frontiers | Frontiers in Sustainable Food Systems

TYPE Perspective
PUBLISHED 29 November 2022
DOI 10.3389/fsufs.2022.1012813

OPEN ACCESS

EDITED BY
Samuel Ayofemi Olalekan Adeyeye,
Hindustan University, India

REVIEWED BY
Abiodun Aderoju Adeola,
Federal University of Agriculture,
Abeokuta, Nigeria
Aida Turrini,
Independent Researcher, Rome, Italy

*CORRESPONDENCE
Matthew A. Pikosky
Matthew.Pikosky@dairy.org

SPECIALTY SECTION
This article was submitted to
Nutrition and Sustainable Diets,
a section of the journal
Frontiers in Sustainable Food Systems

RECEIVED 05 August 2022
ACCEPTED 14 November 2022
PUBLISHED 29 November 2022

CITATION
Pikosky MA, Ragalie-Carr J and Miller GD (2022) Recognizing the importance of protein quality in an era of food systems transformation. *Front. Sustain. Food Syst.* 6:1012813. doi: 10.3389/fsufs.2022.1012813

Recognizing the importance of protein quality in an era of food systems transformation

Matthew A. Pikosky*, Jean Ragalie-Carr and Gregory D. Miller

National Dairy Council, Rosemont, IL, United States

A transformation of current food systems is needed to nourish the growing global population in more sustainable ways. To support this, some are advocating for a shift to plant-based or -exclusive diets. These recommendations – typically borne out of concerns for the environment – often fail to account for unintended nutritional consequences, which could be particularly pronounced for protein intake. While there is enough protein to meet current global needs, the issue of protein quality is often overlooked and oversimplified. High-quality protein, including from animal source foods (ASF), is needed to meet nutritional demands in low- and middle-income countries (LMIC), particularly among vulnerable population groups. In high-income countries (HIC), protein quality is important for at-risk populations who have higher protein requirements and lower energy and/or protein intakes. Further, as the global population increases, driven primarily by population growth in LMIC, it is possible that protein production will need to increase in HIC to support exports to help feed the global population. The global dialogue and resulting dietary recommendations must therefore become more nuanced to consider the interaction between nutritional value and environmental impact to help better reflect trade-offs across multiple domains of sustainability. Nutritional life cycle assessments are one way to help accomplish this nuance and evaluate how all types of food production systems should be refocused to improve their environmental efficiency and nutritional impact.

KEYWORDS
protein, protein quality, food systems, nutrition, sustainability, animal source foods

Introduction

Food systems affect population health, natural resource use, and socioeconomic issues and are in turn vulnerable to environmental changes. This vulnerability – coupled with growing demands to feed a global population of nearly 10 billion by 2050 – has accelerated recommendations to achieve "food systems transformation" (Fanzo et al., 2020). These recommendations take many forms, including national guidance through food-based dietary guidelines (FBDG) or reports from non-governmental organizations.

A prominent theme is a shift to plant-based or -exclusive diets, with emphasis on plant-based proteins, largely for environmental reasons. Cell cultured proteins, insects, and mycoproteins are also being considered as animal protein alternatives, though uncertainties remain regarding their viability on a mass scale. While some recommendations acknowledge the valuable role of both ASF and plant-based foods (PBF) as part of a healthy diet, others argue for PBF to replace ASF (Herforth et al., 2019; Comerford et al., 2021). Among one-third of national FBDG with "protein food" messages, PBF are explicitly presented as substitutes for ASF or are implied to be alternatives through inclusion in the same general message as ASF (Herforth et al., 2019). This perspective over-indexes on the environment and overlooks other domains of sustainable food systems, including nutrition, health, and sociocultural factors (Drewnowski, 2017). This paper focuses on what overlooking other domains of sustainability, particularly nutrition and health, could mean for protein quality.

