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Introduction

Before each meal, almost all of us ponder, consciously or not: "What protein should I eat?" This thinking or question highlights the importance humans place on protein in their daily meals. But what exactly is protein? From a chemistry standpoint, protein is a chain (i.e., a polymer) of amino acids (AAs) linked together by peptide bonds, while the AAs, as the building blocks of proteins, are those carboxylic acids that contain at least one amino group that contains nitrogen.

Proteins are an indispensable class of nutrients for humans and can come from various sources. However, much misinformation surrounds protein nutrition and protein sources, especially when their health impacts and environmental footprint are regarded. This lack of understanding about protein nutrition and production affects people's dietary choices and health consequences and has a broader implication for regional and global protein demand and supply.

People from many parts of the world are struggling with inadequate protein supply to balance their diets. With the global population expected to grow and competition increasing from animal feed industries, it is crucial to consider every available source of protein to meet current and future human dietary demands. Therefore, this issue paper aims to inform:

- People about various sources of proteins that contribute to a healthy diet, empowering them to make educated decisions about their protein choices and food purchases;
- Legislators, in order to prevent policy decisions that could unnecessarily impair protein supply; and
- Investors, in a bid to promote new technologies and solutions to address the issues leading to "protein deserts."

It is imperative to note that this paper does not advocate for the production and consumption of more animal-sourced protein over plant-sourced protein or vice versa. Instead, it aims to provide nutritional guidance on how to simply "formulate" an AA-balanced diet using available but different protein sources as healthy and safe ingredients.

Dietary Requirements of Protein and Amino Acids

Remember, from a nutrition standpoint it is not the dietary protein *per se* but rather the AAs and nitrogen (contained in proteins) that are needed. This is because the AAs and nitrogen are essential nutrients the body requires for its growth, development, reproduction, health maintenance, and other physical activities. Protein-deficient diets can lead to AA and nitrogen deficiency in the body. Also, if the dietary protein is not adequately digested to free AAs (including di- or tripeptides), after entering the gastrointestinal tract of the human body, the protein will have no nutritional value to the body, leading to deficiency in AAs and nitrogen. It is known that a deficiency of AAs and nitrogen in the body could result in not only stunting and impaired physiological development, but also cardiovascular dysfunction, impaired immunity, and a high risk for pathogenic infections (Wu 2016; Li et al. 2021).

From the biochemical standpoint, the human body requires all 20 proteinogenic AAs from the diet for the body's life processes, but not in equal amounts. These 20 AAs are traditionally classified into essential (indispensable) and nonessential (dispensable) AAs. The nine essential AAs (EAAs) are those that cannot be synthesized in the body to meet its biological requirements and therefore must be provided in the diet (i.e., indispensable). The other eleven AAs, termed nonessential AAs (NEAAs), are those that can be synthesized from other nitrogen-containing metabolites (including other AAs) in the body (IOM 2005). That said, this classification has become blurred as more research has accumulated (Hou and Wu 2017), forming a third group called conditionally EAAs. Listed in Table 1 are the three groups of AAs. Regardless, the current understanding in nutriology is that a dietary supply of properly balanced AAs is crucial to maximize or optimize the benefits that the AAs can offer to human health and life. Therefore, a current nutrition principle is that a mixture of EAAs and NEAAs (including non-protein nitrogen supplied for an adequate nitrogen intake) should be supplied to ensure that the requirements for specific AAs and total nitrogen both are met (IOM 2005).

As a dietary guidance, the value of dietary reference intake (DRI) for total protein or total nitrogen was calculated based on the dietary requirement for total protein or total nitrogen. The total protein and total nitrogen requirements are often synonymous because, in most cases, the value of total nitrogen content times 6.25 equals the total protein content. Table 2 lists those DRI values for almost all age groups (infants, children, adolescents, adults, and elderly), including women during pregnancy and lactation (IOM 2006).

A good diet can provide total protein in an amount that meets or exceeds the recommended dietary allowance (RDA), as shown in Table 2, but may not be good enough because the contents of nine EAAs may not meet or exceed the RDA of these nine AAs. A properly balanced diet should meet not only the total protein or nitrogen requirement but also the requirements for the nine EAAs (Brestenský et al. 2019). While Table 3 lists those DRI values for infants and children from 0 through 8 years old, Table 4 lists the DRI values for adolescents (9 through 19 years old) and adults (> 19 years old). Table 5 lists the DRI values for pregnant and lactating women (IOM 2006).

Although the DRI values for total protein and EAAs have been determined for humans at different life stages (Tables 2 through 5), many factors can influence these values. These factors include, but are not limited to, the physiological and pathological states of the subject (e.g., physical activity, health status), as well as the dietary energy intake, the frequency of meals, and some environmental factors, such as temperature and toxic agents (IOM 2005). Wu (2016) summarized the dietary AA requirements of (1) healthy humans with minimum physical activity, (2) healthy humans with moderate or intense physical activity, and (3) obese humans on a weight-reducing program. For example, Wu (2016) merely recommended a dietary protein intake of 1.0, 1.3, and 1.6 g/kg/day for individuals with minimal, moderate, and intense physical activities, respectively, to meet the subject functional needs, such as promoting physical strength and maintaining skeletal-muscle mass (cited in Li et al. 2021). For more accurate recommendations for the protein and AA requirements of humans at different life stages (including infants, children, adolescents, adults, and the women during pregnancy and lactation), readers can refer to the "Protein and Amino Acid Requirements in Human Nutrition: Report of a Joint FAO/WHO/UNU Expert Consultation" (FAO/WHO/UNU 2007).

In practice, the dietary protein sources should be appropriately administered to provide sufficient amounts of EAAs and nitrogen (in metabolically available form) to the body. This is very important because we need to realize that proteins differ in the content and availability (or digestibility) of various AAs. The nutritive quality of a protein source is determined by its ability to meet the nitrogen and EAA requirements, which are uniquely needed for the body's tissue growth, maintenance, and repair, such as the skeletal muscle protein turnover (IOM 2006).

Regarding the nutritional requirements of protein and AAs, it has been accepted that the nutritive values of food proteins are determined largely by the concentration and availability of individual EAAs. Hence, 1 gram of one protein (such as a plant protein) is not equal to 1 gram of another protein (such as an animal protein), although the food label indicates 1 gram protein for both.

There are inherent differences in protein quantity and quality in different sources of dietary proteins (FAO 2013), primarily because they provide varying amounts of different EAAs and NEAAs. For example, the concentrations of lysine in cereals (such as rice or wheat) are significantly low relative to human EAA requirements. In contrast, the concentrations of sulfur-containing AAs (methionine and cysteine) in legumes are low, when compared with animal-sourced foods (Brestenský et al. 2019).

To meet the EAA, as well as the total nitrogen requirements of the human body, one must have knowledge of the AA composition and availabilities in different sources of food protein, because different sources of food protein differ significantly in their composition and amounts of digestible AAs. Reviewed as follows are the AA compositions of plant- and animal-sourced proteins for human diets. We believe that these values can be used as references when specific dietary guidance is recommended to individuals or a group of individuals.

Plant-Sourced Proteins for Human Diets

Given their relatively easy access, plant-sourced proteins have served human beings since ancient times. Some common sources of plant protein are legumes, nuts/seeds, and cereal grains, although fruits and vegetables also contain some protein. Legumes usually contain 20–40% protein, while nuts and seeds contain roughly 15–40%, and cereal grains contain 7–15% protein. Fruits and vegetables are usually not considered a good source of dietary protein because their protein contents are only about 1–5% (Table 6).

All plant-sourced proteins contain all twenty AAs, including the nine EAAs. From the perspective of meeting human dietary AA requirements, however, the AA composition profile, or nutritional quality, of plant-sourced proteins is generally less optimal than animal-sourced proteins because they tend to have insufficient levels of one or more EAAs. Due to this insufficiency, plant-sourced proteins are usually called "incomplete proteins" (IOM 2006).

Cereal Grains

Cereal grains (or cereals) are produced from the seeds of those common plants in the grass family, which account for a considerable portion of human diets worldwide, especially in developing countries (Day 2013). The six major cereal grains are wheat, corn, rice, barley, sorghum, and oats. From the nutrition perspective, the principal value of cereal grains in human diets is to provide the human body with energy; however, cereal grains also provide AAs and nitrogen to the body. In some regions of developing countries, a single cereal grain may still account for the only source of total dietary protein intake.

The compositions of EAAs in the common cereals and pseudocereals are shown in Table 7. Relative to meeting dietary AA requirements, cereal grains are usually limited in the contents of lysine, threonine, and tryptophan, especially for infants and children. Of these six major cereals, however, oats do stand out as having a relatively higher amount of both crude protein (estimated by the total nitrogen content multiplied by 6.25) and digestible lysine than the other five cereal grains (Tables 6 and 7).

It is worth noting that gluten, a protein found in wheat (and similar proteins in barley and rye), can cause a celiac inflammation or disorder due to the inappropriate immune response in the gastrointestinal tracts of some people. Symptoms associated with gluten intolerance include abdominal distension, chronic diarrhea, weight loss, anemia, and dermatitis (Day 2013). However, gluten is used in alternative meat products due to its unique cohesive and viscoelastic properties that can form fibrous proteinaceous networks.

Legumes

Legumes (beans or pulses) usually refer to the edible seeds harvested from leguminous plants that can fix nitrogen from the atmosphere into their seeds or fruits through particular bacterial species. Because of their high protein contents, legumes have formed the dietary basis for a large part of world's population since ancient times, especially in those areas where animal-sourced proteins are barely accessible. Common legume foods include beans, soybeans, peas, chickpeas, lentils, and lupins (Caballero et al. 2013). The main contribution of legume foods in human diets is to provide the human body with AAs and nitrogen, although they also provide calories and other essential nutrients, such as lipids, fiber, minerals, and vitamins (in non-significant amounts).

The compositions of EAAs in these common legumes are shown in Table 7. Different from cereals, legumes are characterized by high lysine content. Consumption of legumes can fulfill the requirements for the majority of EAAs. That said, most legumes are also limited in some EAAs, especially the sulfur-containing AAs (methionine and cysteine) and tryptophan, except for peas and rapeseed (or canola seed) that present a balanced AA profile, including the sulfur AA contents (Table 7).

Soybean and peas are two broadly used plant proteins in food products due to their excellent functional properties, such as water-holding, gelling, fat-absorbing, and emulsifying capacities, while rapeseed proteins have foaming, emulsification, and gel-forming characteristics (Ismail et al. 2020). It has been known that some phytochemicals contained in legumes, such as isoflavonoids, saponins, or anthocyanidins, have various health-promoting qualities in humans, including lowering blood cholesterol level and reducing risks of various cancers (Caballero et al. 2013), and in animals, including the reduction of greenhouse gas (e.g., methane) emissions by ruminants, reducing urinary nitrogen excretion, and anti-parasitic aspects in many small ruminants, such as sheep and goats (Tedeschi et al. 2021). Here, it is worth noting that raw soybeans and other legumes usually contain high levels of protease inhibitors that can interfere with the digestion, absorption, or utilization of dietary nutrients. They may have other adverse antinutritional effects as well, including leaky gut, gut inflammation, and autoimmune response (Hertzler et al. 2020). Therefore, proper processing, such as cooking or fermentation, before eating is critical for legume consumption.

Nuts and Seeds

Nuts and seeds are another group of plant-sourced proteins for humans. The true nuts are those grown and harvested above the ground, such as tree nuts like almonds and pecans. Ground nuts, such as peanuts, are actually legumes that are produced below the ground, but they are usually discussed within the nut group or culinary category (Riley 2022). Seeds represent a diffuse group of products, some of which actually fall under the realm of other categories, such as cereals, pseudocereals, or oilseeds. Oilseeds usually mean oil-bearing seeds (e.g., flaxseed and sesame). For the present purpose, seeds that are consumed primarily in their native form (e.g., almond and sunflower) are all grouped here in the nuts and seeds category, whereas the canola/rapeseeds (from cruciferous plants) are classified in the legume category.

Since nuts and seeds come from a diverse range of plants, their nutritional compositions are quite varied. Just like other plant seeds, nuts and seeds do contain a nutrient reserve to support their future plant embryo development. The major reserve in various nuts and seeds is fat, but in others, it is protein or polysaccharides. In general, nuts and seeds are popularly known to have high protein content (Table 6), but they are also concentrated in calories, unsaturated fatty acids, fiber, and various micronutrients (Caballero et al. 2013).

Nuts and seeds are recommended as valuable contributors to meeting human EAA requirements, especially for vegetarians (Riley 2022). The typical AA compositions of nuts and seeds are shown in Table 7. For most if not all nuts, lysine is the first limiting AA and methionine the second. In general terms, peanuts, pistachios, and cashews have the best overall balance of EAAs, while macadamia nuts have the worst (Riley 2022). While baru almonds can reach 100% of the reference requirements of EAAs, pequi almonds and cashews present even higher content of sulfur AAs (Sá et al. 2020). Sesame is high in the content of phenylalanine and tyrosine relative to other nuts and seeds with reference to human EAA requirements (Sá et al. 2020).

Animal-Sourced Proteins for Human Diets

On the dry matter basis, animal-sourced foods in general contain more protein and AAs than plant-sourced foods (Tables 6 and 7). In terms of nutritional quality, animal-sourced proteins in general contain better-balanced proportions of AAs than plant-sourced proteins as described above (Brestenský et al. 2019). Therefore, on a single-source basis, animal proteins can provide much more balanced EAAs (Table 7). For this reason, they are referred to as "complete proteins," simply with reference to human tissue requirements of AAs (IOM 2006; Li et al. 2021). Furthermore, animal proteins are easily digested in the human gastrointestinal tract with a true digestibility value of 95–98%, whereas the value is 70–85% for plant proteins (Caballero et al. 2013). For human diets, animal-sourced proteins primarily include five categories: meat, poultry, seafood, dairy products, and eggs.

