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Dietary protein considerations in a sustainable and ageing world: a narrative review with a focus on greenhouse gas emissions and skeletal muscle remodelling and maintenance

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Abstract
The rise in interest of plant-based protein foods has been meteoric, often leading to calls to adopt exclusively plant-based diets to reduce the intake of animal-based foods. In addition to impacts on human health, moving to an exclusively plant-based (or indeed animal-based) diet may have detrimental implications in terms of environmental sustainability. The impact of a rapid growth in global population on the sustainability of food systems poses clear consequences for the environment and thus warrants careful consideration at a national and, in some cases, global level. The requirement for high-quality dietary protein in an ageing population to offset chronic disease, such as sarcopenia, is an additional consideration. A reductionist approach to this sustainability issue is to advise a global population switch to plant-based diets. From a dietary protein perspective, the sustainability of different non-animal-derived protein sources is a complex issue. In this review, first we describe the role of dietary protein in combatting the age-related decline in skeletal muscle mass. Next, we explore the efficacy and sustainability of protein sources beyond animal-based proteins to facilitate skeletal muscle remodelling in older age. Taking a holistic approach, we discuss protein sources in terms of the muscle anabolic potential, environmental considerations with a predominant focus on greenhouse gas emissions across the food chain, the relevance of global malnutrition, and nation- and local-specific nutritional needs for dietary protein choices and food systems. Finally, we discuss implications for environmental sustainability and explore the potential of a trade-off between diet quality and environmental sustainability with food choices and recommendations.

Keywords Ageing, Climate change, Muscle, Protein, Protein quality, Sustainability

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Introduction

Food production accounts for 25–30% and approximately one third of greenhouse gas emissions in the UK and world-wide, respectively [1–4], with implications for the environment (e.g., driving biodiversity loss, soil degradation) and climate change. Therefore, in addition to other significant contributors to environmental sustainability, particularly those deemed lower priority (e.g., personal travel, digitalisation, cosmetics/fashion, luxury goods/services), we have a responsibility to critically reflect on the impact of our dietary choices for the health of our planet. All food sources, and indeed foods of the same source, are associated with a unique carbon footprint and make a distinct contribution to diet quality. Therefore, dietary change has the potential to exhibit significant and complex impacts on climate change and population health [1–4].

Dietary protein recommendations for skeletal muscle health across the health- and lifespan continuum continue to evolve given that protein requirements may be higher in clinical populations, including older adults, to combat age-related losses in muscle mass and function (see Morgan et al. 2023 *for review* [5]). The primary nutritional value of dietary protein is the provision of essential amino acids (EAA) for the synthesis of new, functional proteins, including skeletal muscle (termed muscle protein synthesis, MPS). Historically, animal-based proteins have been proposed to stimulate a greater postprandial MPS response (i.e., superior for muscle remodelling) than plant proteins, largely due to their higher 'quality' (defined by multiple factors, including EAA content, amino acid [AA] profile and AA bioavailability) [6]. However, interest in dietary change, in this case to a primarily plant-based diet as a means to reduce intake of animal-based foods, should not be discussed without acknowledging environmental sustainability, most notably contributions to greenhouse gas emissions and climate change. Undoubtedly, the rapid growth in global population has contributed to stressors in food systems, leading to consequences for the environment and the continued existence of our planet and species [7]. A reductionist approach to this issue would advise a disproportionate switch to a plant-based diet for the global population [8]. However, the sustainability of different protein sources is a complex issue. Therefore, the purpose of this narrative review is to highlight the need for a more holistic approach to the challenges ahead surrounding dietary protein choices and sustainability, with a focus on skeletal muscle adaptation in our ageing population and on greenhouse gas emissions. We acknowledge that other nutritional requirements beyond protein exist that are not extensively discussed in this review.

A role for dietary protein to support musculoskeletal health in an ageing society

Proteins, or more specifically their constituent AA, represent the building blocks of body tissues, including muscles, bone, skin, connective tissues, and organs. Dietary protein is essential for various physiological functions including movement, structure, transport, storage, cell signalling, enzymes, immune function, hormones, receptors, as well as energy provision. Hence, protein nutrition plays a crucial role in human health across the health- and lifespan [9–12]. Globally, ageing is associated with a decline in skeletal muscle mass, as well as increased healthcare costs and social service needs [13]. In addition, the gap between lifespan (i.e., total lived age) and health span (i.e., years of life free from disease) [14, 15] continues to grow, and is compounded by the deterioration of skeletal muscle mass, a decrease in habitual physical activity levels and increased prevalence of diseases associated with advanced age [16, 17]. While the cause(s) of age-related muscle and strength loss, or sarcopenia, are multi-faceted, a key contributor is malnutrition, and specifically a reduced dietary protein intake [18, 19]. Hence, with advanced age, an improved awareness of protein intake recommendations is warranted, including the source of protein (e.g., meat, dairy, plant, fish). In addition, ageing is associated with a decline in basal metabolic rate [20]. Hence, while caloric intake requirements may be reduced, there may be a higher demand for some nutrients given older adults are at risk of malnutrition, creating a nutritional dilemma, suggesting that nutrient density is more important with advanced age [21–23]. In this regard, nutrient bioavailability is an important consideration worthy of discussion.