Protein quality

Protein contains essential amino acids (EAA) that are needed for physiological functions across all life stages (Institute of Medicine, 2003). Foods and dietary patterns differ in protein and amino acid (AA) content and thus in their protein quality (Millward et al., 2008). Protein quality is defined as the ability of a dietary protein to meet the body's metabolic demand for AA and nitrogen. It is based on AA composition, digestibility of the dietary protein, and bioavailability of the AA from that dietary protein (Boye et al., 2012; FAO, 2013). Protein quality is therefore critical when assessing nutrient adequacy of the food supply and dietary intake at the individual- and population-level (Cifelli et al., 2016).

There is significant variation in protein quality across ASF and PBF, which is important to consider when recommending shifts in dietary patterns (Gwin et al., 2021). ASF like dairy, eggs, and meat are highly digestible (>90%); depending on the processing method and/or presence of antinutrients, PBF like maize, oat, bean, and pea typically have lower digestibility (45–80%) (van Vliet et al., 2015). There may also be differences in how the protein is metabolized and utilized by the body. For example, AA from soy and wheat are more readily converted to urea than those from milk, which results in a lower potential of these PBF to stimulate muscle protein synthesis (van Vliet et al., 2015). Dietary patterns that include a diverse mixture of ASF and PBF (including common staple foods and neglected or underutilized crops) often have high protein quality as their AA profiles complement one another. It is possible to consume complete protein through a combination of different types of PBF with complementary AA compositions; however, doing so is challenging among population groups that have higher protein requirements and/or are not accustomed to consuming a diverse variety of PBF.

Protein intake and quality across global contexts

Low- and middle-income countries

Ensuring adequate supply and consumption of high-quality protein is a global issue. Complex interactions between food availability, prices, and market structure in LMIC influence access to and consumption of foods (Turner et al., 2020). Influenced by such factors, total energy and protein intakes are typically low among populations in LMIC, where protein intake is primarily driven by protein derived from PBF (Allen, 2012). An analysis of protein intake among adults across 103 countries in Sub-Saharan Africa and Asia found that after adjusting for protein quality, average daily protein intake was below the requirement in all countries (Moughan, 2021). Additionally, demonstrating the importance of protein quality in LMIC, these data can serve as a model of what might happen in HIC if recommendations to substitute ASF with PBF do not consider how such dietary shifts can impact protein quality, particularly among at-risk populations. Such recommendations should specify the types and quantities of foods that can be swapped without compromising nutrient intakes.

Intake of high-quality protein is critical for children and adolescents with high nutrient needs to support periods of rapid growth. Improving dietary quality during early life has been a challenge in LMIC, where children's diets primarily consist of PBF that lack the required energy and nutrient density (Dewey, 2013). Because ASF are dense in complete protein, essential fatty acids, and multiple bioavailable micronutrients, the inclusion of even small amounts in the diet can be beneficial for the undernourished (Neumann et al., 2001; Allen, 2012).

High-income countries

Intake of protein derived from ASF is higher in HIC compared to LMIC. In the United States (U.S.), average per capita protein intake is ∼1.2 g/kg/d, with ∼65% of the protein consumed coming from ASF (Pasiakos et al., 2015). However, it is important to consider how average protein intake and requirements differ by population sub-groups in HIC. Among older adults, experts have recommended the importance of higher protein intakes with considerations for protein quality due to the "anabolic resistance" of aging and risk of sarcopenia (Bauer et al., 2013; Deutz et al., 2014). Optimal intake of dietary protein may alleviate declines in muscle function, muscle wasting, and frailty, and proteins derived from ASF can support muscle protein synthesis because they contain relatively high amounts of EAA that are more digestible and bioavailable (Sahni et al., 2015; Tessari et al., 2016).

Although consuming more total protein from PBF or a combination of complementary plant-based proteins may result in a similar amount of digestible and bioavailable EAA compared to ASF, doing so would require additional calorie consumption that may not be advisable in certain populations. A modeling exercise matching total protein from a vegan dietary pattern to recommended protein intakes illustrated that higher total energy intake would be needed to meet EAA requirements in older women compared to a dietary pattern incorporating ASF due to the lower EAA density (EAA/100 kcal) of most PBF (Fussell et al., 2021). The study did not consider digestibility or bioavailability, which may have further impacted the observed differences.