Meat, Poultry, and Seafood

These three categories of animal-sourced proteins are commonly called meat products (muscle foods), which are derived from the skeletal muscle and its associated tissues (including fat, connective tissue, blood vessels, plus edible offal) taken from mammal, avian, and aquatic species, respectively (Bohrer et al. 2017). The nutrient contents of these meat products are fairly similar. The main differences among or within these products primarily result from the differences in the ratios of fat to protein (Caballero et al. 2013). Overall, all meat products have higher levels of essential nutrients per unit of dry weight than most non-muscle foods, with reference to their calorie contents provided at the same time (Caballero et al. 2013). It is generally recognized that when diets are lacking in muscle foods, greater care is required in the selection of other foodstuffs to ensure that adequate levels of potentially bioavailable essential nutrients (such as EAAs) are present (Caballero et al. 2013).

The popular meat products derived from mammals include beef, pork, lamb, mutton, and veal, commonly called red meat. Cooked red meat contains 28–36% protein, which is highly digestible, provides all EAAs (Table 7), and has no limiting AAs (Williams, 2007). Glutamate/glutamine is present in the highest amount (16.5%), followed by arginine, alanine, and aspartate (Williams, 2007). Lean red meat also has a relatively low content of fat (< 7%), is moderate in the content of cholesterol, and is rich in many essential vitamins (e.g., B3, B6, and B12) and minerals (e.g., P, Zn, and Fe) (Williams 2007).

The compositions of nutrients, including protein and AAs, in poultry (such as chicken and turkey, commonly called white meat) are similar to those of red meats, with a few exceptions in mineral contents (Caballero et al. 2013). Poultry is lower than beef in Fe content, and as in red meat, there are significant amounts of B-vitamins, such as B3, B5, and B6 (Caballero et al. 2013). Like pork, poultry is higher in polyunsaturated fatty acids than beef, lamb, and veal (Caballero et al. 2013).

The category of seafood commonly covers the aquatic species of finfish (including white/lean fish, fatty fish, and cartilaginous fish) and shellfish (including mollusks, crustaceans, and cephalopods) harvested from either the marine body or the freshwater bodies. The muscle of edible fish usually contains 18–20% protein, 1–2% minerals, and 1–20% or more lipids (Caballero et al. 2013). Fish protein, with only slight differences among species, possesses a high nutritive value, similar to that of other meats. It is worth noting its elevated supply of EAAs, such as lysine, methionine, and threonine, compared to white or red meat (Boyd et al. 2022). In addition, partly due to its low collagen content, fish protein is easily digestible, giving rise to a high level of digestibility (Caballero et al. 2013; FAO 2020).

Lean fish, in general, is not an important source of calories, although fatty fish is a significant source in many fish-consuming communities living close to sea, rivers, and lakes (Caballero et al. 2013). Some essential micronutrients in fish include vitamins A and D, calcium, phosphorus, magnesium, iron, zinc, selenium, fluorine, and iodine (Caballero et al. 2013; FAO 2020). The cardiovascular and brain health benefits of eating fish are attributed to the omega-3 fatty acids, including eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which are found primarily in fatty fish such as salmon, tuna, herring, mackerel, and sardines (Caballero et al. 2013; Ferrari et al. 2022).

Dairy Products

Dairy products commonly include three major groups: milk, cheese, and yogurt. All liquid milks derived from different mammalian species are nutrient-dense foods that supply energy and significant amounts of high-quality protein, plus micronutrients (Muehlhoff et al. 2013; Day et al. 2022). Milk can be classified according to its fat content; for example, as whole milk, skimmed milk, semi-skimmed milk, low-fat milk, and standardized milk (Muehlhoff et al. 2013). The protein contents in dairy products range from 0.9% to 3.5% in liquid milk and 7.9% to 36.2% in condensed or dried milk products (Muehlhoff et al. 2013). The principal proteins in milk fall into two groups: caseins and whey proteins at a ratio of 8:2 of the total proteins (Day et al. 2022). Caseins, a family of phosphoproteins, are the unique but main protein component and present as micelles in the milk. Whey proteins are a mixture of globular proteins isolated from whey—the liquid remaining after milk has been curdled and strained.

Cheese is produced by the enzymatic coagulation of casein proteins in the milk, and it is comprised of fat and minerals as well. The protein contents in various cheese products range from 9.7% to 44.9% (Muehlhoff et al. 2013). The liquid byproduct from cheese production is whey, and whey contains an array of acid-soluble proteins. Yogurt is produced by bacterial fermentation of milk, leading to its special texture and tart flavor. The protein contents in various yogurt products range from 3.5% to 10.2% (Shah 2017). The EAA contents of the major kinds of milk and milk proteins are shown in Table 7, showing that whey protein is rich in lysine, methionine, and branched-chain AAs (leucine and isoleucine), while casein contains more valine, histidine, and phenylalanine + tyrosine.

Like other animal-sourced proteins, dairy products also contain carbohydrates (e.g., lactose, 3.2–5.4%), lipids (3.1–9.0%), minerals, and vitamins (Muehlhoff et al. 2013). Calcium and riboflavin are two important nutrients supplied by dairy products (Elmadfa and Meyer 2017). The energy content of milk products ranges from 0.6 to 1.2 kcal/g (Muehlhoff et al. 2013). Here, it is worth noting that lactose intolerance in some individuals may limit their consumption of milk and other dairy products. The symptoms from lactose intolerance may include nausea, abdominal pain, flatulence, bloating, and diarrhea (Muehlhoff et al. 2013).

Eggs

Although the majority of eggs consumed today are chicken eggs, a variety of eggs from other avian species (ranging from the petite quail egg to the very large ostrich egg) are commercially available in different parts of the world as well. The protein contents in various raw eggs range from 12.6% (chicken) to 13.9% (goose) (Table 6). In general, egg protein has a "chemical score" (EAA level in a protein food divided by the level in an "ideal" protein food) of 100, a "biological value" (a measure of how efficiently dietary protein is turned into body tissue) of 94, and the highest "protein efficiency ratio" (a ratio of grams of weight gain to grams of protein ingested in young rats) of any dietary protein (Caballero et al. 2013). The EAA concentrations in egg white, egg yolk, and whole egg are presented in Table 7. Besides protein, eggs contain 75.8% water, 9.9% lipids, and 1.0% vitamins and minerals, plus 0.7% carbohydrates (Caballero et al. 2013).

The cholesterol level in eggs is one of the highest (about 215 mg/egg) among the animal-sourced foods. A common view that human blood cholesterol level reflects dietary cholesterol level resulted in the belief that eggs are a major contributor to hypercholesterolemia and its associated cardiovascular diseases. Although studies have failed to find a significant relationship between egg intake and the risk of cardiovascular diseases, the undue concern resulted in a steady decline in egg consumption since 1970s. However, global egg consumption has been slowly increasing (i.e., > 1 egg/day/person) over the past decade, in part, due to a change in the concern about dietary cholesterol levels (Caballero et al. 2013).

Emerging or Untapped Protein Sources for Human Diets

Innovative efforts across the agricultural sector and beyond continuously create novel sources of protein for humans and animals (including livestock, poultry, pets, and aquaculture) to consume. In some instances, these efforts lead to more sustainable management of limited protein resources globally. Some novel proteins originate from laboratory-based efforts, while others have been in practice for millennia in various geographies. The purpose of this section is to provide a basic overview of some novel protein sources presently being explored.

Plant-based proteins are readily recognized resources. While some plant-protein production systems, such as soybeans and peanuts, are commonplace, new sources of plant proteins are being developed. These include, but are not limited to, plant species such as rapeseed, lupin, and quinoa. These plant-based foods are high in protein as well as in energy, fiber, and other micronutrients (Mattila et al. 2018). However, some significant challenges still exist regarding proper protein production, processing, and utilization.

The history of single-cell protein is quite historic in some regards with major advancements occurring within the past decade around "cultured meat". Research investment in this area continues to grow due to its potential as a substitute for traditional protein sources utilized for food and feed.

Algal production as a source of protein for food or feed is not new as initial efforts occurred during the mid-20th century (Becker 2007). Efforts have determined that such protein can be used as a feed replacement for various livestock with little to no negative impacts on animal production or meat quality (Madeira et al. 2017). In fact, numerous species have been explored for such industrial processes. At this time, such methods have not significantly expanded in part due to costs and aesthetics, such as color, texture, and smell (Becker 2007). Similarly, fungi, such as mushrooms and yeasts, as food have a long history. However, this use extends beyond simply mushrooms for human consumption. Of the approximately 2,000 fungi species used for food production, 300 also offer benefits associated with human health (Strong et al. 2022). Presently, efforts for mass-producing fungal mycelia are occurring globally, although with an emphasis on its use as animal feed. As with other novel sources of protein, mushrooms and mycelia can reduce the cost of livestock production (i.e., less expensive feed) and enhance conversions of feed to animal biomass (Strong et al. 2022). Of course, "cultured meat" is presently in the news due to its novelty. In such cases, animal cells are mass-produced in the laboratory. As with other protein sources previously discussed, the benefits associated with the process are quite numerous; however, there are still a number of challenges ranging from the cost of production to societal views of such material, including government regulations and consumer acceptance (Bryant 2020).

Insect-based protein has been recognized in many parts of the world nearly to the start of recorded history. The use of whole insects as part of cultural diets ranges from Morman crickets for indigenous peoples in North America to silkworms in China. In fact, many forms of whole insect use, including the silkworm, still exist today. Given the current emphasis on sustainability and circular economic approaches to food and feed production, efforts are in play to integrate insect farming as part of the global agriculture sector. Recent research efforts have demonstrated opportunities of such proteins beyond the seasonal occurrences (e.g., Morman cricket, locust) or restricted production (silkworm from fabric industry) to full-fledged industrialization that is occurring globally. Facilities are being developed that can produce 10–30 tonnes of insect biomass daily. Furthermore, these facilities range in complexity from low-technology community farms to industrialized facilities that are completely enclosed with computer automation. Because of the flexibility in facility design, opportunities for the insect industry are not restricted to Global North nations.

Presently, three insect species are primarily produced at an industrial scale. Crickets are generally produced as a food item (Vogel 2010). Like other insect models discussed, they have a quick growth rate, high conversion rate, and are high in protein (although the protein quality is not high). Typically, crickets are harvested and converted to cricket powder, which can then be used as an ingredient for producing human-grade foods, such as energy bars, chips, and other bakery goods. Yellow mealworms, which are beetle larvae, can also be mass-produced and converted into similar food items (Roncolini et al. 2020). However, a limitation on production is their reliance on feed-grade materials that are used for production of other livestock. Thus, modification of regulations governing their use is needed in order to expand the channels of materials that can be used as feed for these miniature livestock. In contrast, the black soldier fly, which is almost globally approved for use as animal feed (Tomberlin and Huis 2020), can be produced on materials of limited value to humans, such as animal waste, as well as post-consumer food waste; however, it should be noted that only pre-consumer food waste is approved at this time in the United States and Europe.

Resulting larvae, which reach peak weight in about ten days, can be harvested and utilized as feed for poultry, pets, select fish species, and swine in the U.S. In all instances, the insects can be harvested and transformed into ingredients that are then used in diet formulations for human and other animals. Most consumers would not know that insect-based protein is present in the resulting products other than being listed on the label.

As with all the previous sources of protein discussed, the environmental benefits are relatively well established, ranging from high feed conversion rates and low greenhouse gas production to multiple generations per year and the suitability for vertically farming, thus allowing for greater production in a given locale. In fact, in many cases, these alternate sources of protein can be fed materials of limited value, such as food waste, contaminated products (e.g., maize with aflatoxin), and livestock and poultry manure. The resulting single cell, in the case of fungi or algae, or insect protein, can be harvested and transformed into food for humans or feed for livestock and poultry.

Balancing a Diet with Complementary Proteins

As discussed above, the fundamental nutrition purpose of consuming protein foods is to supply AAs and nitrogen for life processes of the body. Technically, any individual requires certain amounts of different AAs in certain ratios at any given life stage. However, no single source of protein foods has an AA profile that exactly matches the requirement of the individual for AA and nitrogen, especially when the calories, fatty acids, and micronutrients (vitamins and minerals) need to be provided at the same time. As indicated by the current data on dietary intake, the U.S. population does not meet the dietary recommendations or appropriate nutrient intake (2025 Dietary Guidelines Advisory Committee. 2024). Therefore, the persistent gap between dietary recommendations and actual intakes should be addressed in a timely manner.

According to the proposed *"Eat Healthy Your Way"* dietary pattern, although flexibility in the proportions of plant- to animal-based protein foods is supported, the 2025 Dietary Guidelines Advisory Committee (2024) emphasizes dietary intakes of more plant-based protein foods (e.g., beans, peas, and lentils) while reducing dietary intakes of animal-based protein foods (e.g., red and processed meats), except for eggs and seafood. The authors of this paper do not necessarily say that this recommendation is wrong or missed something, but there is an educated concern that relying exclusively on a single source of plant-protein could result in a number of unintended consequences (Hertzler et al. 2020; Koeler and Perez-Cueto 2022; Ogilvie et al. 2022; NASEM 2023; West et al. 2023).

The obvious differences between plant- and animal-sourced protein foods concern both the quantity and quality of the proteins. Most plant-based foods are relatively low in the content of protein that is also typically less digestible or otherwise unavailable (Mariotti and Gardner 2019; Hetzler et al 2020; Ogilvie et al 2022). Regarding protein quality, few plant proteins contain the EAAs in desirable amounts and ratios relative to animal proteins such as meat and eggs. Most plant sources of protein are deficient in at least a couple of EAAs with lysine and methionine often being the most limiting ones (Hertzler et al. 2020; Agarwal et al. 2023; NASEM 2023).

One way to solve the issue of inadequacy of EAAs in a plant-based protein food is to increase the amount of protein consumption. In reality, most individuals in the western world eat high-protein diets. Published estimates of maximal amount of dietary protein claim that an 80-kg man could possibly consume up to 285–365 g/day (roughly 4–5 g/kg body weight per day) (Bilsborough and Mann 2006). Although there are plenty of anecdotal reports of individuals consuming large amounts of protein in a single meal, it is unlikely that a person could consume that much consistently. Such a large consumption would have to come at the expense of other essential nutrients, particularly micronutrients and fiber (Bilsborough and Mann 2006). If the diet was also very low in fatty acids, the consequences could be severe. Early explorers often lived primarily on very lean meats from wild game resulting in what became known as rabbit starvation or mal du caribou (protein poisoning) due to excessive protein but the lack of fat and carbohydrates (Bilsborough and Mann 2006).

