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Plant-based functional beverages and sarcopenia: Nutritional potential, technological challenges, and future directions

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ABSTRACT

With the global population continuing to age, the prevalence of age-related conditions such as poor muscle health and related sarcopenia is growing. Sarcopenia, the gradual loss of muscle mass and strength associated with aging, has recently become a major public health concern. Traditional interventions rely heavily on animal-based protein, even though there is growing interest in plant-based alternatives. Hence, questions about the feasibility, nutritional effectiveness, and environmental impact of plant-based proteins for muscle health in older adults rise. This review evaluates the potential of plant-based beverages in managing sarcopenia, focusing on the nutritional adequacy of plant proteins and their techno-functional suitability for product development. The narrative and bibliometric analyses indicate that, although animal-derived proteins still dominate sarcopenia management, advances in food technology and changing consumer preferences are opening promising opportunities for plant-based functional products to support healthy aging. Nevertheless, important gaps remain in understanding the nutritional needs of older individuals, especially regarding plant proteins. Future research should address: (1) protein intake guidelines tailored to older adults, covering both dose and protein source for counteracting sarcopenia; (2) exploit the use of processing innovations that enhance digestibility and bioavailability, solubility, and sensory quality of plant proteins; (3) the lack of sex-specific investigations, particularly in postmenopausal women, who are disproportionately affected by sarcopenia; and (4) the need for integrated, evidence-based work that translates current knowledge into practical and cost-effective interventions for sarcopenia management.

1. Introduction

The global population is undergoing a significant demographic shift, marked by a constant rise in the proportion of older adults over years (González-Rocha et al., 2022). These longer lifespans often coincide with declining health and the onset of age-related conditions like frailty, sarcopenia, and related diseases (Wan He, 2016).

Sarcopenia can be defined as the age-related loss of muscle mass, strength, and function in older adults, which can be clinically considered "primary" or age-related, or "secondary" related to other causes, such as sedentary lifestyle, diabetes mellitus, cancer or other chronic disease (Lo et al., 2020). It affects approximately 10 to 16% of the global adult population (>60 years), with ongoing research contributing significantly to improving its diagnosis (Alhmly & Fielding, 2024). Although sarcopenia is primarily associated with aging, its main causes include hormonal changes in men and women (reduced secretion of testosterone, oestrogen, and growth hormone), nutritional deficiencies, chronic inflammation, and a decline in physical activity due to a sedentary lifestyle with advancing age (Keller, 2019). Skeletal muscle makes up about 40% of an adult's body weight, and its maintenance is vital for overall health. Muscles play key roles in movement, posture, bone support, energy regulation, and body protection. Thus, ensuring muscle health is crucial for overall well-being (Duranti, 2025). The concept of muscle health is relatively new that encompasses muscle tissue composition, muscle performance and functional status (Gorce et al., 2025). Hence, muscle health is gaining great scholarly attention worldwide, especially elderly (Duranti, 2025; Kirk et al., 2024). Currently, there is no pharmacological treatment available to prevent or cure this condition; hence, resistance training and nutritional supplementation are the only adopted sarcopenia management approaches (Bruyère et al., 2022).

Considering sports and exercise, a large body of evidence supports their positive effects particularly in managing age-related conditions (C. Smith et al., 2024). Older adults who are less physically active are at a

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higher risk of losing skeletal muscle mass and strength, increasing the likelihood of developing age-related muscle loss (Liu et al., 2024). Resistance exercise, particularly high-intensity training, has been shown to improve muscle strength and trigger positive structural and functional changes in muscle and nerve tissues (González-Rocha et al., 2022; Grgic et al., 2020). The trial conducted by Vikberg et al. (2019) showed positive results with resistance training, demonstrating a significant increase in lean body mass, along with improved physical performance and reduced fat mass in older adults. Other activities, such as aerobic exercise and high-intensity interval training, can complement resistance exercise by enhancing muscle metabolism, mitochondrial function, and insulin sensitivity (Calvani et al., 2023). Hence, physical activity is a significant factor in maintaining muscle health.