Further, few studies have assessed the impact of consuming plant-based or -exclusive diets on skeletal muscle mass and strength among older adults. This highlights the need for further research as the loss of muscle mass and strength that occurs with aging is a public health problem (Fussell et al., 2021; Domi et al., 2022). Some evidence has shown the benefits of including sources of high-quality protein in older adults' diets. An intervention providing dairy foods resulted in improved intakes of protein and calcium and a reduced risk of falls and fractures among older women (Iuliano et al., 2021). A systematic review concluded that higher-quality protein was beneficial for muscle protein synthesis at rest and following resistance exercise in older and young adults, and that it was associated with greater gains in strength when combined with resistance exercise training (Morgan et al., 2021). Most studies included in the review used isolated protein ingredients or whole foods that are of high protein quality (e.g., milk, whey, soy). Studies that employ a broader range of protein quality in the context of mixed dietary patterns are needed, as well as in situations with low protein intake (Morgan et al., 2021).

The trend in overlooking and oversimplifying the importance of protein quality

Although evidence demonstrates the importance of considering protein quality and quantity when designing dietary recommendations, the topic has often been overlooked or oversimplified (Millward et al., 2008; Burd et al., 2019; Comerford et al., 2021). For example, driven by concerns for the environmental impact of current dietary practices, several countries have adapted FBDG that promote increased consumption of PBF and decreased consumption of ASF, either directly or indirectly, while not acknowledging a consideration for protein quality (Brink et al., 2019; Meltzer et al., 2019).

Typical recommended PBF to address protein intake include legumes, nuts, and seeds. Achieving transformation to sustainable healthy diets as defined by the EAT-*Lancet* Commission would require >100% increase in the global consumption of foods like legumes and nuts (Willett et al., 2019). Yet, intake of these foods is low – average per capita consumption of legumes is 21 g/day globally and 9.3 g/day in the U.S., which is below the recommendation in the Dietary Guidelines for Americans (DGA) (Dry Bean Council US, 2021; Semba et al., 2021a). Shifting dietary patterns toward higher legume, nut, and seed consumption requires significant changes in behavior, knowledge, and food preparation skills. A question therefore remains on how feasible such shifts would be given current dietary practices (Semba et al., 2021b).

Some research indicates recommendations to swap PBF for ASF can negatively impact intakes of protein and select micronutrients, particularly when modeled based on current consumption patterns. A study modeling different dietary scenarios using NHANES data found that increased intake of PBF resulted in an increased percentage of children (2–18 years) and adults (≥19 years) not meeting the Estimated Average Requirement (EAR) for protein, vitamins A and D, and calcium, which are nutrients of concern in the U.S. (Cifelli et al., 2016). Another modeling study found that doubling the intake of PBF led to a decrease in protein intake by about 22% among women and men aged ≥51 years. Additionally, protein intake among women ≥71 years decreased below the RDA and the percentage not meeting the EAR increased to 33% (Houchins et al., 2017). This demonstrates the potential detrimental effect on dietary outcomes if population groups increase PBF intake while decreasing ASF intake.

ASF's nutritional contributions to the protein quality debate

ASF are recognized for contributing to the overall quality of diet but have also received negative attention for their environmental impact. Early assessments of the effect of macrobiotic diets (i.e., diets based on whole-grain cereals, pulses, and vegetables) on infant and child growth and development in the Netherlands demonstrated the importance of including ASF in the diet. Results from these studies observed markedly lower intakes of energy and protein among children receiving macrobiotic diets compared to those receiving omnivorous diets, which was linked with linear growth faltering, fat and muscle wasting, and delayed development (Dagnelie and van Staveren, 1994).