Muscle anabolic considerations for dietary protein sources: considering the 'quality' of protein

The potential for alternative, non-animal-derived, protein sources to support skeletal muscle remodelling across the health- and lifespan likely represents an area of intense future research [6]. However, that dietary protein sources differ in multiple characteristics including, but not limited to, AA composition (i.e., content of each of all 20 AA), digestion characteristics, protein density, nutritional composition and form, justifies the need for assessments of environmental impact to include nutritionally, and more specifically protein, relevant functional units [6, 24–26]. This notion highlights the additional challenge of accurately quantifying the sustainability of protein-rich foods.

Protein quality is typically measured by the protein digestibility-corrected amino acid score (PDCAAS) [27] or the digestible indispensable amino acid score (DIAAS) [28], and differs between protein sources and within protein foods of the same source. The quality of a protein source is determined by several factors, including the leucine (a particularly anabolic AA) content [29] and AA bioavailability (digestion and absorption kinetics) that influence the muscle anabolic potential of the protein source [30]. In general, animal-based proteins have a higher proportion (typically > 10%) of leucine than plant-based proteins (typically < 10%), and contain all 9 EAA, whereas most plant-based proteins contain negligible amounts of one or more of these EAA that theoretically limits the muscle anabolic response [30]. However, some exceptions exist including maize protein that contains ~ 12% leucine, and quinoa that exhibits a full complement of all EAA, albeit with low total protein content.

Animal-based foods are suggested to be the largest contributors (~ 50%) to diet-related greenhouse gas emissions in the UK [6, 31] when expressed in absolute terms. Conversely, plant-based protein sources are typically associated with a lower carbon footprint [6, 32, 33]. However, when corrected to protein content, these differences between plant and animal proteins are less defined than when expressed per kg of edible food [32, 33]. For example, van der Heijden and colleagues combined data from numerous studies and expressed greenhouse gas emissions per 30 g portion of dietary protein (as well as per dose of leucine, branched-chain amino acids, and EAA, with more relevance to the mechanistic regulation of muscle protein turnover) [6]. Notwithstanding variation depending on the specific source and production methods, these data are consistent with previous work that demonstrates meat as the most environmentally expensive protein source, followed by vegetables and dairy. In comparison, fish-derived dietary protein tends to be substantially lower in greenhouse gas emissions and at a similar level to plant-based sources [6, 32]. These differences are clearly less evident compared with the per kilogram edible food comparison, and in some cases are negligible (See Fig. 3 and Supplementary Table 1 in van der Heijden et al., 2023 [6]). Indeed, when expressed relative to markers of protein quality, (e.g., per kg of digestible lysine [an EAA] or as a per 100 g of food for DIAAS), research has shown the environmental footprint of several animal-derived proteins (e.g., pork, egg, and milk production) to be similar to that of plant proteins [34, 35]. Protein source, and by extension protein quality, likely represents an important consideration in the context of advancing knowledge regarding environmental consequences of various protein-rich food sources while also supporting human nutrition, particularly in older adults where protein (and EAA in particular) requirements may be higher to maintain skeletal muscle mass [5] (see 'Protein intake considerations in older age' below).

Alternative protein sources for supporting skeletal muscle remodelling in an ageing society

