	8.7		41.2		5.9	10.1	
The Netherlands										
Bilthoven	9.8	8.7	1.3	9.8		52.8		2.7	5.8	
Utrecht	8.7	9.6	1.3	11.9		51.2		3.2	6.7	
United Kingdom										
General population	7.5	11.7	2.2	6.7		54.6		3.7	4.0	
Health-conscious	5.2	10.0	3.7	12.9		40.6		3.0	2.1	
Denmark										
Copenhagen	7.8	10.1	0.3	5.6		58.2		2.4	8.5	
Aarhus	8.0	8.9	0.1	6.0		59.2		3.1	8.2	
Sweden										
Malmo	9.1	7.9	1.4	5.6		53.7		4.6	4.7	
Umea*	9.1	6.2	0.8	4.8		58.4		7.2	3.4	
Norway										

South and East	5.7	7.5	0.4	7.8		59.0		4.7	7.9	
North and West	7.2	6.7	0.3	7.8		58.6		5.4	6.8	
Indonesia	NA	NA	19.31	NA	NA	45.04	1.01	NA	NA	Khusun et al., 2022
Philippines	NA	NA	NA	NA	19	NA	NA	NA	NA	(Angeles-Agdeppa and Custodio 2020)

Table 3: Protein digestibility in diets in different regions

Legend to Table 3: Estimated true human fecal digestibility values for proteins in diets from different area and countries (data from Gilani et al. (2005)).

Country or area	**Diet**	**Digestibility (%)**
North America	Mixed	94
North America	Lactovegetarian	88
North America	Vegetarian	93
India	Rice, red gram dahl, milk powder, vegetables	75
India	Ragi, red gram, potatoes, milk powder, vegetables	54
Guatemala	Black beans, corn tortilla, rice, wheat rolls, cheese, eggs, vegetables	77
Nigeria	Cassava, rice, dried fish, vegetables	91
Ceylon	Rice, meat, fish, dairy products, breads, fruits, vegetables	87
Brazil	Rice, beans, meat, eggs, vegetables	78
Philippines	Mixed	88

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