Another issue associated with a high-protein diet is that the body would receive excessive amounts of other AAs that were not limiting in the first place. One problem is that those excessive AAs could end up in the large intestine and then promote harmful bacteria to grow, which would negatively impair gut health (Wang et al. 2018). Another problem is that the body needs to metabolically catabolize those absorbed excess AAs and then excrete them in the form of urea through kidney function because the human body cannot store free AAs that are not used for protein synthesis, for example. This process of catabolism and excretion is a metabolic burden to the body, especially the liver and kidney (Garibotto et al. 2010). In addition, some nutritionists argue that consuming significantly more low-protein plant-based foods could result in the consumption of excess calories compared to eating a balanced diet (Hertzler 2020; Pinckaers et al. 2021).

In human population, vegans consume strictly plant-based foods (such as legumes, nuts, and seeds) and no animal products. Fruitarians primarily consume fruits, nuts, and seeds, often with a focus on raw foods. Purely from a perspective of protein or AA requirements, it seems possible to support a "normal" lifestyle based solely on plant-only diets; however, the question of AA deficiency definitely has been overlooked (Mariotti and Gardner 2019; Herzler et al. 2020). It is known that individual plant protein foods, such as beans, peanuts, and macadamia nuts, are not nutritionally equivalent in quality to one another, let alone to the quality of ideal or complete protein sources (Park et al. 2021).

There are a number of other perhaps unforeseen problems associated with purely vegan diets that are not related to the protein content (Pinckaers et al. 2021; Koeler and Perez-Cueto 2022; Ogilvie et al. 2022; West et al. 2023). One likely well- known problem that is not easily remedied is the risk of deficiencies in both mineral and fatty acids, including omega-3 fatty acids. Plants are relatively low in iron, and plant iron is present in a non-heme form that is not as easily absorbed as the heme iron in animal products. Similarly, most plant foods are low in calcium, selenium, and iodine. Low calcium, together with low vitamin D content, can greatly increase the risk of bone fracture (Ogilvie et al. 2022).

Another common problem associated with purely vegan diets is a deficiency of vitamin B12, which is not synthesized by plants. A major source of B12 is foods of animal origin. It is worth noting that many of the new plant-based meat substitutes, including the lab-cultured meats, are also deficient in vitamin B12 and also some other micronutrients (NASEM 2023). Thus, vegans should take a B12 supplement or consume B12 fortified foods (Koeder and Perez-Cueto 2022; Oglivie 2022; NASEM 2023). A further potential issue associated with vegan diets can be the presence of various anti-nutritional compounds that interfere with the digestion and/or absorption of dietary nutrients. These compounds include protein binders, enzyme inhibitors, and inflammatory mediators. Examples include protease inhibitors, phytates, tannins, lectins, oxalates, and goitrogens (Hertzler et al, 2020; Bekhit et al. 2022).

In general, most micronutrient deficiencies can be corrected by selective consumption of key foods rich in those micronutrients. For example, omega-3 fatty acid deficiency could be corrected by adequate consumption of plant-based foods such as walnuts, flaxseed, and canola oil (Koeder and Perez-Cueto 2022), while many of the anti-nutritional compounds can be removed by food processing, such as soaking, fermentation, and/or heating (Hetzler et al. 2020; Ogilvie 2022; Pinckaers et al. 2021). However, it should also be kept in mind that such processing may have negative effects on the nutritional value of the foods.

Vegetarians consume dairy products (lacto-vegetarians) and/or eggs (lacto-ovo or ovo-vegetarians), while flexitarians follow a mostly plant-based diet but occasionally eat meat and other animal products. Pescatarians primarily consume plant-based foods but often include fish and seafood in their diet. The drive to consume more plant-based foods in the western world is partly related to both the proven and perceived benefits of such diets in reducing the risk of some chronic illnesses (Hetzler et al. 2020; NASEM 2023; Rosenfeld et al. 2023), perhaps because plant products contain bioactive compounds (e.g., flavonoids and polyphenols) that reportedly benefit human health. Again, such effects are not directly related to the protein content or the quality of the foods.

Given the potential negative effects of a purely plant-sourced protein diet, it is crucial that consumers are aware of these implications and take adequate precautions to prevent any nutrient deficiencies or anti-nutritional toxicities. Most vegans and vegetarians in the U.S. are aware that they should mix different protein sources, as reflected in the concept of using complementary proteins. For example, legumes (e.g., beans, chickpeas) are usually deficient in sulfur-containing AAs (methionine and cysteine), whereas cereal grains are sufficient in such AAs but deficient in lysine. However, legumes do contain relatively sufficient lysine. Thus, from the complementary protein standpoint, combining legumes with cereals can provide a much better EAA profile (Mariotti and Gardner 2019; Hertzler et al. 2020). Additional strategies to ensure an ideal balance of EAAs include combining different plant materials, such as nuts, seeds, pseudocereals, or protein isolates, and supplementing with animal products, such as dairy and/or eggs (Mariotti and Gardner 2019; Hertzler et al. 2020; Pinckaers et al. 2021; NASEM 2023). For a very balanced diet, some emerging alternative protein sources, such as insects, microorganisms, or crystalline AAs, can be used as a complementary protein source (Bekhit et al. 2022; NASEM 2023). Ideally, complementary proteins should be consumed in each meal to ensure the simultaneous availability of all AAs required by the body, as the body cannot store free AAs for an extended period while waiting for other AAs to be eaten. However, consuming complementary proteins at different meals throughout the day can still provide a sufficient AA supply to meet the body's requirements.

Global Protein Demand: Where is it Abundant and Scarce?

Current Consumption of Protein

Specific global demand for protein may be challenging to precisely quantify because of methodological limitations. In general, the most precise estimates of food availability could be compiled from the Food Balance Sheets published by the Food and Agriculture Organization of the United Nations (FAO 2023). These sheets reported the estimated supply of each food item available in a country over a specific period by considering the supply available from production within the country plus import, and the utilization of these commodities minus any amounts used for exports, livestock feed, seed, and other losses (FAO 2023). Based on these numbers, nutrients such as energy, protein, and fat available for consumption can be estimated. A limitation of the Food Balance Sheets is that the values represent an aggregate amount of a food item or nutrient supply available for human

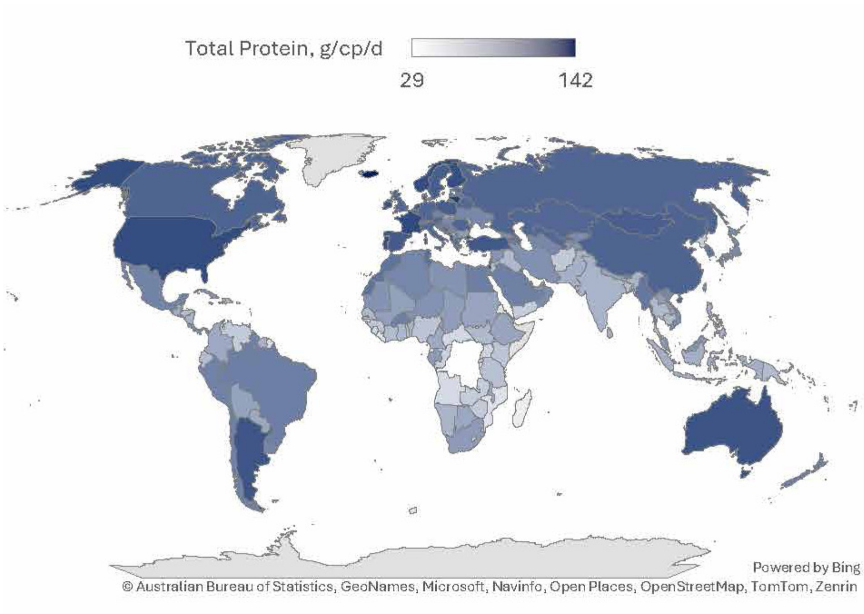

Figure 1. Total protein supply in grams per capita per day for 2020. Source data: (FAO 2023)

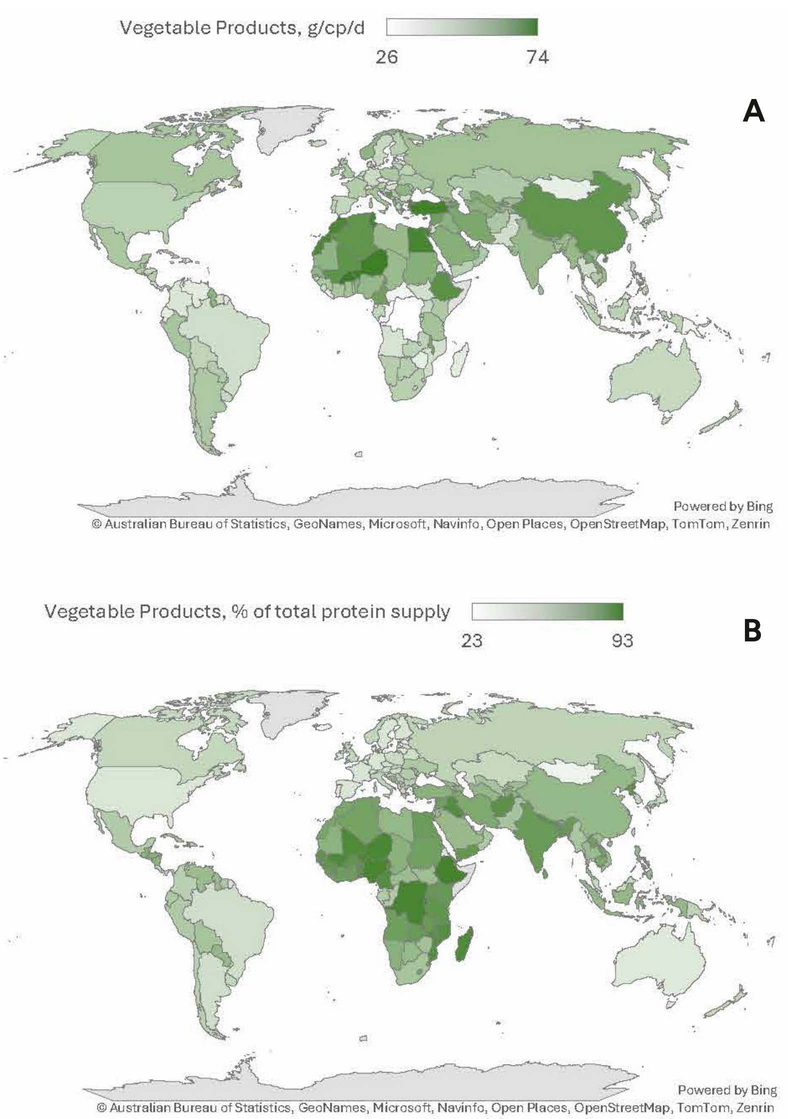

Figure 2. Protein supplies from vegetable products in grams per capita per day (A) or as a percentage of total protein supplies (B) for 2020. Source data: FAO (2023). Microsoft product screen shot(s) reprinted with permission from Microsoft Corporation.

consumption but not the true consumption per se. In addition, the availability does not indicate actual consumption based on socioeconomic, geographic, or seasonal factors influencing food availability within that country (FAO 2023). Moreover, these estimates do not include non-commercial production, such as home-grown produce or food gathered from hunting and fishing. Put differently, the values may underestimate consumption in rural areas where more land is available for agricultural activities like crop production or animal raising and overestimate consumption in poor urban areas. Similarly, assessment of nutrient supplies may underestimate consumption in affluent areas and overestimate it in less affluent areas within a country. Regardless, the supply per capita of a nutrient or food item could be used to calculate the changes in availability (surpluses or shortages) and establish projections for future supply needed to meet demographic or socioeconomic changes in a country (FAO 2023).

For animal- and plant-sourced foods, we will only focus here on the availability of proteins and their sources. As discussed in previous sections of this paper, animal-sourced proteins include meat (beef, poultry, pork, lamb, and their associated offal), dairy products (milk, cheese, and yogurt), eggs, and fish/seafood (finfish, mollusks, etc.), while the plant-sourced proteins include legumes and pulses (beans, lentils, chickpeas, etc.), cereal grains (wheat, barley, corn, etc.), starchy roots (cassava, potatoes, yams, etc.), and oil crops (soybean and peanuts). Although starchy roots and cereals have relatively low protein contents, they are still considered a significant source of protein for populations that consume these commodities as food staples.