Concerns surrounding the sustainability of increased production of animal-based proteins to meet growing global consumer demands is driving nutritional research into alternative, novel, non-animal-derived protein sources (e.g., plant-based, fungal, algal, insect, microflora, bacteria, cultivated meat, food waste products and other alternatives to traditional animal production systems) that are considered more sustainable, as well as beneficial to human health, in order to meet recommended protein intakes for an ageing population. Context is important when considering the role of protein nutrition in the support of skeletal muscle remodelling, specifically with respect to older adults. As discussed previously, several studies have suggested that plant proteins are less potent in stimulating MPS compared with animal proteins ingested at an equivalent dose [30, 36]. This notion was assumed to be attributed to the typically lower EAA content, limited content leucine, lower digestibility (due to the presence of anti-nutritional factors, interactions with other food components such as fibre, the structure of the protein itself, or a combination of such factors), and/or higher splanchnic extraction of AA of plant proteins [37, 38]. However, these potential shortcomings can be overcome relatively easily in a mixed-diet and via protein extraction, EAA fortification, protein blends that exhibit complementary EAA profiles and/or simply increasing protein intake to meet EAA requirements [37, 38]. As a note of caution, increasing the recommended amount of a plant protein source could require as much as 60 g of certain plant proteins (e.g., seven large potatoes), which equates to a dose that many people find challenging to consume in one serving. The role of the food matrix and meal composition in an ageing context is also a developing area of interest [36]. A growing body of research has also demonstrated that animal-free protein sources can effectively stimulate MPS in a comparable manner to animal-based proteins [37, 39–42]. Indeed, studies have reported dietary protein intake to be associated with improved musculoskeletal health independent of the dietary pattern (e.g., plant- vs. animal-based) [e.g., 43].

The application of an exclusively plant-based, lower-quality, protein diet may however be concerning if insufficient quantities of dietary protein (and EAA in particular) are consumed. This is based on the notion that whilst a single AA deficiency may not be vital in the context of the acute muscle anabolic response [44], cumulative small AA deficiencies over an extended time period may impair postprandial MPS rates, with consequences for skeletal muscle health [45]. In this scenario, a compensatory increase in muscle protein breakdown, and thus atrophy, will likely ensue to provide a continuous endogenous supply of EAA for critical physiological functions across tissues and organs [46–48]. This inadequacy is exacerbated by observations of reduced peripheral availability of AA with ageing (in part via increased splanchnic retention of AA [49]), as well as impaired oral health in older adults (contributing to impaired protein digestibility and absorption) [50] which contribute to age-related muscle loss [49]. The increased splanchnic retention of AA is also a feature of ingesting plant-based proteins compared with animal-based proteins, due to their lower digestibility [42, 51, 52]. Nevertheless, in practice, foods are rarely consumed in isolation and, assuming sufficient intake of dietary protein, the skeletal muscle adaptive response, particularly when combined with resistance exercise training, is likely not to be significantly impaired in predominantly plant-based compared with animal-based diets [39]. However, based on available evidence, we cannot exclude the possibility that a sudden switch to an exclusively lower-quality, low protein, diet may be detrimental to musculoskeletal health in older age, but such conjecture requires further exploration.

Protein intake considerations in older age

The RDA for protein (set in the UK at 0.75 g·kg^{-1} body mass·day^{-1}) has been suggested by some, but not all, scientists to be insufficient for older adults to maintain skeletal muscle on a population level [53]. This standpoint is likely explained, at least in part, by an impaired postprandial response of MPS to protein ingestion in older age (termed 'anabolic resistance'), which is driven largely by the availability of EAA following consumption of protein-rich foods [12, 54, 55]. Several studies in older adults support the notion that higher (than the RDA) protein intakes benefit lean mass outcomes (e.g., lean body mass, muscle mass, bone health, metabolic health, body composition, strength, function) [56–63]. Notwithstanding, we acknowledge that achieving high(er) protein intake recommendations can be challenging, particularly for older adults. Indeed, one in three older adults fail to consume even the protein RDA [64]. This observation is exaggerated in older adults owing to issues such as reduced appetite, dysphagia, digestive issues, psycho-social barriers and/or medication interactions [22]. Dietary choices that increase the peripheral availability of AA (e.g., isolated protein consumption, food enrichment with AA, protein hydrolysation) may represent effective strategies for compromised older populations. Nevertheless, based on current evidence, if protein intake is ≥ 1.6 g·kg^{-1}·day^{-1}, the impact of protein source and/or 'quality' on muscle remodelling may be negligible [30]. This notion assumes that if sufficient diversity of plant-based foods is contained within the diet, an individual would meet their daily EAA requirements with relative ease beyond this dose. This diversity of foods is not generally considered a challenge in developed nations, at least in healthy populations where individuals consume sufficient calories and protein from a diverse range of foods [65–68]. Based on current available evidence, older adults that are adopting an exclusively plant-based diet will likely have to pay particular attention to their diets to achieve sufficient intakes of all EAA, though, it is also worthy of note that consuming such doses of protein (≥ 1.6 g·kg^{-1}·day^{-1}) can be challenging, particularly in older adults, highlighting an additional reason why elimination of protein dense animal foods might bring about further challenges to an ageing population.