ASF are rich sources of essential fatty acids and multiple micronutrients that are commonly lacking in the diets in LMIC, including vitamin A, vitamin B12, vitamin D, iron, zinc, and calcium (Neumann et al., 2001). They are particularly important for infants, young children, adolescents, and pregnant and lactating women who are undergoing physiological changes and have higher nutrient requirements (Nordhagen et al., 2020). Micronutrients in ASF have high bioavailability and enhance the absorption of nutrients from PBF with high phytate and fiber content that may inhibit the absorption of minerals (Gibson et al., 2003).

Animal products differ in their nutrient composition. Using dairy as an example, milk and milk products contain 13 essential nutrients, including high-quality protein, vitamin A, vitamin B12, vitamin D, riboflavin, folate, and calcium (Allen and Dror, 2011). Studies have consistently shown a positive association between dairy intake and linear growth in children aged 12–60 months. Further, the elimination of cow's milk from the diet has been found to be associated with a reduction in height and an increased risk of bone fractures among children (Goulding et al., 2004; Clark et al., 2020).

In the U.S., dairy is under-consumed relative to recommendations in the DGA (Krebs-Smith et al., 2010). Few people reach the recommended intakes of several key nutrients without consuming the recommended amounts of dairy foods (Weaver, 2014). A trend toward decreasing ASF intake could further reduce the intake of this food group.

In terms of plant-based milk alternatives, it is important to consider the variation in their nutritional profiles and that most do not provide the same nutrients as cow's milk. A study comparing the nutrient composition and carbon footprint of cow's milk and plant-based beverages (e.g., soy, oat, almond, coconut, and rice beverages) found that the protein and EAA content of cow's milk was higher. Although the carbon footprint of cow's milk was higher compared to plant-based beverages when expressed per serving, when expressed based on index of nutritional value (i.e., ability to contribute to meeting EAA requirements), the carbon footprint of cow's milk was lower than that of all plant-based drinks examined, except for soy beverage (Singh-Povel et al., 2022). These findings reflect the importance of considering the nutritional value of food choices when reporting environmental impact and making broader conclusions regarding sustainability.

Achieving the nuance needed through nutritional-based functional units in life cycle assessments

The sustainability of food systems can be measured across four domains: health, environmental, economic, and societal (Drewnowski, 2017). Each domain has respective metrics. For example, nutrient profiling models estimate the nutrient density of foods. Life cycle assessments (LCA) evaluate environmental impacts of foods relative to land, water, and energy use. Choices related to dietary protein may be influenced by culture. Assessments of food consumption patterns across populations can be used to understand the cultural and societal importance of such foods (Drewnowski, 2017).

The complexity lies in integrating metrics across domains to capture a holistic impact of food production. A study examining the relationship between the energy and nutrient content of foods and associated greenhouse gas emissions (GHGE) found that many foods with low GHGE had relatively low nutritional value; meat and dairy products, which were more nutrient-dense, had higher GHGE values per 100 g but lower values per 100 kcal. This raises the question as to whether the higher GHGE cost of some foods could be offset by their higher nutritional value (Drewnowski et al., 2015). Another analysis expressed GHGE of ASF and PBF relative to EAA and found the perceived environmental advantage of plant-based protein production to be smaller than previously estimated. Expressing land use relative to EAA also negated some perceived advantages of plant-based proteins (Tessari et al., 2016). When evaluating the environmental impact of animal- and plant-based foods, different conclusions can be drawn between assessments based on protein quantity and those that account for protein quality. For example, GHGE for milk production has been estimated as ∼400% higher than for plant production when expressed as per ton of gross protein consumed. This difference was reduced to 59% when expressed based on kilograms of digestible lysine consumed to account for protein quality. Milk production was also the most efficient production system in terms of water use when expressed on a digestible lysine basis (Moughan, 2021).

Incorporating nutritional-based functional units (FU) in LCAs is one way to harmonize the environmental and nutritional impacts of food production and dietary patterns. They may include nutrient quantity, calories (i.e., per 100 kcal), amount of individual nutrient (i.e., grams of protein), composite scores of several nutrients, and nutrient quality (i.e., Digestible Indispensable Amino Acid Score). One methodology incorporated protein quality and quantity into LCAs to more comprehensively compare ASF and PBF in terms of protein content and quality and environmental impacts (Berardy et al., 2019). Another methodology has introduced an emissions per unit nutrient density metric to examine GHGE from food production to compare different types of food products based on their nutritional value rather than according to a singular nutrient or specific attribute like weight (Doran-Browne et al., 2015). Nutritional-based FU may be helpful in ensuring protein quality is not overlooked in the effort to deliver on healthy diets from sustainable food systems.