Based on the FAO data, the global protein supply currently stands at 85 g/cp/d (Figure 1), indicating an improvement in the average protein available for consumption, which was 70 g/cp/d, reported between 1986 and 1988 (Grigg 1995). However, looking at individual countries it is evident that inequality in protein supplies has continued since the late 1980s, at which time the range was between 27 in Mozambique and 127 g/cp/d in Iceland (Grigg 1995). Currently the range varies widely from 29 g/cp/d in the Democratic Republic of the Congo to 142 g/cp/d in Iceland. Despite this improvement in protein supply worldwide, the supply remained greatest in Argentina (114 g/cp/d), North America (91–119 g/cp/d), Western Europe (98–142 g/cp/d), Australia (115 g/cp/d), New Zealand (93 g/cp/d), and Russia (106 g/cp/d). Some improvement in protein supplies, from 65 to 107 g/cp/d, was observed in China between 1988

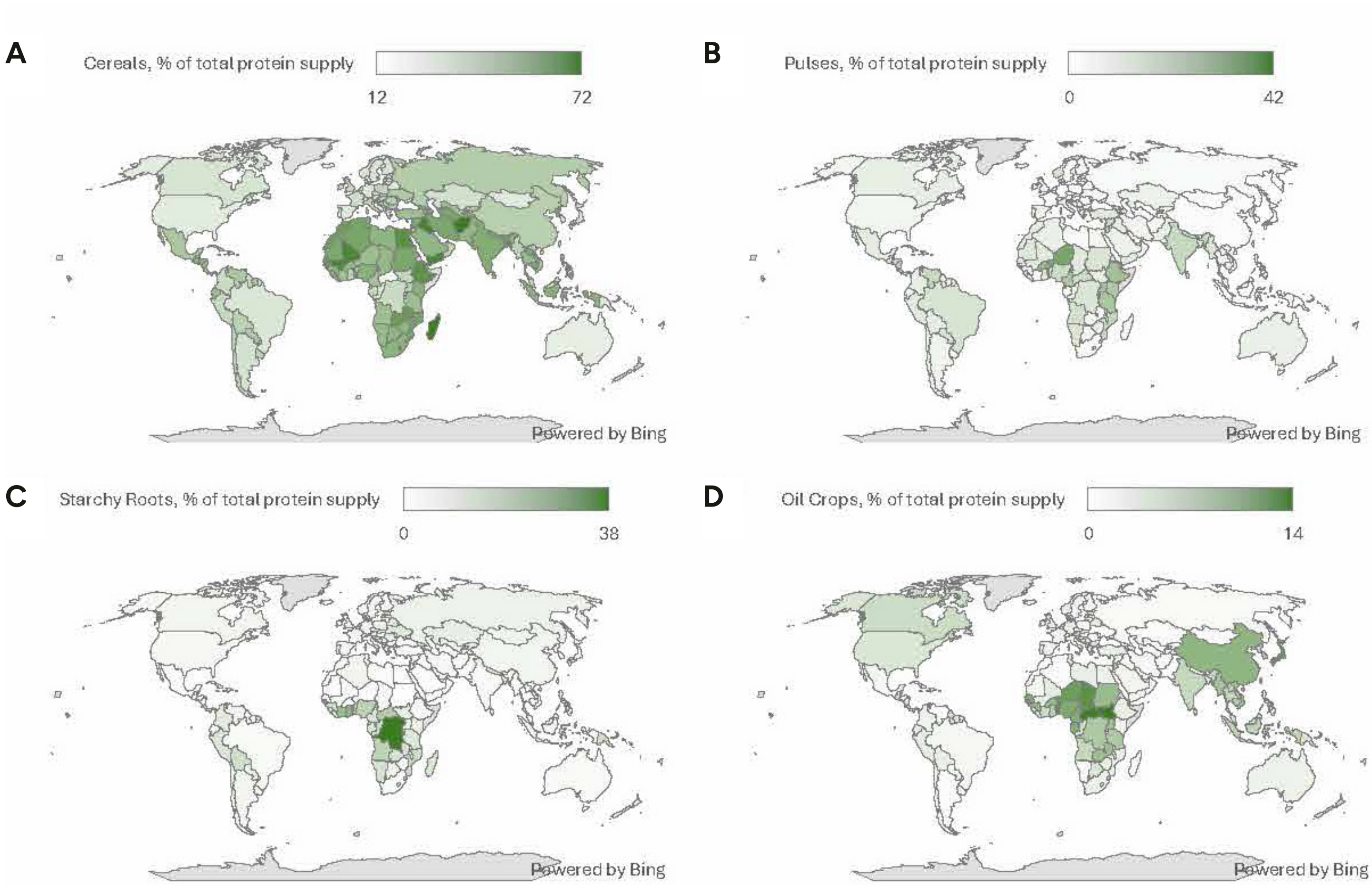

Figure 3. The contribution of cereals (A), pulses (B), starchy roots (C), and oil crops (D) protein to total protein supplies in 2020. Source data: FAO (2023).

and 2020, while Turkey increased from 85 to 113 g/cp/d, and India from 50 to 64 g/cp/d. The lowest protein supplies persisted in parts of South America, the majority of West and Central Africa, and South and South-East Asia (Grigg 1995; FAO 2023), a condition that has remained relatively unchanged over the last three decades.

Protein intake differs by country and region and also in terms of its plant or animal sources. Currently, plant-sourced proteins (Figure 2A) represent the larger proportion (60%) of total protein supplies worldwide compared with those from animal sources, which make up the balance. Plant/vegetable products contributed between 26 and 74 g/cp/d (Mean 51 g/cp/d), with the best supplies found in Burkina Faso (74 g/cp/d), Turkey (73 g/cp/d), Niger (73 g/cp/d), Egypt (73 g/cp/d), Ethiopia (66 g/cp/d), and China (65 g/cp/d). The lowest plant protein supplies were found in the Democratic Republic of the Congo (26 g/cp/d), Zimbabwe (31 g/cp/d), and Mongolia (31 g/cp/d). It is important to note that these estimates should not be taken at face value. For example, although supplies were relatively low in the Democratic Republic of the Congo, vegetable proteins still accounted for 89% of the total protein consumed, whereas in Mongolia plant proteins contributed only 29% of total protein supplies (Figure 2B). In fact, in most of Africa and South and Southeast Asia, plant protein supplies represented a large proportion (51–89%) of total protein supplies. Meanwhile, in countries with relatively high protein supplies, like North America, Australia, and Western Europe, plant proteins comprise 29–44% of total protein supplies. Cereals remain the most important single source of protein worldwide (Mean 38%, Range 12–72% of total protein supplies; Figure 3A), followed by pulses (Mean 5%, Range 0–42% of total protein supplies; Figure 3B), starchy roots (Mean 3%, Range 0–38% of total protein supplies; Figure 3C), and oil crops (Mean 4%, Range 0–14% of total protein supplies; Figure 3D).

Protein supplies from animal sources were 3–108 g/cp/d (mean 34 g/cp/d; Figure 4A). Countries with the greatest supplies were Iceland (103 g/cp/d), Mongolia (78 g/cp/d), the U.S. (76 g/cp/d), France (76 g/cp/d), and Australia (75 g/cp/d), whereas the lowest supplies were in the Democratic Republic of the Congo (3 g/cp/d), Madagascar (5 g/cp/d), Nigeria (7 g/cp/d), and Mozambique (7 g/cp/d). A significant proportion of proteins in countries with high protein supplies is derived from animal sources (Figure 4B). Conversely, countries with low protein supplies, i.e., most of Africa and South and Southeast Asia, are also those with lower protein supplies from animal sources. A growth in the proportion of proteins from animal sources occurred in China, which

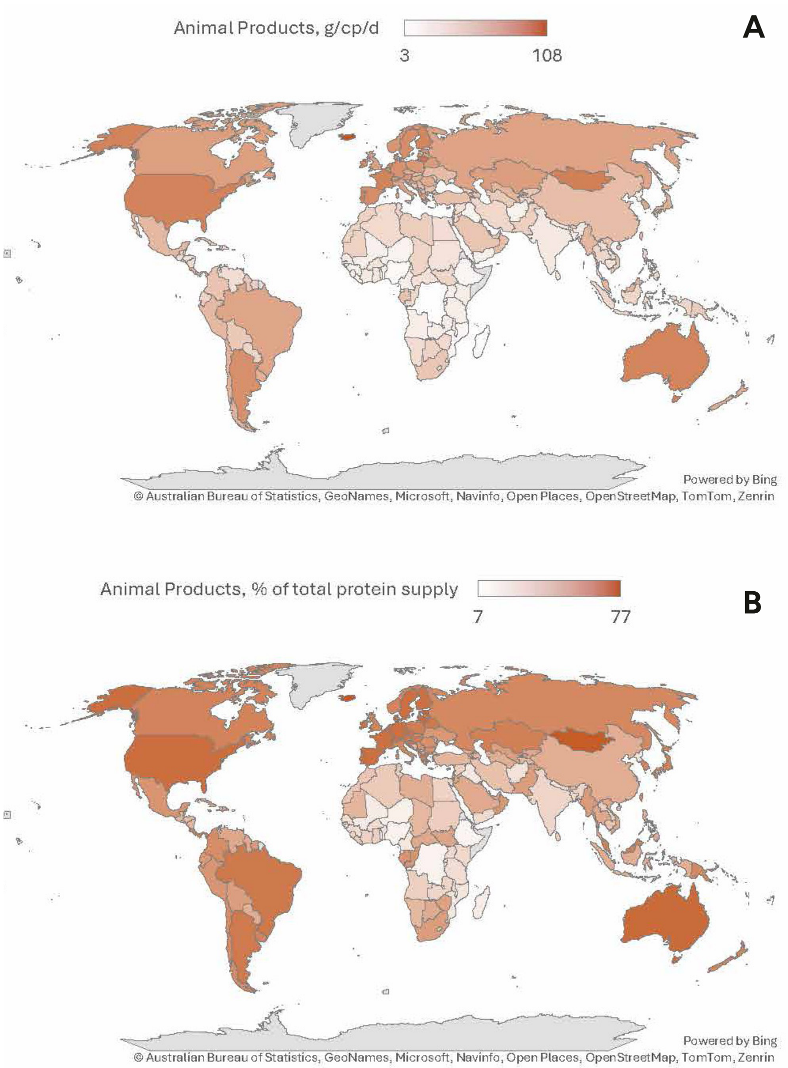

Figure 4. Protein supplies from animal products in grams per capita per day (A) or as a percentage of total protein supplies (B) for 2020. Source data: FAO (2023). Microsoft product screen shot(s) reprinted with permission from Microsoft Corporation.

increased from < 19 to 39%; Egypt, which increased from < 19 to 24%; and Mongolia, which increased from 50–59 to 71%. Despite some improvement in protein supplies, the contribution of animal products remained low (11–27%) for most of West Africa, the Democratic Republic of Congo, and Ethiopia. Among the sources of animal protein, meat remains the most important (Mean 17%, Range 2–45% of total protein supplies; Figure 5A), followed by milk (Mean 11%, Range 0–38% of total protein supplies; Figure 5A), fish and seafood (Mean 7%, Range 0–34% of total protein supplies; Figure 5C), and eggs (Mean 4%, Range 0–8% of total protein supplies; Figure 5D).

To assess the global demand for protein and make predictions for future needs, it is important to consider current protein supplies. Presently, worldwide protein supply, regardless of sources, is at 85 g/cp/d. The RDA for protein is around 0.85 g/kg/d (Campbell et al. 2008). For an average adult weighing around 70 kg, this would amount to needing approximately 60 g/cp/d. While this recommendation might appear to be less than the current supply (85 g/cp/d), it is important to note that protein intake in many countries is below the recommended levels, especially when protein quality—in terms of AA digestibility and utilization—is considered (Moughan 2021).

The disparity of protein supply worldwide emphasizes the significance of understanding and meeting the regional demand for proteins to address malnutrition. In other words, even if the global supply of protein increases, there is no guarantee of equitable distribution. During the mid-1980s, international food trade accounted for just 12% of the total global food output (Grigg 1995), which suggests that the most significant proportion of food produced is consumed locally. While global food production being traded internationally increased to 23% by 2010, indicating some progress, it is important to note that many African countries continued to face challenges in achieving food self-sufficiency (D'Odorico et al. 2014). This situation might have affected their capacity to secure protein, especially during an emergency like the COVID-19 pandemic, due to the disruption in international trade and a reduction in their gross domestic product (Swinnen and McDermott 2020).

Understanding the expanding and considerable global demand for protein necessitates an examination of the underlying factors influencing this demand. Factors such as population growth, increasing incomes, evolving dietary choices, growing awareness of protein's role in diets, and the emergence of new protein sources all play crucial roles. The United Nations projects that the world population will reach 9.5 billion by 2050, with the largest population growth occuring in Africa (United Nations 2022). Even at the current rates of protein consumption, an increase in protein supplies is definitely required to meet the demands of a larger world population, especially in Africa.

Future Protein Demand

Predicting future protein demand hinges on multiple factors that may change simultaneously, making such prediction less certain. Several different scenarios could be used to predict the global demand for protein in the future (Henchion et al. 2017). For example, the most simplistic scenario assumes that population growth will be the driving force in total protein demand without a change in the current consumption levels. Based on this scenario, the global demand for protein would increase by 32% (Henchion et al. 2017). This scenario also assumes that rising incomes and social mobility will not result in protein demands different than those currently experienced. However, rising incomes in developing countries are likely to alter the preference of the population in term of the type of protein to be consumed. For example, trends suggest that consumption of meat and milk stagnated in developed countries, but is rising in