Environmental considerations for protein-rich food sources across the food chain

Food supply chains operate globally. Many people are conscious of what they eat from a health, ethical and environmental perspective, however, much controversy and misinformation exist regarding the sustainability of commonly consumed protein-rich foods. This controversy stems from the complexity of the food chain and the notion that that environmental consequences are associated with every stage of the food chain from production (e.g., farming methods [intensive/extensive], land/water use, associated deforestation, feed), processing and manufacturing (e.g., packaging, transportation), consumer activities (e.g., storage, cooking) and food waste disposal, and these effects on the environment are not necessarily mutually exclusive for protein sources across the spectrum of protein 'quality' [69] (Fig. 1). Such controversy is exacerbated by the ever-growing influence of mis-informed individuals on social media platforms. The complexity of the food chain raises significant questions regarding our ability to precisely measure the *true* environmental impact of our foods, using carbon footprint-based methods, even before considering whether the consumer is sufficiently informed. Another challenge is created by the sustainability metric of choice, e.g., greenhouse gas emissions, energy use, water usage, waste reduction rate, biodiversity CO_2 savings, energy reductions, product recycling rate, supplier sustainability. Further, assessing the impact of foods on climate change should not only account for carbon emissions but the many other factors that influence climate change, as well as carbon sequestration, and that methane production should be evaluated differently than CO_2 [70, 71]. Nevertheless, expressed in absolute terms, animal-based foods are considered the largest contributors to diet-related greenhouse gas emissions in the UK [6] and refrigeration of dairy products and meat are particularly energy intensive [72]. Notwithstanding, it is noteworthy that not all animal-based foods require refrigeration (e.g., cured meat), and therefore are associated with different environmental impacts even at the level of supplier and

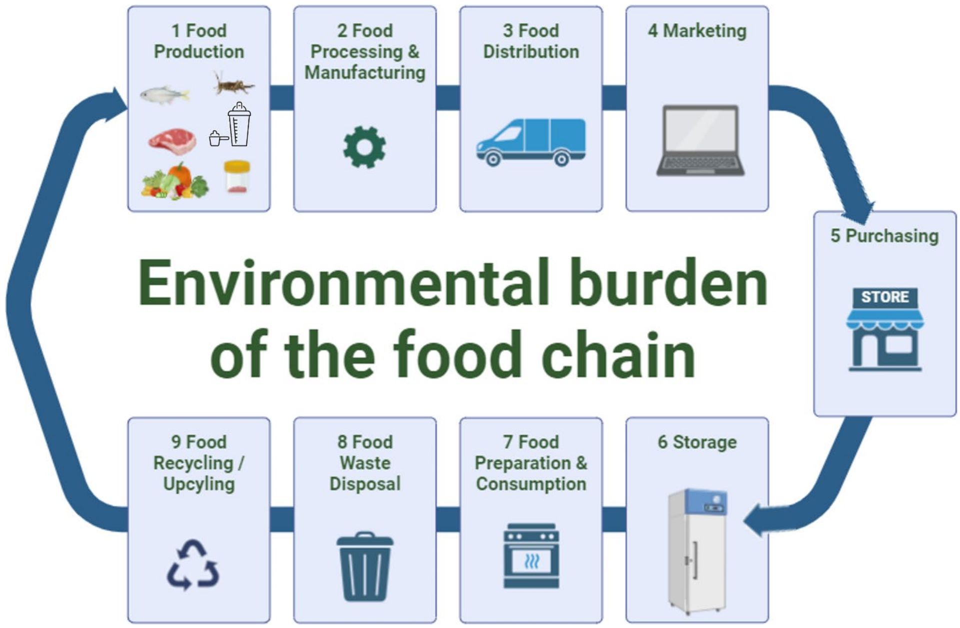

Fig. 1 Environmental consequences are associated with all stages of the food chain from food production, food processing, manufacturing, distribution and transport, marketing, purchasing, storage, food preparation and consumption, food waste disposal and food recycling, and these consequences are not mutually exclusive for protein sources across the spectrum of protein quality, nor consistent for a given protein source

consumer storage. A significant proportion of produce goes to waste during processing and transportation due to damage, with some forms of produce more vulnerable to damage than others [73]. Regarding waste, according to the Food and Agriculture Organization (or 'FAO'), approximately one third of all edible produced food is wasted every year across the entire supply chain [74], accelerating environmental consequences associated with global food production and highlighting the need for urgent action [73]. This notion is important because food wastage is considered a significant contributor to the environmental impact of foods, and perishable fresh fruit and vegetables are more likely to be disposed of than fresh meat and fish [73, 74]. Ultimately, there is growing consensus that food systems need to provide a diversity of both plant and animal sourced foods, not least for their protein content (and EAA in particular) but other vital nutrients [75, 76] to meet global nutritional requirements and the increased nutritional requirements of older age, whilst minimizing environmental consequences [2, 24, 75, 77, 78].