Conclusions regarding the environmental impact of food products can vary depending on the metrics used, each of which has strengths and limitations. Deciding which approach to use may depend on context – for example, nutrients of concern differ across populations and countries, as do trade-offs between the nutritional contribution and environmental impact of foods. Utilizing a variety of metrics to make comparisons between findings may allow for more comprehensive assessments to inform public health guidance.

Discussion

It is critical that the dialogue surrounding food systems transformations consider the multiple domains of sustainability

– health, environmental, economic, and societal. Traditionally, assessments of the sustainability of food production and consumption have focused on the environmental dimension. There is a lack of evidence on how shifts in food systems and dietary patterns will impact other dimensions of sustainability, which are all interconnected. Research is needed on the impact of consuming plant-based or -exclusive diets on health outcomes among population sub-groups with unique nutritional needs, such as older adults, so that the most vulnerable can make well-informed dietary choices. Evidence is also lacking on the ability of populations with low intakes of legumes, nuts, and seeds to increase consumption of these foods and on the affordability and availability of such PBF across regions and population groups of different socioeconomic and cultural backgrounds. Changes in the food market, including development of ultra-processed foods, lab-grown meat, plant-based beverages, and animal protein alternatives like insects and mycoproteins, require further exploration to evaluate their role. Without such evidence, the feasibility of recommendations that have shifted toward plant-based or -exclusive diets remains unclear.

There is also a need for more robust assessments and standardized metrics for food systems that capture the complexity of sustainability and the trade-offs across the domains. The utilization of a variety of metrics can help address the limitations and constraints of each individual metric and allow for the presentation of a more complete picture. This can provide more comprehensive information for decision-makers and the public seeking to understand how to optimize sustainable production and consumption of both ASF and PBF. Studies focused on evaluating the environmental impact of dietary patterns should consider the nutritional value of food choices and the nutrient requirements of a population, with attention placed on the dietary needs of population sub-groups, particularly those that are at at-risk. While nutritional-based FU can help achieve this nuance, additional questions must be asked to determine which FU would be the best to use, which can vary depending on the overall goals of the study. Further work is needed to expand the use of nutritional-based FU to include more types of dietary and environmental data, and economic considerations like affordability and accessibility.

It is recognized that plant-based diets may be the preferred dietary choice for many. However, it is important to consider how diets can be optimized in terms of meeting intake requirements for protein, AA, and key micronutrients like vitamins A and D, B-vitamins, calcium, iron, and zinc. PBF and ASF contain different quantities and combinations of nutrients and thus play complementary roles in the diet (Comerford et al., 2021). As ASF provide relatively higher quality protein it is important to consider their contribution to optimal health and nutrition outcomes. Moreover, it is critical to take a holistic perspective on the linkages between health, the environment, and socioeconomic factors when assessing the sustainability of food production systems, food choices, and dietary patterns to inform dietary recommendations.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

Author contributions

MP, JR-C, and GM developed article conceptualization. MP and GM supported the original draft preparation. All authors contributed to the review, editing, and subsequent draft preparation. All authors have read and agreed to the published version of the manuscript.

Funding

This study was funded by National Dairy Council, Rosemont, IL, United States. The funder was involved in the conceptualization, development, and publication of this review.

Acknowledgments

We would like to thank Monica Pasqualino for her research support.

Conflict of interest

MP, JR-C, and GM are employees of National Dairy Council, Rosemont, IL, United States.