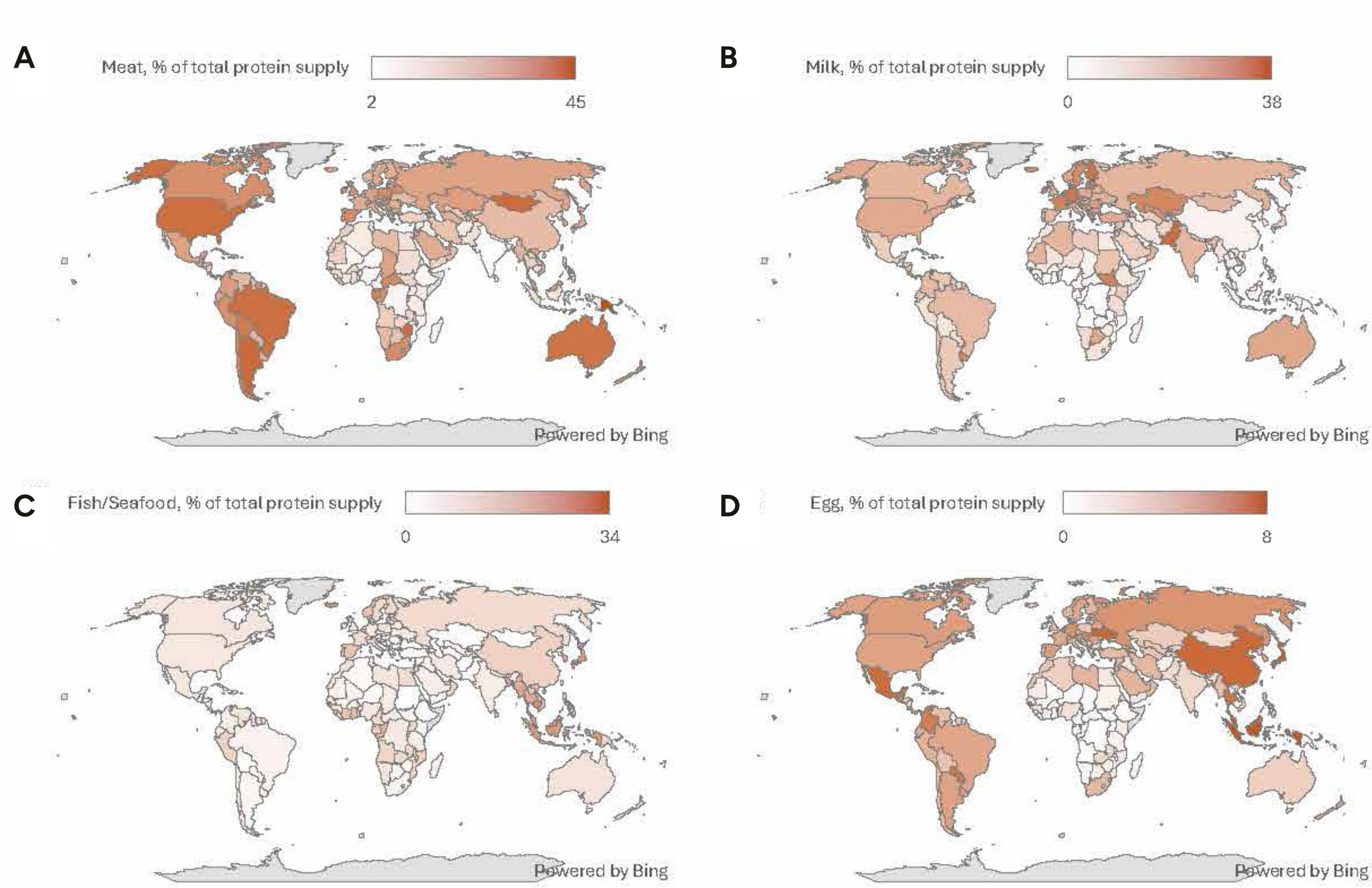

Figure 5. The contribution of meat (A), milk (B), fish and seafood (C), and egg (D) protein to total protein supplies in 2020. Source data: FAO (2023). Microsoft product screen shot(s) reprinted with permission from Microsoft Corporation.

developing countries (Delgado 2003). In fact, animal protein consumption is highly correlated with income rather than total protein intake. An analysis of the causes of spatial variation in protein consumption suggests that protein cost and social mobility are the most important factors affecting protein consumption in general (Grigg 1995). Historically, when wages started to increase in Europe in the early to mid-1900s, consumption of plant protein increased initially without a change in the consumption of animal products; however, once more disposable income was available, the consumption of animal proteins increased at the expense of plant proteins (Grigg 1995). A more recent example is the social mobility and rising income in China, which increased total protein consumption from 60-69 g/cp/d in 1986-1989 to 107 g/cp/d in 2020.

Currently, the RDA for protein is 0.8-0.85 g/kg/d (Table 2). Some experts argue that this allowance was determined using laboratory techniques that are less sensitive than what is currently available. By using new sensitive techniques, it is proposed that the current RDA may not be enough to sustain health across the lifespan, especially for the elderly and high-need populations like pregnant and lactating women. In fact, it was suggested that 0.94–1.30 g/kg/d is needed to maintain muscle mass (Nishimura et al. 2023). Others proposed that 1.2–1.6 g/kg/d would be needed to control satiety and weight management, and a minimum of 1.2 g/kg/d to prevent age-related sarcopenia in the elderly (Phillips et al. 2016). It was also suggested that 1.5 g/kg/d was needed during late gestation, and 1.7-1.9 g/kg/d were recommended in lactating women (Weiler et al. 2023). It remains uncertain whether these proposed protein intake levels will be adopted as new RDAs. If that is the case, it would be expected that global protein consumption would increase, especially in developed countries, independent of any population growth.

It is worth noting that the choice of protein sources and types can vary widely based on cultural, economic, and personal factors. Sustainability and ethical considerations associated with animal protein production and consumption are gaining some importance, especially in developed countries, with respect to making dietary choices. This is leading to the exploration of those alternative or untapped protein sources discussed above.

The Environmental Impact of Protein Production

The efficiency of producing protein for human consumption from plant and animal sources varies considerably. The protein not used to meet human requirements can harm the environment and impact ecosystems and biomes with different intensities and longevities. There are essentially three ways to contaminate the environment due to current food or feed production: (1) inevitable losses that occur during the entire production and commercialization sectors; (2) inefficient use of protein (and other nutrients as well) in animal feed and human food that ends up in the manure pit or sewer system; and (3) incomplete or lack of recycling, upcycling, or reusing byproducts or subproducts originating from the production and commercialization sectors.

Most proteinaceous compounds reaching the environment are in animal feed or human food wastes due to the inherent losses during planting, cultivating, harvesting, transporting, storing, processing, animal feeding, and food preparation, or are the nitrogenous compounds found in feces and urine due to incomplete animal digestive and metabolic processes (i.e., unavoidable losses; CAST 1995). Similarly, nonprotein nitrogen compounds, such as urea, nitrates, and ammonia, commonly used as plant fertilizers or ruminant animal-grade supplements, can also reach the environment due to losses during the application (e.g., leaching, runoff, or erosion) or the unavoidable losses by plants or animals during digestive, absorptive, or metabolic processes. Such inevitable losses occur because these animals' physiological processes are intrinsically inefficient, meaning that not all nutrients (AAs or nonprotein nitrogenous compounds) can be fully digested, absorbed, or metabolized by animals or their gastrointestinal tract microorganisms. Similarly, although their efficiency of utilization may differ, plants cannot absorb all the nonprotein nitrogenous compounds (e.g., fertilizers) that are applied in the field, used for in vitro production of plants or plant products, or even hydroponics (i.e., cultivation of plants without soil).

Another source of proteinaceous compounds reaching the environment is the inherent generation of subproducts or byproducts to produce human food that is not reused, recycled or upcycled, but ends up in the land or soil, water streams, underground water sources, or atmosphere. The only way to minimize their contribution to environmental contamination is by increasing their utilization through recycling or upcycling to replace other nonprotein and protein sources, such as their use for ruminant or fish nutrition. Therefore, wastes and losses of food and feed protein and nonprotein nitrogenous compounds into the environment always occur, and they can adversely impact soil, water, and air.

Causes of Environmental Pollution

Environmental pollution comes from point sources (factory discharge pipes) or nonpoint sources (crops and livestock production) (CAST 1995). Overfeeding nitrogen (protein or nonprotein sources) to livestock likely had its inception with the now phased-out practice of increasing the recommended amount in the diet by a "safety margin" (usually by 10%) to overcome uncertainties in the nitrogen content of feed ingredients and unknown variations in animal requirements, thus ensuring animals would get the "minimum" amount they needed to perform adequately.

However, overfeeding nitrogen (or any other nutrient) creates a two-edged sword dilemma. When an animal is provided with more nitrogen than its body can effectively use, the excess nitrogen will be converted to ammonia, urea, or other nitrogenous compounds in the animal body and later be excreted into the environment through eructation, urination, or defecation. Additionally, adverse effects on the animal are the second possible unintended consequence of overfeeding. For instance, (1) high ammonia levels can be toxic to animals, causing respiratory issues, reduced feed intake, and stress on animal's organs; (2) inefficient rumen fermentation, given the incorrect amounts of protein versus carbohydrate and true protein versus nonprotein sources, can lead to fermentation disorders and rumen health issues (e.g., acidosis); and (3) excess dietary nitrogen can reduce an animal's feed conversion efficiency, leading to higher production costs and subsequent economic losses for livestock producers.

Precision diet formulation aims to provide the accurate amount that livestock requires of a specific nutrient (especially nitrogen) for the targeted performance in growth, development, and reproduction (Vasconcelos et al. 2006; Klopfenstein and Erickson 2022). Therefore, the idea of including an incremental supply of nitrogen (or any other nutrient) beyond the recommended level as a "safety margin" to overcome limitations in assessing the composition of feed ingredients and animals' "true" requirements has become obsolete given the accumulated scientific knowledge and advancements in computer decision support tools (i.e., modeling) in animal nutrition. Instead, the "safety margin" needs to be redefined as the difference between the amount of nutrient livestock require for optimal performance and the maximum amount that can be fed without causing harmful effects to the animal and the environment, serving as a buffer to account for undetectable variations in individual animal responses, variations in the quality of feed ingredients, and environmental factors that can reduce the targeted amount of a nutrient an animal consumes (e.g., feed losses due to rain, wind, sunlight, birds).

A safety margin is supposed to ensure that animals receive enough nutrients to meet their nutritional needs without pushing the limits of their physiological capacities while minimizing the risk of overfeeding and the associated health issues. Many different nutrition models are currently available that account for the majority of factors that can alter the animal's requirement for nitrogen, such as age, body weight, stage of production (e.g., growth, lactation), and the quality of feed being offered. Therefore, because a safety margin is frequently unfeasible, it is highly discouraged, given that the boundaries between animal performance and environmental impact are unclear and the extra economic gain might not offset the medium- to long-term ecological damage.

While providing enough nitrogen is crucial for livestock's well-being and productivity, avoiding overfeeding is also essential to ensure animals' health and optimize their

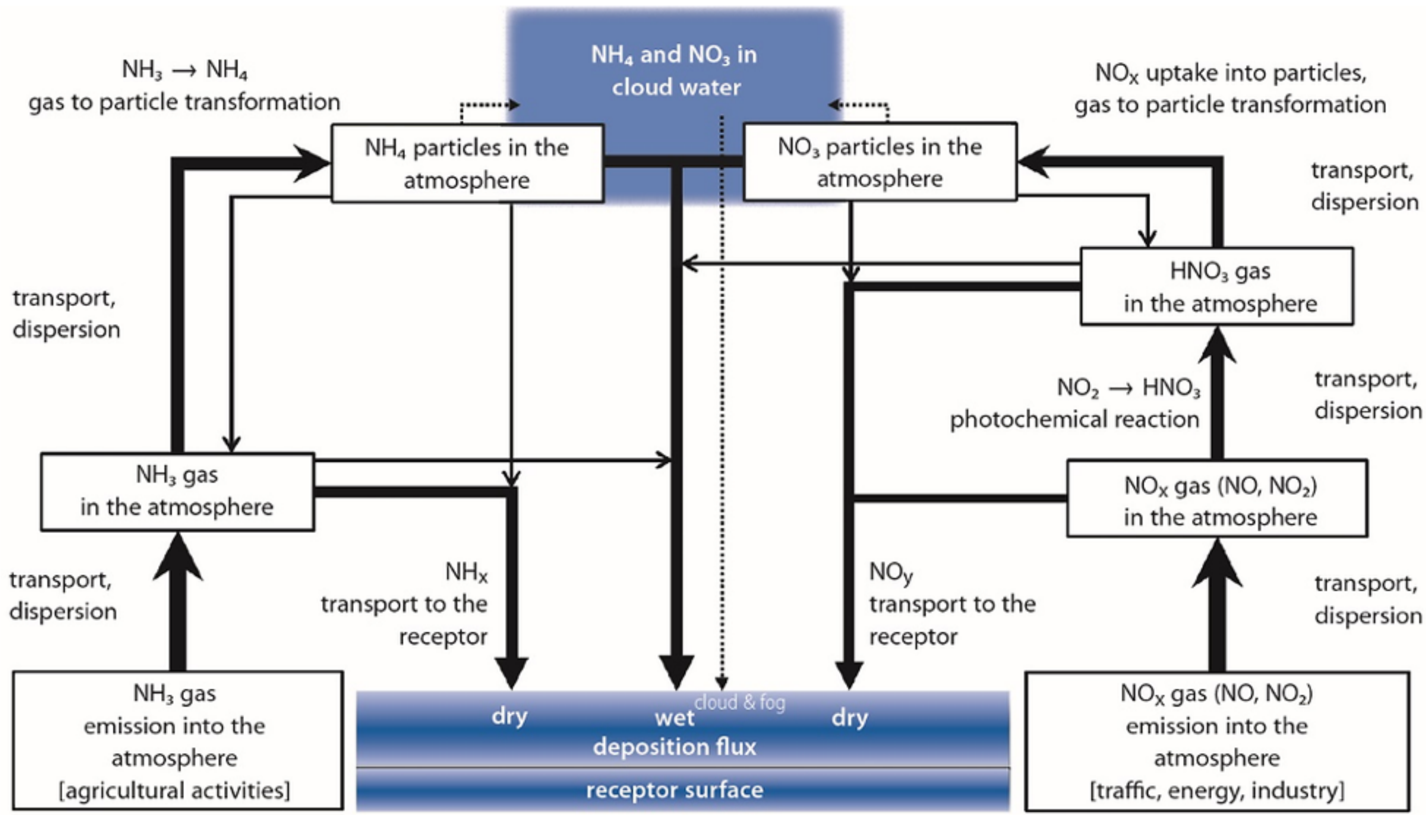

Figure 6. Different nitrogen emissions and pathways. Adapted from: OECD (2018). This is an adaptation of an original work by the OECD. The opinions expressed and arguments employed in this adaptation should not be reported as representing the official views of the OECD or of its Member countries.

performance. Proper nutrient and feed management are necessary for successful sustainable livestock farming. Sustainable agricultural practices, such as precision diet formulation, nutrient management, feed management (Vasconcelos 2007; Cowley et al. 2017), efficient irrigation techniques, agroforestry including silvopastoral systems (Huertas et al. 2021), low-input organic farming, and promoting food protein sources with low ecological footprints, can mitigate the environmental impacts of wasted or excreted nitrogenous compounds. Therefore, implementing policies and regulations to encourage sustainable farming and supporting research and development of innovative and environmentally friendly protein sources for human nutrition can also reduce the ecological impacts of food production and excessive nitrogenous compound usage.