Despite the message often being lost amongst the controversy, arguably the biggest challenge to minimising the environmental impact of food production relates to the marked increase in global food demand and food production, regardless of the source of dietary protein [79]. This trend has led to destruction and displacement of natural resources [80]. Accordingly, claims also exist that eating more animal foods means that more natural habitat needs to be cleared and deforested for livestock. However, whilst there is some evidence behind such claims [81], the additional land required for the increased demand of plant-based foods (should animal-based foods be abolished), could have similar consequences for the environment, and indeed various crop practices are associated with a significant carbon footprint [82, 83]. Further, it might be naive to suggest that grazing land (which is largely unsuitable for crops) would be left untouched as a 'natural carbon sink' if not occupied by livestock. Instead, whilst speculative, this land would likely be purchased for development and urbanisation, creating further environmental and ecological challenges. Indeed, unless truly 'untouched', whether left for grazing, urbanised, or for crops, environmental consequences and ecological challenges will always exist, not least destruction of habitats supporting diverse organisms. There are clearly many trade-offs in our dietary choices that justifies a more holistic approach to reducing the environmental and ecological consequences of food production.

One promising avenue to increased food sustainability and security is to explore ways to maximise food use regardless of the source. To this end, several studies have investigated different means to increase the palatability and quality of protein sources that are disposed of during the food production process. For example, various fish species (e.g., blue whiting, nile-tilapia, sprat) have been investigated for their skeletal muscle anabolic properties using by-products that are typically disposed during production [84–86]. Indeed, much of the existing supplement literature focuses on whey protein, which itself is a by-product of cheese manufacturing [30]. Despite some complexities, there is also potential to salvage high-quality protein from meat co-products which could be explored further to minimise the environmental impact of the food production process and maximise food use [87]. For example, chicken feet have recently received attention in the UK media as a 'trendy' food source. Chicken feet are particularly rich in collagen protein but are often discarded as a waste product in the UK. Indeed, in parts of Asia and the Caribbean, chicken feet are common cuisine. Undoubtedly, opening novel routes to protein production also offers opportunities to valorise waste and reduce other environmental impacts [88], and requires continued attention. The use of other food sources, including insects and fungal and algal proteins, have been proposed as an alternative approach to developing high-quality protein with a lower carbon footprint to support skeletal muscle health, that may be produced on a more viable and sustainable scale. As such, these alternative protein sources may contribute to global sustainability and food security, whilst addressing global malnutrition [6, 89–91]. Insects are already a popular food source across Asia, Africa, and South America, and relative to their total composition, provide high amounts of protein (~40-60%, providing all of the EAA required for human nutrition), which is higher than beef (~20–25%), all whilst being associated with reduced environmental consequences [6, 89–91].

Lab-based meats (including synthetic/cultivated '*meats*') and the production of synthetically produced isolated protein supplements (e.g., microflora bacterial protein) to mimic higher-quality animal-based proteins are also receiving increasing attention as a potential means to meet growing food demand. Indeed, the first laboratory-grown '*burger'* was released in 2013 following relatively new food technology utilising an in vitro–cultured 'meat' approach, with the use of stem cells harvested from the muscle of live animals [92, 93]. However, whilst such approaches have ethical and potentially environmental advantages over conventional livestock agriculture [93, 94], the current energy cost associated with 'cellular agriculture' and ultra-processed foods, is significantly greater than more traditional approaches and the feasibility of cellular agriculture to support global demand for food has been questioned [95]. Therefore, future efforts should continue to explore ways to reduce the energy cost and maximise the viability of cellular agriculture, with a focus on novel technologies.

The impact of ultra-processed foods (defined as an industrially formulated edible substance derived from natural food or synthesized from other organic compounds) on muscle anabolism and metabolic health has also been questioned [96, 97]. A transition to a more plant-based diet *may* encourage more healthy food choices that could, in theory, improve whole-body metabolic health with positive consequences to muscle health [98, 99]. By contrast, plant-based meat alternatives have flooded the market, many of which are considered ultra-processed foods, which we still do not know their true impacts on health [100]. These foods often contain many similar ingredients including protein isolates, emulsifiers, binders, and other additives, and are made using industrial processing methods [101]. Importantly, whilst research is in its early stages, ultra-processed foods have been linked with various negative health outcomes including obesity, type 2 diabetes, cancer and other chronic diseases, likely due to a combination of their poor nutritional content, synthetic additives and lack of fibre [102].