Publisher's note

References

Allen, L. H. (2012). Global dietary patterns and diets in childhood: implications for health outcomes. *Ann. Nutr. Metab.* 61, 29–37. doi: 10.1159/000346185

Allen, L. H., and Dror, D. K. (2011). Effects of animal source foods, with emphasis on milk, in the diet of children in low-income countries. *Nestle. Nutr. Workshop Ser. Pediatr. Program.* 67, 113–130. doi: 10.1159/000325579

Bauer, J., Biolo, G., Cederholm, T., Cesari, M., Cruz-Jentoft, A. J., Morley, J. E., et al. (2013). Evidence-based recommendations for optimal dietary protein intake in older people: a position paper from the PROT-AGE Study Group. *J. Am. Med. Dir. Assoc.* 14, 542–559. doi: 10.1016/j.jamda.2013.05.021

Berardy, A., Johnston, C. S., Plukis, A., Vizcaino, M., and Wharton, C. (2019). Integrating protein quality and quantity with environmental impacts in life cycle assessment. *Sustainability.* 11, 2747. doi: 10.3390/su11102747

Boye, J., Wijesinha-Bettoni, R., and Burlingame, B. (2012). Protein quality evaluation twenty years after the introduction of the protein digestibility corrected amino acid score method. *Br. J. Nutr.* 108 Suppl 2, S183–211. doi: 10.1017/S0007114512002309

Brink, E., van Rossum, C., Postma-Smeets, A., Stafleu, A., Wolvers, D., van Dooren, C., et al. (2019). Development of healthy and sustainable food-based dietary guidelines for the Netherlands. *Public Health Nutr.* 22, 2419–2435. doi: 10.1017/S1368980019001435

Burd, N. A., McKenna, C. F., Salvador, A. F., Paulussen, K. J. M., and Moore, D. R. (2019). Dietary protein quantity, quality, and exercise are key to healthy living: a muscle-centric perspective across the lifespan. *Front. Nutr.* 6, 83. doi: 10.3389/fnut.2019.00083

Cifelli, C. J., Houchins, J. A., Demmer, E., and Fulgoni, V. L. (2016). Increasing plant based foods or dairy foods differentially affects nutrient intakes: dietary scenarios using NHANES 2007-2010. *Nutrients* 8, 422. doi: 10.3390/nu8070422

Clark, D. C., Cifelli, C. J., and Pikosky, M. A. (2020). Growth and development of preschool children (12-60 months): a review of the effect of dairy intake. *Nutrients* 12, 3556. doi: 10.3390/nu12113556

Comerford, K. B., Miller, G. D., Reinhardt Kapsak, W., and Brown, K. A. (2021). The complementary roles for plant-source and animal-source foods in sustainable healthy diets. *Nutrients* 13, 3469. doi: 10.3390/nu13103469

Dagnelie, P. C., and van Staveren, W. A. (1994). Macrobiotic nutrition and child health: results of a population-based, mixed-longitudinal cohort study in The Netherlands. *Am. J. Clin. Nutr.* 59, 1187s—96s. doi: 10.1093/ajcn/59.5.1187S

Deutz, N. E., Bauer, J. M., Barazzoni, R., Biolo, G., Boirie, Y., Bosy-Westphal, A., et al. (2014). Protein intake and exercise for optimal muscle function with aging: recommendations from the ESPEN Expert Group. *Clin. Nutr.* 33, 929–936. doi: 10.1016/j.clnu.2014.04.007

Dewey, K. G. (2013). The challenge of meeting nutrient needs of infants and young children during the period of complementary feeding: an evolutionary perspective. *J. Nutr.* 143, 2050–2054. doi: 10.3945/jn.113.182527

Domi,ć, J., Grootswagers, P., van Loon, L. J., and de Groot, L. C. (2022). Perspective: vegan diets for older adults? A perspective on the potential impact on muscle mass and strength. *Adv. Nutr.* 13, 712–725. doi: 10.1093/advances/nmac009

Doran-Browne, N. A., Eckard, R. J., Behrendt, R., and Kingwell, R. S. (2015). Nutrient density as a metric for comparing greenhouse gas emissions from food production. *Clim. Change.* 129, 73–87. doi: 10.1007/s10584-014-1316-8