Impacts of Environmental Pollution

Nitrogen emissions originate primarily from human activities, such as the combustion of fossil fuels and agricultural practices that release nitrogen oxides (NOx) and ammonia (NH_3) into the atmosphere. These emissions are then transported through the air, leading to atmospheric deposition onto land and water surfaces. Deposition occurs through dry and wet processes; dry deposition involves directly settling particles onto the surfaces, while wet deposition involves NOx and NH_3 being dissolved in rain or other precipitation and deposited onto the earth surface. This excess nitrogen could have detrimental ecological effects, contributing to air and water pollution, eutrophication of aquatic systems, and disruption of natural nutrient cycles.

Nitrogen emissions and deposition pathways are closely linked to food and feed production due to their connection with agricultural practices. In this context, nitrogen emissions stem from synthetic fertilizer application, livestock farming, and manure management, releasing nitrogen compounds such as NH_3 and NOx into the atmosphere, as shown in Figure 6. These emissions can then contribute to atmospheric deposition on agricultural lands, impacting soil nutrient levels and potentially increasing crop yields.

Water pollution: Nitrogen-based fertilizers, such as urea, ammonium nitrate, natural or composted (CAST 1995) manure from large animal operations, including feedlots, dairies (Rieck-Hinz et al. 1996), swine (Choudhary et al. 1996), and poultry farms, and many agroindustry water waste, such as sugarcane wastes (Faminow 1998), are commonly used for biofuel feedstock (Vancov et al. 2015) or in crop production, except in situations limited by law. When these fertilizers are over-applied or not appropriately managed, they can contribute to water pollution. Excess nitrogen can leach into water bodies (Clark et al. 2017) along with phosphorus (Carpenter 2005), leading to the eutrophication of lakes, rivers, and groundwater, where nutrient levels increase and disrupt the ecological balance. Eutrophication can result in harmful algal blooms, oxygen depletion, and the degradation of aquatic habitats.

Greenhouse gas emissions: Food protein production is associated with greenhouse gas emissions, given that the production and use of synthetic fertilizers release nitrous oxide (N_2O), a potent greenhouse gas. Livestock manure also releases N_2O directly through nitrification and denitrification of its nitrogen in the soil (Figure 7) and indirectly, though at a much smaller proportion, via the denitrification of volatilized NH_3 that returns to the soil with rain, snow, or wind (Suddick et al. 2013). In addition to N_2O, livestock farming, particularly enteric fermentation in ruminants, releases methane (CH_4), another potent greenhouse gas. The extent and intensity of CH_4 emission, however, are relative to the size and development of the energy sector of each country. In the United States, CH_4 from cattle production is responsible for less than 3% of the total anthropogenic greenhouse gas emissions (Dillon et al. 2021; Tedeschi and Beauchemin 2023). Both N_2O and CH_4 emissions contribute to climate change and global warming.

Land use, deforestation, and habitat loss: Protein production requires significant land resources. Expanding agricultural land for protein crops or grazing livestock can lead to the conversion of natural ecosystems, such as forests, grasslands, and wetlands. This conversion can result in habitat destruction, loss of biodiversity, and soil degradation. Although controversial, the expansion of agriculture, including protein crops and animal production, might drive deforestation, particularly in regions with high biodiversity (Faminow 1998). Natural forests, mainly in the tropical and subtropical regions, are cleared to make way for croplands (especially for soybean) or pastureland (for beef cattle), resulting in the loss of valuable habitats for wildlife and carbon sinks. Deforestation contributes to releasing carbon dioxide (CO_2) into the atmosphere, besides reducing biodiversity. However, the intensive production systems associated with judicious use of fertilization and grass-legume consortium to support greater stocking density might improve economic return and reduce environmental burden due to reduced forest clearing and lower use of synthetic fertilizers (Rueda et al. 2003).

Resource allocation: The production, processing, and transportation of protein-rich foods requires energy inputs for irrigation, machinery, transportation, and processing facilities. Thus, the reliance on fossil fuels for energy contributes to carbon emissions and air pollution, further exacerbating the environmental impacts. These food production processes are tightly linked. Not only do protein and nonprotein nitrogenous compounds have an ecological impact, but all the resources associated with protein food production through agriculture carry ecological implications with long-lasting implications for the environment.

The Conversion Efficiency of Feed Protein and Nonprotein into Human Foods

As mentioned above, many different protein sources can be produced for human nutrition, and each has varying environmental impacts and issues. Figure 8 shows the flow

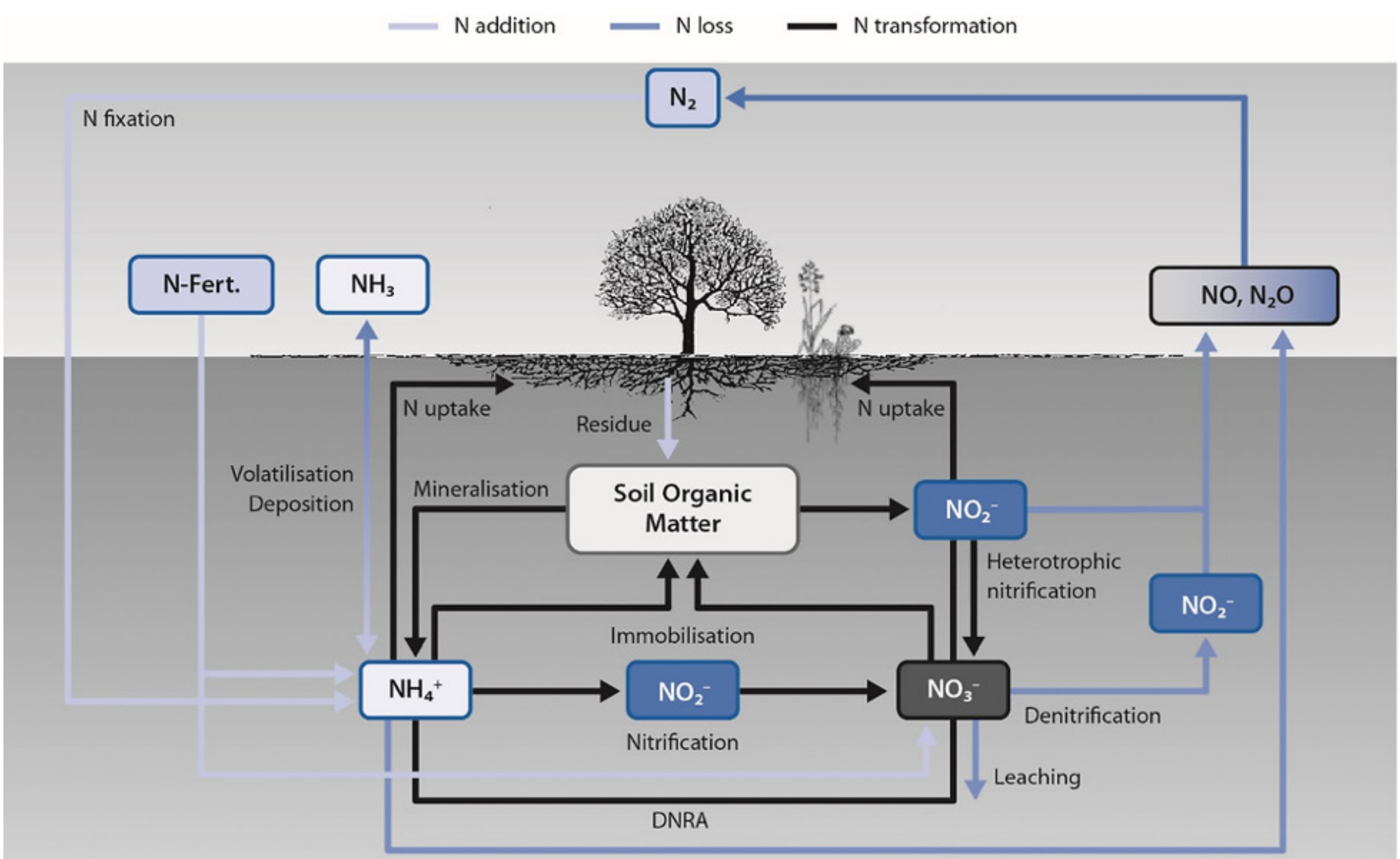

Figure 7. Nitrogen pathways in the soil. Adapted from: OECD (2018). This is an adaptation of an original work by the OECD. The opinions expressed and arguments employed in this adaptation should not be reported as representing the official views of the OECD or of its Member countries.

of nitrogen-containing compounds. It also compares how efficiently ruminants and nonruminants use protein and nonprotein sources to create protein-rich food for humans (indicated by blue arrows). Additionally, the figure depicts how efficiently humans utilize these protein-rich foods. This efficiency is influenced by food preparation losses and the amount of edible food in a given portion.

The efficiencies of use signify which proportion of the original resource (i.e., nitrogen) is retained during the synthesizing or making processes; in other words, some inefficiencies are associated with each process because a portion of the resources are lost or cannot be captured wholly. While some inefficiencies are intrinsic to the functions of transforming matter from one form to another, others might be reduced with better management (e.g., better nutrition, harvesting, storing) or better genetic material (e.g., genetically modified organism, high-production, and resistant or tolerant genotypes).

The efficiencies shown in Figure 8 represent conceptual nitrogen retention efficiencies through the successive steps of transformation from feed to human food and ultimately to human utilization. They are expressed as the proportion of the original nitrogen resource retained after accounting for losses during biological synthesis and food preparation. Importantly, these efficiencies do not represent direct physiological conversions of edible feed protein into edible animal protein. Rather, they summarize the overall retention of nitrogen or protein-equivalent material through the production and consumption chain. The values in Figure 8 (e.g., 50–80%) should thus be interpreted as indicative of the relative magnitude of nitrogen retention from feed to human food, incorporating unavoidable biological and processing losses, not as empirical conversion coefficients derived from feeding trials.

Figure 8 (red lines) also depicts the non-repurposed portion of proteinaceous compounds of subproducts or byproducts that are inherently generated during human food production. The contribution of these subproducts or byproducts to environmental contamination can be minimized if they are reused, recycled, or upcycled in other agricultural activities. Repurposing proteinaceous compounds in subproducts or byproducts is not represented in Figure 8. One way to reuse leftover materials is by feeding them to animals. This includes unprocessed wastes like fruit and vegetable scraps, bakery leftovers, and residues from various industries (breweries, distilleries, sugarcane). Another approach involves using mechanically and chemically treated crop residue (e.g., rice straw, wheat straw, corn stover) to improve its nutritional value for animal feed (Tedeschi et al. 2023). Chicken litter, a mix of manure, bedding, feathers, and spilled feed, can also be repurposed.

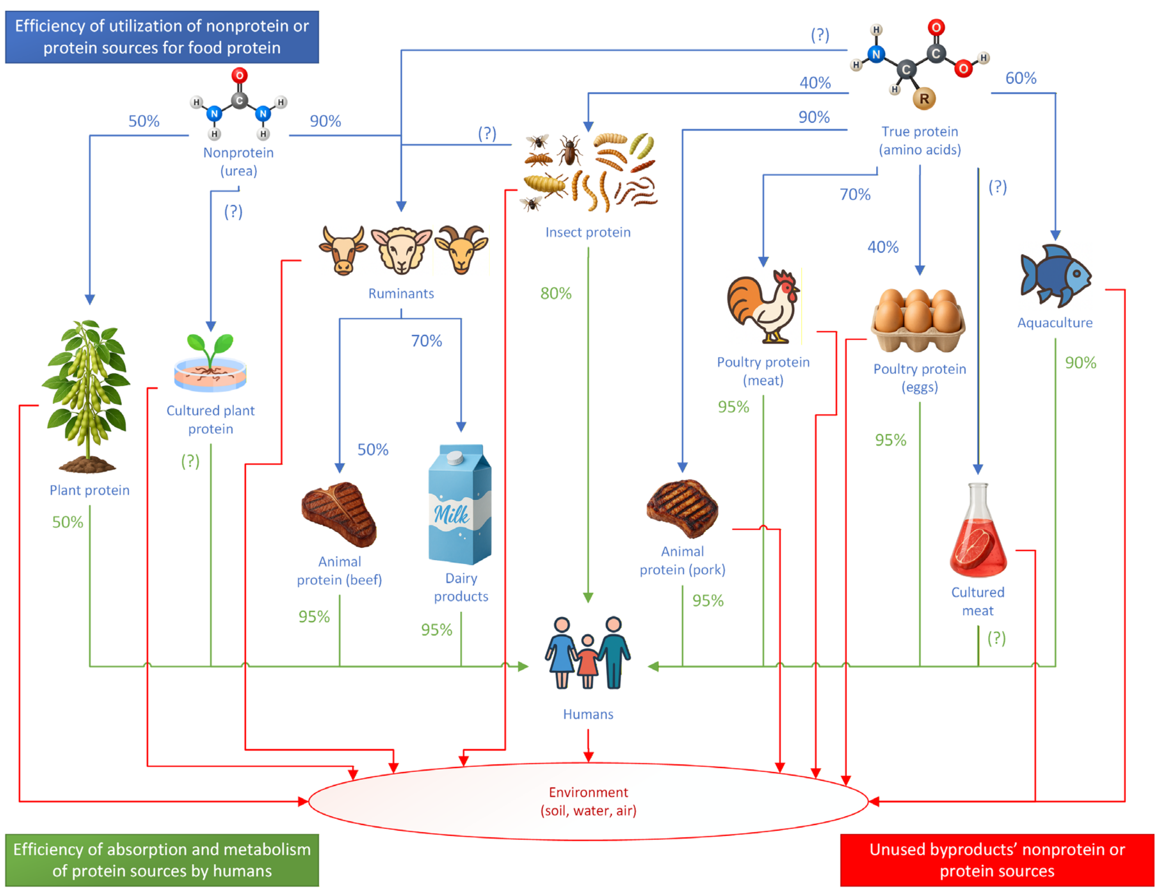

Figure 8. The nonprotein and protein nitrogen flow of different food protein sources for humans. The blue lines represent the efficiency of utilizing nonprotein and protein feed sources by different food production processes; the green lines represent the human efficiency in using them through food preparation, storage, and metabolism to support growth and development; and the red lines represent the nitrogen content of byproducts or subproducts generated by the activity that is not repurposed (i.e., recycled, upcycled, or reused) by other activities. [Visualization created and refined using artificial intelligence tools (ChatGPT), Adobe PhotoShop, and SnagIt.] Source data: CAST (1995, 1999).