However, specific nutrients are known to complement physical activity in sarcopenia patients. A key nutrient in maintaining muscle mass is protein. Animal protein remains the primary source of dietary protein in many regions (Fig. 1A). In Europe, the average consumption is 67.6 g per capita per day, which is comparatively lower than in countries such as Iceland (106.1 g), China and Hong Kong SAR (95.4 g), and the United States (85.1 g), where intake is notably higher (Food and Agriculture Organization of the United Nations (FAO), 2023). Globally, plants are the major protein source, accounting for approximately 60% of a person's diet, while 40% of the daily protein intake is animal-based. These proportions vary by country. In Europe, the ratio is reversed, with about 60% of protein intake coming from animal sources and 40% from plant-based sources. Older adults generally consume fewer animal

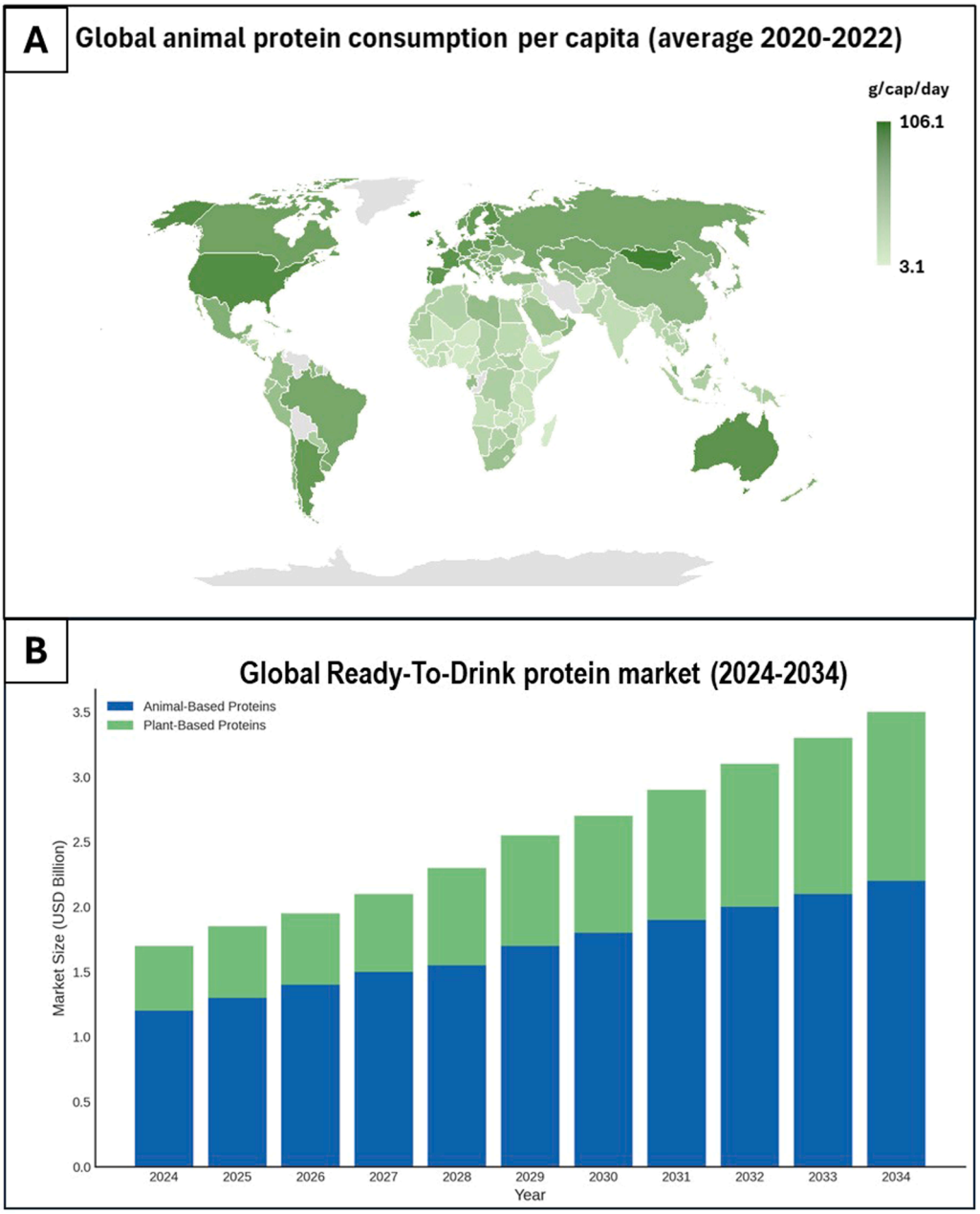


Fig. 1. (a)World heat map detailing the amount of animal protein consumed per capita per day. Protein consumption increases with depth of colour. Data range 3.1–106.1 g/day of protein. Grey indicates that data were not available for the country. Data taken from the 2025 FAOSTAT database in an 2020–2022 average values (available from: https://www.fao.org/faostat). Word map generated using Microsoft Excel. (b) Global Ready-To-Drink Protein Market, 2024–2034 (USD billion). Adapted from DataHorizzon Research (2023) and GlobeNewswire (2023). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

products due to factors such as a reduced appetite for protein-rich foods, decreased chewing efficiency, metabolic conditions that limit animal food consumption, and socio-economic challenges (Berrazaga et al., 2019). Hence, high-protein beverages provide a practical and accessible strategy to boost daily protein intake (Leidy, 2017), especially for elderly individuals with sarcopenia who frequently experience dysphagia or other swallowing impairments, positioning them as the preferred delivery format (Štreimikytė et al., 2020).