Drewnowski, A. (2017). The chicago consensus on sustainable food systems science. *Front. Nutr.* 4, 74. doi: 10.3389/fnut.2017.00074

Drewnowski, A., Rehm, C. D., Martin, A., Verger, E. O., Voinnesson, M., Imbert, P., et al. (2015). Energy and nutrient density of foods in relation to their carbon footprint. *Am. J. Clin. Nutr.* 101, 184–191. doi: 10.3945/ajcn.114.092486

Dry Bean Council US (2021). Production facts. *What is the per capita bean consumption in the U.S.?* Available online at: https://usdrybeans.com/industry/production-facts/#FAQ3no11 (accessed July 11, 2022).

Fanzo, J., Bellows, A. L., Spiker, M. L., Thorne-Lyman, A. L., and Bloem, M. W. (2020). The importance of food systems and the environment for nutrition. *Am. J. Clin. Nutr.* 113, 7–16. doi: 10.1093/ajcn/nqaa313

FAO (2013). *Dietary protein quality evaluation in human nutrition.* Report of an FAO expert consultation. FAO food and nutrition paper 92. Rome, Italy: FAO.

Fussell, M., Contillo, A., Druehl, H., and Rodriguez, N. R. (2021). Essential amino acid density: differences in animal- and plant-based dietary patterns designed for older women. *Nutr. Today.* 56, 70–75. doi: 10.1097/NT.0000000000000466

Gibson, R. S., Yeudall, F., Drost, N., Mtitimuni, B. M., and Cullinan, T. R. (2003). Experiences of a community-based dietary intervention to enhance micronutrient adequacy of diets low in animal source foods and high in phytate: a case study in rural Malawian children. *J. Nutr.* 133, 3992s—9s. doi: 10.1093/jn/133.11.3992S

Goulding, A., Rockell, J. E., Black, R. E., Grant, A. M., Jones, I. E., Williams, S. M., et al. (2004). Children who avoid drinking cow's milk are at increased risk for prepubertal bone fractures. *J. Am. Diet. Assoc.* 104, 250–253. doi: 10.1016/j.jada.2003.11.008

Gwin, J. A., Carbone, J. W., Rodriguez, N. R., and Pasiakos, S. M. (2021). Physiological limitations of protein foods ounce equivalents and the underappreciated role of essential amino acid density in healthy dietary patterns. *J. Nutr.* 151, 3276–3283. doi: 10.1093/jn/nxab262

Herforth, A., Arimond, M., Álvarez-Sánchez, C., Coates, J., Christianson, K., Muehlhoff, E., et al. (2019). Global review of food-based dietary guidelines. *Adv. Nutr.* 10, 590–605. doi: 10.1093/advances/nmy130

Houchins, J. A., Cifelli, C. J., Demmer, E., and Fulgoni, V. L. (2017). Diet modeling in older americans: the impact of increasing plant-based foods or dairy products on protein intake. *J. Nutr. Health Aging.* 21, 673–680. doi: 10.1007/s12603-016-0819-6

Institute of Medicine (2003). *Dietary Reference Intakes: Applications in Dietary Planning.* Washington, DC: National Academies Press.

Iuliano, S., Poon, S., Robbins, J., Bui, M., Wang, X., de Groot, L. C., et al. (2021). Effect of dietary sources of calcium and protein on hip fractures and falls in older adults in residential care: cluster randomised controlled trial. *BMJ.* 375, n2364. doi: 10.1136/bmj.n2364

Krebs-Smith, S. M., Guenther, P. M., Subar, A. F., Kirkpatrick, S. I., and Dodd, K. W. (2010). Americans do not meet federal dietary recommendations. *J. Nutr.* 140, 1832–1838. doi: 10.3945/jn.110.124826

Meltzer, H. M., Brantsæter, A. L., Trolle, E., Eneroth, H., Fogelholm, M., Ydersbond, T. A., et al. (2019). Environmental sustainability perspectives of the nordic diet. *Nutrients* 11, 2248. doi: 10.3390/nu11092248