It can be used as fertilizer for non-horticultural crops (like corn or soybeans). In some cases, with proper processing (e.g., ensiling, acid treatment, or pelleting) and following regulations, it can even be used as feed for ruminant animals and fish.

Animal-based proteins: There are fundamentally two sources of animal products of interest: meat and dairy. Meat production, especially from conventional livestock farming, can have significant environmental impacts. It requires large amounts of land, water, and feed resources. Meat production is often associated with deforestation, greenhouse gas (primarily CH_4) emissions, water pollution, and animal welfare concerns. Likewise, dairy production has environmental issues similar to meat production, but to a lesser degree in most cases, given the larger number of beef cattle than dairy cattle. The intensity and extent of deforestation are intrinsic to specific regions and circumstances of livestock production, especially grazing cattle in tropical and subtropical areas, due to the expansion of pastureland and increased cereal production to raise confined cattle, swine, and poultry. However, not all livestock production leads to deforestation, and sustainable practices such as agroforestry (e.g., increased carbon sequestration, erosion control, and habitat preservation), robust land use policies (e.g., discourage deforestation), and livestock management (e.g., rotational grazing, improved feed efficiency, and waste management) can be employed to reduce their environmental burden. As shown in Figure 8, when considering the six routes to produce ruminant meat and milk from nonprotein nitrogen, protein nitrogen, and insect feed, the overall efficiencies of converting feed into food and human use of food vary from 50% to 80%. Some estimates, such as the efficiency of insect protein, are currently unavailable. Furthermore, these values do not consider using subproducts or byproducts as feeds, and no meat or dairy can be produced solely from nonprotein nitrogenous compounds; a balanced diet must be used. The overall efficiencies likely range from 50% to 90% when including the nonruminant and aquatic species.

Figure 8, however, does not explicitly consider that a high proportion of the protein fed to ruminants is from sources that are not edible by humans, such as grasses and herbaceous legumes, crop residues, and byproducts of food and fiber processing. Based on the analyses of the three largest beef and dairy-raising countries with wide variations in the proportion of forages, grains, and human-inedible byproducts in their diets (CAST 1999), on average, more than 1 kg of human-edible protein (in meat and milk) per kg of human-edible protein input, with reported average rations of 4.17 for beef, 4.20 for swine, 4.21 for poultry, and 4.24 for milk (CAST 1999). As shown in Table 8, the ratios above unity do not indicate a biochemical conversion efficiency exceeding 100%; rather, they reflect that most of the feed protein is non-edible to humans. In other words, ratios above one indicate that humans benefit more by feeding human-edible nonanimal protein to animals. The highest efficiency (6.12 kg human-edible protein per kilogram of human-edible protein consumed) was for beef cattle in Argentina (Table 8) because most diet proteins are from forages. This production system will return about six times more human-edible protein in the form of animal products (meat or milk) for each amount of human-edible protein fed to animals. Pork and poultry yielded less than 1 kg of human-edible protein (output) per kilogram of human-edible protein consumed (input) because most diets were based on cereal grains. Because ruminant animals contribute to human protein (in the form of meat and milk) worldwide (Table 8), the focus should not be on eliminating them but minimizing their environmental impact, as described previously. In summary, the values in Figure 8 are best understood as conceptual nitrogen-retention efficiencies and not as direct feed-to-edible-protein conversion ratios.

Plant-based proteins: This group comprises pulses, grains, nuts, and seeds. Pulses such as beans, lentils, and chickpeas are considered more environmentally friendly than animal-sourced proteins. Under normal production conditions, they have lower greenhouse gas emissions and require less water and land. However, greenhouse gas emissions can become a much more significant problem due to the transportation of foods, especially those produced far from the consumer market. Leguminous plants can improve soil health through nitrogen fixation. Still, their large-scale production practices can also contribute to deforestation, excessive water use, and indiscriminate use of synthetic fertilizers and pesticides, which can also harm ecosystems. Soybean production is a significant driver of deforestation, particularly in tropical and subtropical regions. Nuts and seeds generally have lower environmental impacts than animal-sourced proteins. However, their production can still require significant water use (high water footprint primarily when cropped in semi-arid regions), and issues related to monocropping and pesticide use may also arise.

When the environmental impacts of plant and animal proteins are compared on a crude-protein basis, plant proteins often appear to be more sustainable. However, these comparisons are substantially altered when protein quality and AA digestibility are taken into account. Leroy et al. (2022) highlighted that proteins from animal sources generally have a higher EAA content, superior digestibility, and greater bioavailability of key micronutrients such as zinc, iron, and vitamin B12. Likewise, Vieux et al. (2022) demonstrated that diets providing less than approximately 45% to 60% of total protein from animal sources could not simultaneously meet nutrient-based recommendations and maintain diet affordability. Therefore, when environmental footprints are expressed per unit of digestible or utilizable protein rather than crude protein mass, the apparent advantage of plant proteins diminishes because larger quantities are needed to achieve equivalent nutritional adequacy. Evaluating sustainability solely on a protein-mass basis overlooks the nutritional density and quality of protein-rich foods, reinforcing the need to consider both the quantity and quality of protein supplied in comparative assessments.

There has been some public encouragement to shift towards more plant-based diets to reduce the demand for livestock products and, consequently, the pressure on deforestation. However, this "alternative solution" is vastly oversimplified and manipulated to reap public appeal (Tedeschi and Beauchemin 2023). It does not consider that animal products have other nonprotein components (e.g., zinc, iron, vitamin B12, conjugated linoleic acid) with greater bioavailability than nonanimal sources (Leroy et al. 2022; Vieux et al. 2022; Chungchunlam and Moughan. 2024). As shown in Figure 8, plant-based and cultured plant proteins have an overall efficiency of about 30%, likely because of the large amount of fertilizer loss and wasted produce, nuts, fruits, and grains, yielding a low efficiency of use by humans. In this case, humans' efficiency of use of food (50%) can be enhanced when plant-based products are recycled (or upcycled) through food processing and bakery wastes fed to livestock, especially ruminants and swine, as discussed above.

Alternative sources of protein: Insect farming has gained traction as a more sustainable protein source due to its efficient feed conversion, low greenhouse gas emissions, and reduced land and water requirements. However, societal acceptance and regulatory frameworks for insect consumption are still evolving, and their nutritive value as animal feed or human food is not fully known. Aquatic sources of protein have the potential to be environmentally friendly, as they can be grown using less freshwater and land compared to terrestrial crops. Algae and seaweed absorb carbon dioxide while growing, potentially mitigating climate change impacts. Like insect farming, their nutritive value is largely unknown, and the "real" cost of producing them requires further investigation, mainly in the realm of the net balance of carbon, year-round productivity, and processing and transportation concerns.

The specific environmental impacts can vary based on farming practices, supply chains, and regional factors. Sustainable agricultural practices, such as organic farming, regenerative agriculture, and efficient resource management, are essential for minimizing the environmental issues associated with food protein production. There is likely no one solution to the environmental pollution and global warming crisis, and combining several approaches might yield the best long-term, sustainable solutions to many of these pervasive problems.

Final Remarks

The global demand for protein is undergoing a significant shift, with consumers predominantly favoring animal-sourced proteins over plant-based or alternative sources. Despite this preference, plant-based proteins currently account for approximately 60% of the total protein supply worldwide. Several factors, including population growth, income levels, and evolving dietary preferences, are expected to continue shaping future protein demand in terms of both quantity and quality (i.e., protein sources).

The quality of dietary protein depends not only on its AA (especially the EAA) profile but also on its digestibility and net AA utilization efficiency. A lack of nutrition knowledge among the general public often leads to unhealthy diets that are unbalanced in AA profile or deficient in micronutrients. While the primary cause of human AA deficiency is protein-deficient diets, it can also occur when protein intake is adequate but of low quality, lacking in one or more EAAs. Animal-sourced proteins are generally more effective at supplying EAAs than plant-sourced proteins due to their superior AA profile and digestibility.

While both plant and animal proteins contain high percentages of certain AAs that include glutamine, glutamate, aspartate, asparagine, phenylalanine, tyrosine, and branched-chain AAs, plant proteins typically lack sufficient amounts of lysine, glycine, proline, threonine, tryptophan, and sulfur-containing AAs, which are more abundant in animal-sourced proteins. Notably, taurine and creatine, absent in plants, are abundant in meat and other animal-sourced proteins (Li et al. 2021). In practice, for optimal growth and health maintenance of body tissues, especially skeletal muscle, a diet solely based on animal protein is preferable to one solely based on plant protein. However, a complementary mix of animal and plant proteins is ideal for a balanced diet because other essential nutrients (such as minerals, vitamins, and fiber) are contained in different protein foods. Some investigators recommended that a healthy diet should consist of 65% animal protein and 35% plant protein, with the ratio possibly increasing to 70% versus 30%, or even 75% versus 25% (Li et al. 2021).

Vegetarian diets are common in many parts of the world, primarily due to the limited access to animal-sourced foods. However, in recent decades, various vegetarian eating patterns have emerged in Western countries where animal-sourced foods are abundant. Reasons for this shift include influences from foreign cuisines, religions, and philosophies, as well as some evidence suggesting that vegetarian diets are associated with a reduced risk of certain diseases. Additionally, debates surrounding the economic and environmental sustainability of food production have further promoted vegetarian eating (Caballero et al. 2013).

For vegetarians, it is essential to plan diets according to the DRI (Tables 2–5) or authoritative nutritional recommendations to ensure they are nutritionally adequate and healthful (Caballero et al. 2013). Ideally, more or at least two plant proteins should be consumed together to improve the adequacy and balance of AAs, although low digestibility remains a problem, particularly for infants and young children (Day et al. 2022). When selecting plant-sourced proteins for vegetarian diets, it is recommended to combine cereal grains with legumes (nuts and seeds) to take advantage of the complementary AA profiles between the two categories of plant proteins.

Different sources of protein foods differ not only in their AA profile, but also in their overall nutrient compositions that include lipids, vitamins, minerals, fiber, calories, and other health-promoting or anti-nutritional chemicals. A well-balanced diet should contain all these nutrients in close-to-ideal proportions relative to the body's requirements of different nutrients and calories. An authoritative guideline, such as those provided by IOM (2005), FAO/WHO/UNU (2007), or USDA/USDHHS (2020) can be used as a reference. However, we should remember that it is not essential to balance AA contents and other nutrients at every meal, especially under conditions where total protein intake substantially exceeds the minimum requirement (Young and Pellett 1994). Consuming complementary proteins at different meals throughout the day can ensure adequate AA nutrition and nitrogen retention.

Finally, it is worth noting that current data on the incidence and mortality of chronic diseases associated with the consumption of animal- or plant-sourced proteins or the emerged sources of proteins are less critically significant than data reported on individual proteins or protein categories, regardless of their sources. Therefore, for optimal health outcomes, an individual consumer should focus on studying and taking advantage of the individual protein foods readily available rather than fixating on specific protein sources or categories.

While global protein production is increasing overall, numerous countries still face protein shortages, highlighting significant disparities in current protein production and supplies. Like many other human activities, protein agriculture does have environmental impacts, including nitrogen emissions, water pollution, deforestation, and greenhouse gas emissions. To mitigate these impacts, addressing inefficiencies and losses occurring during protein production and commercialization is essential. Implementing sustainable agricultural practices, precision diet formulation for animals, and promoting the use of alternative protein sources such as insect farming might reduce particular environmental impacts in some parts of the world. Policies and regulations supporting sustainable farming practices and research into innovative and environment-friendly protein sources are crucial for long-term food and environmental sustainability.

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Tables

Table 1. Nutritional Classification of Amino Acids in Human Diets[1]

Indispensable	Dispensable	Conditionally Indispensable[2]	Precursors of Conditionally Indispensable
Lysine	Alanine	Arginine	Glutamine/glutamate, asparate
Methionine	Aspartic acid	Cysteine	Methionine, serine
Tryptophan	Asparagine	Glutamine	Glutamic acid/ammonia
Threonine	Glutamic acid	Glycine	Serine, choline
Valine	Serine	Proline	Glutamate
Isoleucine		Tyrosine	Phenylalanine
Leucine			
Histidine			
Phenylalanine			

[1] Adapted from IOM (2005, 2006).

[2] These amino acids, usually in the dispensibe group, are so called because the body's synthesis of them can be limited under some special pathophysiological conditions, such as prematurity in young infants or individuals with severe catabolic stress.

	DRI, g/kg/day (g/day)				
	EAR[3]		RDA[4]		AI[5]
Life stage	**Male**	**Female**	**Male**	**Female**	
0 ~ 6 mo					1.52 (9.1)[6]
7 ~ 12 mo	1.00	1.00	1.20 (11)	1.20 (11)	
1 ~ 3 yo	0.87	0.87	1.05 (13)	1.05 (13)	
4 ~ 8 yo	0.76	0.76	0.95 (19)	0.95 (19)	
9~ 13 yo	0.76	0.76	0.95 (34)	0.95 (34)	
14 ~ 18 yo	0.73	0.71	0.85 (52)	0.85 (46)	
19 ~ 30 yo	0.66	0.66	0.80 (56)	0.80 (46)	
31 ~ 50 yo	0.66	0.66	0.80 (56)	0.80 (46)	
51 ~ 70 yo	0.66	0.66	0.80 (56)	0.80 (46)	
> 70 yo	0.66	0.66	0.80 (56)	0.80 (46)	
Pregnancy[7]		0.88		1.10 (71)	
Lactation		1.05		1.30 (71)	

Table 2. Dietary Reference Intake (DRI) of Total Protein[1] at Different Life Stages[2]

[1] The nitrogen content in dietary protein is approximately 16%.
[2] Data (grams of protein needed per kg body weight per day) were adapted from IOM (2006).
[3] EAR (Estimated Average Requirement): the average daily intake level estimated to meet the requirements of half of the healthy individuals in the group.
[4] RDA (Recommended Dietary Allowance): the average daily intake level sufficient to meet the requirements of nearly all the healthy individuals in the group.
[5] AI (Adequate Intake): an average intake value estimated for the whole group of healthy breast-fed infants.
[6] Values in parentheses are examples of the total protein intake (g/day) calculated from the RDA (g/kg/day) times the reference (or typical) body weights (kg).
[7] The values were estimated only for the second half of pregnancy. For the first half of pregnancy, the protein intakes are the same as those for the non-pregnant females.