Protein beverages reflect the same consumer trends as dietary proteins, with a continued emphasis on animal-based products. The ready-to-drink (RTD) beverage market in 2023 was valued at approximately USD 1.56 billion and is projected to reach USD 2.26 billion by 2028. Simultaneously, as shown in Fig. 1B, the plant-based protein beverage sector is experiencing significant growth. The global plant-based protein drink market was estimated at USD 10.61 billion in 2023 and is expected to double to USD 20.83 billion by 2033. Plant-based protein drinks, derived from sources such as soy, pea, and almond, cater to various consumer needs, including post-workout recovery and meal replacement (DataHorizzon Research, 2023; GlobeNewswire, 2023). Even though animal-based proteins dominate the market, plant-based proteins are gaining attraction. Soy protein has been used for many years, and pea protein is emerging as a popular alternative due to its high protein content, functional benefits, environmental sustainability, affordability, and low allergenic potential. While a few RTD protein beverages exist that may support muscle health, they are often not specifically focused on sarcopenia, but rather on general muscle maintenance or recovery. They also tend to be expensive as they are typically formulated for clinical nutrition (Liu et al., 2021).

Given the rapid expansion of the protein beverage market, it is reasonable to explore market segmentation opportunities targeting sarcopenic individuals, particularly through affordable, plant-based alternatives. Also, many research studies (Bauer et al., 2015; Kim et al., 2016; Leidy, 2017; Li et al., 2021; Robinson et al., 2018; Rondanelli et al., 2016) focused on dietary supplementation in older adults using mainly dairy protein beverages. The limitation of animal-based interventions is that not everyone can consume dairy-based products due to lactose intolerance, allergies, dietary preferences, or ethical concerns; therefore, plant-based protein beverages may provide a more sustainable, inclusive, and accessible alternative for older adults at risk of sarcopenia (Cannataro et al., 2021; Ganapathy & Nieves, 2020).