Increasing the production of animal-derived proteins using some farming practices (e.g., intensive agriculture) clearly does not offer a sustainable solution to meeting global protein needs [31]. However, it is important to acknowledge the efforts of farmers to maximise efficiency of farming practices and implement environmentally friendly practices over the last decade, solutions including regenerative planting, using methane from animal waste for energy production, and using natural flora to filter runoff towards water sources in proximity. To this end, some of the adverse effects of farming could also be mitigated by changes in farming practices, including a shift to using alternative protein sources in livestock feed [103]. There have also been recent attempts to influence livestock at source to maximise the sustainability of our food systems. For example, the use of probiotics in livestock may represent a viable method to reduce greenhouse gas emissions associated with meat production while improving the performance of animal-based diets [104, 105]. Strategies such as feed optimisation, veterinary care, smart manure utilisation and better herd management could lead to pronounced reductions in greenhouse gas emissions associated with livestock [106–108]. However, whilst clearly the impacts of such foods in the context of protein nutrition on human health requires further research, these approaches have the potential to maximise the sustainability of our food systems to support environmental alongside human longevity. Changing dietary consumption patterns by replacing resource-intensive foods with more resource-efficient, but equally nutritious, alternative protein will likely represent a focus of this aim [109]. Beyond dietary change, reducing the carbon footprint of all foods by maximising efficiency, minimising food loss and waste, and adopting 'circular food production systems' (i.e., a system where foods never become waste and food/nature is regenerated) is of upmost importance and requires urgent attention [2, 110].

Global malnutrition: an important consideration for environmental sustainability, dietary protein choices and food systems

Nutritional considerations across the globe can vary substantially. With specific reference to population growth, whilst this is expected to occur predominantly in developing countries, a significant and continued demographic change is expected in high-income countries, such as increases in the number of older people, which are likely to also have a growing impact on lower income developing countries in years to come [88]. This is pertinent to note as, as referenced above, there is a growing consensus that older people have a greater requirement for protein and therefore a greater global need for protein. The planetary health diet is a 'flexitarian' diet created by the EAT-Lancet commission as part of a report released in The Lancet in 2019 at an attempt to address global sustainability and nutritional needs [111]. However, this diet, which emphasizes the addition of plant-based foods, incorporates dairy and eggs and encourages meat to be consumed less frequently [111], has received widespread criticism [112], largely because any 'planetary diet' must also be compatible with the poorest and most vulnerable. Malnutrition, most notably micronutrients but also including protein deficiency [113, 114], is observed globally, affecting billions of people in lower- and higher-income countries [2, 115, 116]. Dietary proteins are derived from various foods (e.g., animal-, plant-, fungal-, bacterial-based foods), with plant-based sources dominating the protein supply (~60%), although their relevant contribution to the overall protein intake at the population level differs between global regions [88]. Diets in lower income countries are typically dominated by starchy staple, low protein quality (often deficient in specific AA and/or poorly digestible) and density foods that lack diversity (often highly dependent on a single source of plant protein), whereas diets in higher income countries are typically high in nutrient poor ultra-processed foods (meat consumption is also very unevenly distributed toward higher-income countries, e.g., ~ 50% of protein intake in the USA is derived from animal products [31, 78, 117]). In addition to the role that animal foods play in addressing macro- and micronutrient deficiencies across the globe [118], livestock industries are also an important component of agricultural economies and provide livelihoods for up to 1 billion deprived smallholder farmers in the developing world, thereby offering pathways out of poverty [119]. This is particularly important for areas unsuitable for crop cultivation where livestock is the only option for rural livelihoods. Animal-based foods are also the most readily available source of high-quality proteins. In addition to EAA, animal-based protein foods are a rich source of energy, as well as other essential nutrients (e.g., iron, zinc, and vitamin B12) that can be difficult to obtain solely from plant sources [118, 120], which is important to note given the high prevalence and vulnerability of malnutrition in older adults, particularly in developed countries with ageing populations [21]. On the other hand, at least in well-developed nations, there is evidence to suggest that reducing meat intake, and intake of animal-derived foods, may indeed improve metabolic health, and reduce the risk of chronic disease and premature mortality [121–123]. However, it is pertinent to note that these associations are between the high consumption of animal products rather than dietary proteins per se, and disease risk is often confounded by other unfavourable lifestyle factors, as well as differences in food cooking methods and food choices [88, 121–123]. Together, this highlights some of the unique challenges that parts of the globe face, likely justifying a nation-specific approach to sustainability and malnutrition [116, 124].