Table 3. Dietary Reference Intake (DRI) of Indispensable Amino Acids[1] for Infants and Children (0 through 8 years old)[2]

	DRI, g/kg/day (g/day)		
Life stage & Amino acid	**EAR[3]**	**RDA[4]**	**AI[5]**
Infants (0 ~ 6 mo)			
Lysine			107 (640)6
Methionine + cysteine			59 (353)
Tryptophan			28 (167)
Threonine			73 (436)
Valine			87 (519)
Isoleucine			88 (529)
Leucine			156 (938)
Histidine			36 (214)
Phenylalanine + tyrosine			135 (807)
Infants (7 ~ 12 mo)			
Lysine	62	89 (801)	
Methionine + cysteine	30	43 (387)	
Tryptophan	9	13 (117)	
Threonine	34	49 (441)	
Valine	39	58 (522)	
Isoleucine	30	43 (387)	
Leucine	65	93 (837)	
Histidine	22	32 (288)	
Phenylalanine + tyrosine	58	84 (756)	
Children (1 ~ 3 yo)			
Lysine	45	58 (696)	
Methionine + cysteine	22	28 (336)	
Tryptophan	6	8 (96)	
Threonine	24	32 (384)	
Valine	28	37 (444)	
Isoleucine	22	28 (336)	
Leucine	48	63 (756)	
Histidine	16	21 (252)	
Phenylalanine + tyrosine	41	54 (648)	
Children (4 ~ 8 yo)			
Lysine	37	46 (920)	
Methionine + cysteine	18	22 (440)	
Tryptophan	5	6 (120)	
Threonine	19	24 (480)	
Valine	23	28 (560)	
Isoleucine	18	22 (440)	
Leucine	40	49 (980)	
Histidine	13	16 (320)	
Phenylalanine + tyrosine	33	41 (820)	

[1] Cysteine and tyrosine are conditionally indispensable amino acids. While methionine is a precursor of cysteine, phenylalanine is the precursor of tyrosine.
[2] Data were adapted from IOM (2006).
[3] EAR (Estimated Average Requirement): the average daily intake level estimated to meet the requirements of half of the healthy individuals in the group.
[4] RDA (Recommended Dietary Allowance): the average daily intake level sufficient to meet the requirements of nearly all the healthy individuals in the group.
[5] AI (Adequate Intake): an average intake value estimated for the whole group of healthy breast-fed infants.
[6] Values in parentheses are examples of the total amino acid intake (mg/day) calculated from the RDA (mg/kg/day) times the reference (or typical) body weights (kg).

	DRI, g/kg/day (g/day)			
	EAR[3]		RDA[4]	
Life stage	**Male**	**Female**	**Male**	**Female**
9 ~ 13 yo				
Lysine	37	35	46 (1.66)[5]	43 (1.59)
Methionine + cysteine	18	17	22 (0.79)	21 (0.78)
Tryptophan	5	5	6 (0.22)	6 (0.22)
Threonine	19	18	24 (0.86)	22 (0.81)
Valine	23	22	28 (1.01)	27 (1.00)
Isoleucine	18	17	18 (0.65)	21 (0.78)
Leucine	40	38	49 (1.76)	47 (1.74)
Histidine	13	12	17 (0.61)	15 (0.56)
Phenylalanine + tyrosine	33	31	41 (1.48)	38 (1.41)
14 ~ 18 yo				
Lysine	35	32	43 (2.62)	32 (1.73)
Methionine + cysteine	17	16	21 (1.28)	19 (1.03)
Tryptophan	5	4	6 (0,37)	5 (0.27)
Threonine	18	17	22 (1.34)	21 (1.13)
Valine	22	20	27 (1.65)	24 (1.30)
Isoleucine	17	16	21 (1.28)	19 (1.03)
Leucine	38	35	47 (2.87)	44 (2.38)
Histidine	12	12	15 (0.92)	14 (0.76)
Phenylalanine + tyrosine	31	28	38 (2.32)	35 (1.89)
> 19 yo				
Lysine	31	31	38 (2.66)	38 (2.17)
Methionine + cysteine	15	15	19 (1.33)	19 (1.08)
Tryptophan	4	4	5 (0.35)	5 (0.29)
Threonine	16	16	20 (1.40)	20 (1.14)
Valine	19	19	24 (1.68)	24 (1.37)
Isoleucine	15	15	19 (1.33)	19 (1.08)
Leucine	34	34	42 (2.94)	42 (2.39)
Histidine	11	11	14 (0.98)	14 (0.80)
Phenylalanine + tyrosine	27	27	33 (2.31)	33 (1.88)

Table 4. Dietary Reference Intake (DRI) of Indispensable Amino Acids[1] for Adolescents (9 through 19 years old) and Adults (> 19 years old)[2]

[1] Cysteine and tyrosine are conditionally indispensable amino acids. While methionine is a precursor of cysteine, phenylalanine is the precursor of tyrosine.
[2] Data were adapted from IOM (2006).
[3] EAR (Estimated Average Requirement): the average daily intake level estimated to meet the requirements of half of the healthy individuals in the group.
[4] RDA (Recommended Dietary Allowance): the average daily intake level sufficient to meet the requirements of nearly all the healthy individuals in the group.
[5] Values in parentheses are examples of the total amino acid intake (g/day) calculated from the RDA (mg/kg/day) times the reference (or typical) body weights (kg).

	DRI, g/kg/day (g/day)	
Life stage & Amino acid	**EAR[3]**	**RDA[4]**
Pregnancy[5]		
Lysine	41	51 (3.29)5
Methionine + cysteine	20	25 (1.61)
Tryptophan	5	7 (0.45)
Threonine	21	26 (1.68)
Valine	25	31 (2.00)
Isoleucine	20	25 (1.61)
Leucine	45	56 (3.61
Histidine	15	18 (1.16)
Phenylalanine + tyrosine	36	44 (2.84)
Lactation		
Lysine	42	52 (2.84)
Methionine + cysteine	21	26 (1.42)
Tryptophan	7	9 (0.49)
Threonine	24	30 (1.64)
Valine	28	35 (1.91)
Isoleucine	24	30 (1.64)
Leucine	50	62 (3.39)
Histidine	15	19 (1.04)
Phenylalanine + tyrosine	41	51 (2.79)

Table 5. Dietary Reference Intake (DRI) of Indispensable Amino Acids[1] for for Pregnant and Lactating Women[2]

[1] Cysteine and tyrosine are conditionally indispensable amino acids. While methionine is a precursor of cysteine, phenylalanine is the precursor of tyrosine.
[2] Data were adapted from IOM (2006). For pregnant women, the values were estimated only for the second half of pregnancy. For the first half of pregnancy, the amino acid intakes are the same as those for non-pregnant females.
[3] EAR (Estimated Average Requirement): the average daily intake level estimated to meet the requirements of half of the healthy individuals in the group.
[4] RDA (Recommended Dietary Allowance): the average daily intake level sufficient to meet the requirements of nearly all the healthy individuals in the group.
[5] Values in parentheses are examples of the total amino acid intake (g/day) calculated from the RDA (mg/kg/day) times the reference (or typical) body weights (kg).

Table 6. Protein Concentration for Selected Foods of Plant and Animal Origin[1]

[1] Data were mainly adapted from Young and Pellett (1994), Sá et al. (2020), and Caballero et al. (2013). n/d = not determined.

Food	Protein %
Cereals & Pseudocereals	
Corn	9.4
Wheat, hard	12.6
Wheat, durum	13.7
Wheat flour	10.3
Rice, brown	7.9
Rice, white	7.1
Barley	12.5
Sorghum	11.3
Oats	16.9
Rye	14.8
Triticale	13.2
Millet	11.0
Spaghetti	12.8
Buckwheat	13.3
Amaranth	14.5
Bulgur	12.2
Legumes	
Soybean	36.5
Bean, white	21.9
Bean, kidney	23.6
Lima bean	21.5
Wing bean	29.7
Mung bean	23.9
Chickpea	19.3
Cowpea	23.5
Pigeon pea	21.7
Lentil	28.1
Lupine	36.2
Nuts & Seeds	
Almond	20.4
Peanut	25.8
Brazil nut	14.3
Cashew	15.3
Coconut	3.3
Pecan	8.00
Pistachio	14.9
Walnut	14.3
Cottonseed	41.0
Flaxseed 1	26.4
Flaxseed 2	20.9
Chia 1	n/d; < 24
Chia 2	24.6
Pumpkin seed	24.5
Sesame seed	17.7
Sunflower seed	22.8

Food	Protein %
Vegtables	
Bean, green	1.8
Broccoli	3.0
Cabbage	1.2
Carrots	1.0
Cassava	1.3
Okra	2.0
Onion	1.2
Peas, green	5.4
Pepper, sweet	0.9
Potato	2.1
Spinach	2.9
Squash	1.2
Sweet potato	1.7
Taro	1.5
Tomato	0.9
Turnip	0.9
Yam	1.5
Fruits	
Apples	0.2
Avocados	2.0
Bananas	1.0
Figs	0.8
Orange	0.9
Peach	0.7
Pear	0.4
Pineapple	0.4
Plantain	1.3
Plum	0.8
Animal Products	
Beef, lean, raw	21.4
Beef, lean, cooked	29.8
Beef, top round, broiled	31.8
Pork, lean, cooked	27.5
Pork, ham, roasted	29.4
Lamb, lean, cooked	26.7
Veal, lean, cooked	31.9
Veal, top round, fried	33.2
Broiler, roasted	28.9
Turkey, roasted	29.3
Fish, raw	20.0
Fish, fried	31.8
Milk, powder	26.1
Egg, chicken	12.6
Egg, goose	13.9

Plant-Sourced Proteins	Lysine	Methionine + Cysteine	Tryptophan	Threonine	Valine	Isoleucine	Leucine	Histidine	Phenylalanine + Tyrosine
Cereals & Pseudocereals									
Corn	29	44	8	36	51	39	128	27	100
Corn meal	29	32	5	26	46	38	109	27	88
Wheat flour	27	41	13	31	47	37	75	26	85
Wheat, durum	24	36	13	30	44	26	70	23	73
Rice	28	44	14	37	63	45	88	26	82
Rice protein concentrate	21	39	11	28	45	34	62	17	104
Rice protein isolate	23	40	12	29	44	34	64	17	86
Barley, dehulled seed	37	42	16	35	53	38	71	22	87
Sorghum	16	7	n/d	29	43	34	127	18	76
Oat	43	43	9	35	54	39	76	25	91
Buckwheat protein	52	42	17	35	52	38	68	25	80
Amaranth	43	41	n/d	31	21	19	43	27	55
Quinoa	24	6	10	67	9	8	24	19	27
Legumes									
Soybean	73	31	16	47	55	54	90	28	99
Isolated soy protein	56	26	13	39	51	49	56	25	94
Soy protein concentrate	62	28	12	36	47	45	76	25	86
Bean	62	10	n/d	24	43	40	72	30	81
Faba bean	63	27	8	39	48	35	85	31	77
Pea	69	70	n/d	35	47	42	71	22	77
Pea protein concentrate	67	19	9	38	49	44	76	24	97
Chickpea	55	22	10	32	37	38	65	23	82
Cowpea	71	n/d	n/d	38	59	48	83	38	95
Canola	56	45	13	44	55	23	71	31	70
Lentil	69	26	5	44	46	35	71	29	71
Lupine	45	13	10	40	41	40	69	39	80
Nuts & Seeds									
Almonds, Baru	66	30	11	55	56	33	74	23	89
Almonds, Pequi	30	62	10	22	40	28	65	28	67
Peanut	39	16	7	22	40	35	70	25	88
Cashew	45	36	17	36	54	42	73	23	87
Brazil nut	25	34	n/d	43	63	40	79	18	62
Flaxseed 1	37	26	16	44	48	40	61	25	75
Flaxseed 2	41	38	n/d	39	53	42	61	21	76
Sesame	38	30	7	27	50	39	74	30	97
Sunflower seed	44	51	n/d	40	54	50	68	26	89
Hemp protein isolate	27	32	10	34	47	36	65	32	83
Hemp seed protein meal	39	38	11	38	47	36	69	33	77
Animal Proteins									
Beef	70	35	10	36	46	40	65	31	61
Pork	76	30	11	40	47	39	71	37	68
Chicken	100	31	n/d	46	51	52	85	34	40
Freshwater fish	33	14	6	38	44	38	57	33	52
Marine fish	76	30	20	65	84	50	96	7	38
Cow milk	84	30	14	47	65	53	99	28	95
Goat milk	97	42	15	54	80	69	105	30	111
Sheep milk	90	33	17	49	69	54	105	29	99
Casein	85	33	14	46	76	59	102	31	114
Whey protein	109	52	17	88	69	74	121	16	75
Whole egg	78	47	12	51	64	57	91	25	98
Egg white (albumin)	62	38	10	36	49	46	68	17	77
Egg yolk	104	50	18	71	72	65	115	33	114

Table 7. The Compositions of Essential Amino Acids in the Proteins of Common Plant- and Animal-sourced Foods (mg/g Protein)[1]

[1] Data were adapted from Day (2013), Sá et al. (2020), and Day et al. (2022). Other data can be seen from Li et al. (2021). n/d = not determined.

Table 8. Ratios of Human-Edible Protein From Animal Source to Human-Edible Protein From Nonanimal Sources Fed to Animals[1,2]

Country	Beef meat	Dairy products	Pork meat	Poultry meat
Argentina	6.12	1.64	0.11	0.69
Mexico	4.39	1.06	0.21	0.83
United States	1.19	2.08	0.29	0.62

[1] Adapted from CAST (1999).
[2] Here, the animals include ruminants, nonruminants (swine), and poultry.