Hence, plant-based beverages offer distinct advantages in the context of sarcopenia. First, they provide a more inclusive alternative for older adults who cannot consume dairy products (Pandey et al., 2025). Second, their liquid format is particularly suitable for elderly individuals experiencing reduced appetite, chewing difficulties, or dysphagia, making supplementation easier and more acceptable (Štreimikytė et al., 2020). Finally, plant-based beverages represent a more sustainable nutritional strategy that can help meet the increasing protein demands of an aging population without excessively depleting natural resources, aligning with the global need to reduce environmental impact and promote sustainable food systems (McTernan et al., 2026).

This review examines the role of plant-based protein alternatives in promoting muscle health, with a particular focus on their relevance to aging populations. In addition to supporting muscle maintenance, plant-based proteins offer a sustainable solution to environmental challenges associated with animal-based protein sources. The review synthesizes recent research on plant-based beverages and their impact on muscle health, specifically in the context of sarcopenia among older adults.

The key objectives of this review are:

- To highlight the need for sustainable protein sources for elderly and to clarify the significance of both protein quantity and quality in the prevention of sarcopenia;
- To critically assess the potential of plant-based proteins, with an emphasis on their nutritional limitations and techno-functional constraints;
- To explore the roles of complementary macronutrients and micronutrients in mitigating sarcopenia;
- To evaluate the influence of processing techniques and emerging innovations on the nutritional and functional properties of plant-based ingredients;
- To critically evaluate gap in the contemporary research landscape through a bibliometric analysis of the existing literature of the past 10 years using SCOPUS and Web of Science (WoS) and following PRISMA guidelines and established methodologies (Appicciutoli et al., 2025; Krzywonos & Piwowar-Sulej, 2022).

2. Sarcopenia and its pathogenesis

Sarcopenia refers to the age-related loss of muscle mass, strength, and function. It is characterized by a deterioration of muscle quantity and quality leading to a gradual slowing of movement, a decline in strength and power, and an increased risk of fall-related injuries (Cannataro et al., 2021). Although the term is applied clinically to denote loss of muscle mass, sarcopenia is often used to describe both a set of cellular processes (denervation, mitochondrial dysfunction, and inflammatory and hormonal changes) and a set of outcomes such as decreased muscle strength, decreased mobility and function, increased fatigue, a greater risk of falls, and reduced energy needs (Takeuchi et al., 2019). Whilst primarily associated with aging, sarcopenia can also develop in younger individuals due to physical inactivity, malnutrition, or chronic diseases such as cancer and heart failure (Alhmly & Fielding, 2024). Its prevalence increases with age, ranging from 5 to 13% in those aged 60–70 and rising to 11–50% in people over 80 (D. Liu et al., 2024). These estimates are based on the diagnostic criteria of the European Working Group on Sarcopenia in Older People (EWGSOP2) and encompass all stages of sarcopenia (Spexoto et al., 2022). In both men and women, a decline in skeletal muscles seems to become detectable after the age of 45 years with strength loss accelerating after 65 (Liu et al., 2024). This gradual decline in skeletal muscle after midlife is closely linked to the change in muscle protein turnover and the development of muscle protein resistance (Hudson et al., 2020). When muscle decline starts, muscle protein breakdown (MPB) becomes dominant over muscle protein synthesis (MPS) resulting in a prevalence of lean muscle loss that accumulates over years (Srivastava et al., 2024). Concurrently, aging is associated with the development of anabolic resistance, defined as a reduced sensitivity of skeletal muscle to anabolic stimuli such as dietary protein intake and resistance exercise, thereby attenuating the stimulation of MPS (Hudson et al., 2020). Although all essential amino acids contribute to muscle protein synthesis, certain amino acids, particularly leucine, play a central role in optimizing the anabolic response and limiting muscle protein breakdown. Leucine is essential to activate the mammalian target of rapamycin complex 1 (mTORC1), a multiprotein complex that is responsible for protein translation by managing various signalling cascades triggering MPS (Layman, 2024). Together with insulin (growth hormone), glucose (energy), and muscle contraction (exercise), the mTORC1 anabolic pathway is activated, resulting in the synthesis of muscle proteins (Cannataro et al., 2021; Layman, 2024). On the other hand, with aging, the suppression of MPB is less pronounced. This has been linked to impaired intracellular signalling at the myofibre level (Cannataro et al., 2021).