A well-managed livestock system can generate many other local benefits, including carbon sequestration, improved soil health, biodiversity, and watershed protection, as well as maintain a circular flow of materials (otherwise referred to as 'circular food production systems') to help alleviate global malnutrition whilst maximising environmental sustainability [125]. Ruminants (a sub-classification of livestock including cattle, sheep, and goats that are able to acquire nutrients from plant-based food by fermenting them in a specialized four-chambered stomach prior to digestion) are also capable of making use of marginal lands that are not suitable for direct human food production, and therefore could play an important role in maximising land use for food production and preventing global malnutrition [126]. Furthermore, evidence exists that whilst grain-fed production systems could contribute to approximately double the human-edible protein they consume, equivalent figures for grass-fed systems exceed 1500 times [127], highlighting the importance of farming methods employed to the efficiency of food systems. Indeed, unlike many other sectors, agriculture has the capacity to capture, manage and store carbon, with the potential of addressing global malnutrition at net zero emissions [127]. Hence, reductionist efforts to abolish global meat intake and intake of animal-based foods may hinder progress towards addressing global malnutrition and sustainability. Moreover, a global adoption of the so-called 'modern Western diets' (characterised by high consumption of ultra-processed foods), to which the world is seemingly rapidly transitioning, is both quantifiably not achievable and is likely not sufficient to meet human dietary requirements [128–131]. In the most developed nations, young healthy populations are already eating more meat than guidelines recommend [132]. However, as current global meat production and (over)consumption estimates are likely unsustainable [132, 133], reductions in meat intake can likely be achieved whilst not entirely abolishing meat intake from the human diet at a population/global level to achieve a balance of preventing global malnutrition in vulnerable populations, whilst improving global environmental sustainability.

Putting policy into practice: implications for environmental sustainability and beyond

In this review we have made clear the essential role that dietary protein plays in the context of a balanced diet, particularly in an ageing population [5], and that rapid global population growth clearly presents many challenges, not least a significant increase in food demand that inevitably has environmental consequences. Future research in the field of protein nutrition will likely prioritise new food production systems and other alternatives to traditional animal production systems and the exploration of novel, alternative, sustainable protein sources that can effectively support skeletal muscle remodelling across the health- and lifespan. While a relatively simple system that labels a food type with a given environmental cost does not exist, future attempts to develop these systems should develop more holistic and comprehensive systems that allow consumers to make suitable and more informed decisions based on more accurate, and location-specific, environmental impact data, combined with population specific nutritional needs (e.g., older, clinical, malnourished populations) and nutritionally functional unit data (e.g., dose of leucine, branched-chain amino acids, EAA). Recognising proficient protein sources in the diet is challenging for consumers. Currently, this information is limited to the amount of protein per 100 g of product or per portion, with no consideration to the EAA composition. To facilitate a more informed consumer environment, an online readily available database of AA compositions of all foods would be an extremely useful resource to ensure consumers are suitably informed.

While scientific consensus should always be challenged, doing so requires strong, novel, and high-quality evidence across disciplines and areas of expertise combining to tackle these significant challenges. Although evidence is accumulating that plant-based proteins are equivalent to animal-based proteins in stimulating MPS and with a lower-carbon footprint, the weight of evidence and context-specific evidence (i.e., older adults, proximity to physical activity behaviours, food matrices, comprehensive sustainability metrics/forecasts) is not currently available to recommend a complete shift from animal-based proteins. These data should, when available, be shared with leading local policy makers and independent nutrition policy regulators and widely disseminated via practitioners so that suitable interventions can be applied to combat climate change alongside healthy ageing. However, quantifying precise environmental impact figures (whether it be plant-, animal-based or otherwise) is complex, can be politically charged, and associated with numerous conflicts of interest. In addition, the nutrition field is rife with polarisation, whereby categorisation and characterisation of entire groups of people occurs based on food choices (e.g., vegans, omnivores). Moreover, the development of tribalism of those associating with a particular diet, rather than objective critical discussion and debate to advance knowledge and knowledge exchange/inform policy and therefore requires urgent attention to address these challenges.

Addressing food systems with a nutritional-environmental 'trade-off'

This review clearly articulates that multiple considerations are relevant when addressing food systems in a more holistic manner in an ageing society. These factors include, but are not limited to, home and/or local produce, maximising land use, food availability, food diversity, food fortification, consumption of less ultra processed foods while simultaneously acknowledging the nutritional value of all foods. Indeed, we and others acknowledge that meat intake should be reduced in regions that can *afford* that choice (financially, environmentally, and for health). However, the same notion is true for several plant-based foods, particularly those that are not locally sourced [133, 134]. It is hard to disagree that higher-income developed countries, at least at a population level, could reduce their intake of animal-based foods, and more specifically their meat intake. However, other animals (including cattle, sheep, goats) graze pasture that is unfit to grow human-edible crops, turning grass (which humans cannot digest) and other plants into high value protein [135], which might be critical in an ageing population whereby high-quality protein intakes may be higher to maintain musculoskeletal health.