Millward, D. J., Layman, D. K., Tomé, D., and Schaafsma, G. (2008). Protein quality assessment: impact of expanding understanding of protein and amino acid needs for optimal health. *Am. J. Clin. Nutr.* 87, 1576s—81s. doi: 10.1093/ajcn/87.5.1576S

Morgan, P. T., Harris, D. O., Marshall, R. N., Quinlan, J. I., Edwards, S. J., Allen, S. L., et al. (2021). Protein source and quality for skeletal muscle anabolism in young and older adults: a systematic review and meta-analysis. *J. Nutr.* 151, 1901–1920. doi: 10.1093/jn/nxab055

Moughan, P. J. (2021). Population protein intakes and food sustainability indices: The metrics matter. *Global Food Secur.* 29, 100548. doi: 10.1016/j.gfs.2021.100548

Neumann, C., Harris, D. M., and Rogers, L. M. (2001). Contribution of animal source foods in improving diet quality and function in children in the developing world. *Nutr. Res.* 22, 193–220. doi: 10.1016/S0271-5317(01)00374-8

Nordhagen, S., Beal, T., and Haddad, L. (2020). *The role of animal source foods in healthy, sustainable, and equitable food systems.* Discussion Paper Series #5 Geneva, Switzerland: Global Alliance for Improved Nutrition (GAIN). doi: 10.36072/dp.5

Pasiakos, S. M., Agarwal, S., Lieberman, H. R., and Fulgoni, I. I. I., V. L. (2015). Sources and amounts of animal, dairy, and plant protein intake of US adults in 2007–2010. *Nutrients.* 7, 7058–7069. doi: 10.3390/nu7085322

Sahni, S., Mangano, K. M., Hannan, M. T., Kiel, D. P., and McLean, R. R. (2015). Higher protein intake is associated with higher lean mass and quadriceps muscle strength in adult men and women. *J. Nutr.* 145, 1569–1575. doi: 10.3945/jn.114.204925

Semba, R. D., Rahman, N., Du, S., Ramsing, R., Sullivan, V., Nussbaumer, E., et al. (2021b). Patterns of legume purchases and consumption in the United States. *Front. Nutr.* 8, 732237. doi: 10.3389/fnut.2021.732237

Semba, R. D., Ramsing, R., Rahman, N., Kraemer, K., and Bloem, M. W. (2021a). Legumes as a sustainable source of protein in human diets. *Global Food Secur.* 28, 100520. doi: 10.1016/j.gfs.2021.100520

Singh-Povel, C. M., van Gool, M. P., Gual Rojas, A. P., Bragt, M. C. E., Kleinnijenhuis, A. J., Hettinga, K. A., et al. (2022). Nutritional content, protein quantity, protein quality and carbon footprint of plant-based drinks and semi-skimmed milk in the Netherlands and Europe. *Public Health Nutr.* 25, 1416–1426. doi: 10.1017/S1368980022000453

Tessari, P., Lante, A., and Mosca, G. (2016). Essential amino acids: master regulators of nutrition and environmental footprint? *Sci. Rep.* 6, 26074. doi: 10.1038/srep26074

Turner, C., Kalamatianou, S., Drewnowski, A., Kulkarni, B., Kinra, S., Kadiyala, S., et al. (2020). Food environment research in low- and middle-income countries: a systematic scoping review. *Adv. Nutr.* 11, 387–397. doi: 10.1093/advances/nmz031

van Vliet, S., Burd, N. A., and van Loon, L. J. (2015). The skeletal muscle anabolic response to plant- versus animal-based protein consumption. *J. Nutr.* 145, 1981–1991. doi: 10.3945/jn.114.204305

Weaver, C. M. (2014). How sound is the science behind the dietary recommendations for dairy? *Am. J. Clin. Nutr.* 99, 1217s—22s. doi: 10.3945/ajcn.113.073007

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., et al. (2019). Food in the anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems. *Lancet.* 393, 447–492. doi: 10.1016/S0140-6736(18)31788-4