The rapid increase in food demand due to global population growth, combined with the consumption of foods that are not locally sourced, have a significant (direct and indirect) impact on the environment [136, 137]. Aligned with the food demand to minimise the environmental consequences associated with food production, food systems must be developed that sustainably provide a diversity of both locally sourced plant- and animal-based foods. Factors such as environmental sustainability must be carefully considered alongside global nutritional requirements/malnutrition in a delicate balance (or 'nutritional-environmental 'trade-off'). It is likely that small dietary modifications would help achieve a significantly lower-carbon footprint associated with our dietary choices, alongside improving diet quality [2, 138, 139].

This review has almost exclusively focussed on greenhouse gas emissions. However, it is important to acknowledge that consequences for the environment encompass climate change alongside biodiversity, water, land use and soil health, and these should all be considered in environmental metrics [2, 138, 139]. An integrated food system that encompasses sustainability, diet quality, socioeconomics and governance is urgently required, rather than society becoming a victim of 'simplification' [2]. Indeed, there is no current agreed consensus on the recommendations for animal-based foods in human nutrition, nor the role of animals in achieving global environmental sustainability. Hence, the true (intended and unintended) effects of a marked decrease in livestock and animal-based foods on society is largely unknown [140]. Moreover, although agricultural-associated greenhouse gas emissions could in theory be reduced by removing animal-derived proteins from the food system, this would come at a cost of severe nutrient deficiencies, a likely increase in overall energy consumption, a significant socio-economic impact, and an increase in the global supply of protein requirements by >50%, with largely unknown impacts on the environment [117]. Ultimately, a planet without livestock represents a very different planet to what we see and live in today and one where food systems will need to develop pragmatic ways to supply all nutrients for human health to >8 billion people worldwide, all whilst minimising environmental and ecological consequences [140]. Filling the gap left by restricting animal source foods would require higher crop production to meet nutritional needs, which would come with its own generation of emissions, and therefore a drastic reduction of animal-based food consumption may even be counterproductive [135]. Further, considering all contributors to greenhouse gas emissions, and notwithstanding environmental transformation associated with human dietary patterns [111, 141], animal-based foods only actually contribute a small proportion of total global greenhouse gas emissions, meaning that any dietary switch only has the potential to have very small effects on reducing environmental impact (current estimates lie at ~10% of total global greenhouse gas emissions being directly attributable to the production of animal-derived foods [111]), and this is assuming that plant-based foods are unequivocally and consistently associated with reduced greenhouse gas emissions irrespective of differences across different stages/parts of the global food chain. Further, plant-based food production is itself not associated with zero environmental impact [142, 143], lessening the potential impact of any animal-related dietary change on environmental impacts of our food choices. Ultimately, future efforts should direct attention to the most suitable approaches to achieve sustainable food systems for the continued, healthy, existence of our planet and our species. The global search continues for a more sustainable and environmentally friendly source of protein that can offer similar muscle-remodelling potential to animal-based proteins [144].

Conclusions

In this review we have explored the efficacy and sustainability of protein sources to facilitate and support skeletal muscle remodelling and maintenance in older age. This review discussed the muscle anabolic considerations for protein sources, environmental considerations across the food chain associated with different food choices, and the relevance of global malnutrition and location-specific nutritional needs for dietary protein choices and food systems. To conclude, whilst a growing body of research has demonstrated that animal-free protein sources can effectively stimulate and support muscle remodelling in a manner that is comparable to animal-based proteins, food systems need to sustainably provide a diversity of plant and animal sourced foods for their protein content as well as their respective vital nutrients to adequately support human nutrition and health globally, especially in older adults where protein requirements are elevated. To this end, action is needed to address food systems with consideration for a nutritional-environmental 'trade-off.' At this point, we cannot definitively recommend whether a predominantly animal- or plant-based diet is better for the environment when considering the challenge in the context of meeting EAA requirements for musculoskeletal health in an ageing society.

Abbreviations

AA	Amino acids
DIAAS	Digestible indispensable amino acid score
EAA	Essential amino acids
FAO	Food and Agriculture Organization
MPS	Muscle protein synthesis
PDCAAS	Protein digestibility-corrected amino acid score
RDA	Recommended dietary allowance

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Data availability

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Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
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