Aging muscle requires a higher dose and leucine content in protein, and a stronger contractile stimulus, to achieve the same MPS response seen in younger adults; if usual intake and activity are not adjusted, the muscle remains in a state of negative protein balance (Landi et al., 2016; Layman, 2024). Although aging results in a diminished anabolic response, higher doses of amino acids especially leucine (e.g., 10–15 g, with at least 3 g of leucine) can overcome this anabolic resistance and stimulate a protein synthesis response comparable to that of younger adults (Landi et al., 2016).

Other causes that accelerate the development of sarcopenia are hormonal changes in men and women (reduced release of testosterone,

oestrogen, and growth hormone), nutritional deficiencies, chronic inflammation, and particularly a decrease in physical activity due to sedentary lifestyle with advancing age (Keller, 2019). Among the various factors, the two most important causes of sarcopenia in older adults are insufficient muscle use and inadequate nutrition lacking essential nutrients needed in later life (Wochenschr & Morley, 2016). Since, currently, there is no widely approved specific pharmacological treatment to prevent or cure this disease; resistance training and nutritional supplementation are the only adopted sarcopenia management approaches (Bruyère et al., 2022).

As for other disease, sarcopenia contributes to a considerable financial burden on hospital care. Sarcopenia is independently associated with an increased likelihood of hospital admission, while frailty, regardless of the assessment tool used, is linked not only to a higher risk of hospitalization but also to significantly elevated hospital costs (Bauer et al., 2013; Liu et al., 2024; Robinson et al., 2018).

Specifically, frailty increases hospital admission costs by approximately 23.7% per year compared to healthy individuals. The presence of frailty in individuals with sarcopenia substantially amplifies costs, with increases of 46–56% per patient per year at follow-up. Older adults with both conditions exhibit a higher risk of hospitalization and markedly increased healthcare expenditures (Álvarez-Bustos et al., 2022). More broadly, disease-related malnutrition, which frequently coexists with sarcopenia, imposes a significant burden on healthcare systems (Cannataro et al., 2021). Sarcopenia contributes substantially to healthcare expenditures in the United States, with annual hospitalization costs estimated at $40.4 billion, disproportionately affecting older adults, women, and Hispanic populations (Goates et al., 2019). Similarly, in Europe, sarcopenia has been associated with significantly increased healthcare costs. A study conducted in Portugal found that sarcopenia increased hospitalization costs by 58.5% in patients under 65 and by 34% in older adults (Antunes et al., 2017). In the United Kingdom, excess annual healthcare costs due to muscle weakness, were estimated at £2707 per person per year, contributing to a total burden of approximately £2.5 billion across the older adult population (Pinedo-Villanueva et al., 2019). The economic burden of sarcopenia further underscores the need for protein-enriched nutritional interventions which, alongside a healthy lifestyle, may help mitigate associated healthcare costs (Robinson et al., 2018).

3. The role of dietary protein in muscle health

Dietary protein plays a significant role in muscle health, especially when treating sarcopenia. This section discusses the impact of protein quantity and protein quality on decelerating muscle loss during aging. As already mentioned, animal proteins are predominantly used to formulate high protein beverages for muscle health. However, due to environmental impacts of animal-based proteins, there is a need for research and product development of plant-based products. Hence, plant protein ingredients, their techno-functional properties and nutritional value, and their limitations are highlighted in this section. Building on the previously discussed ease of beverage consumption in older adults, it should be noted that particular emphasis is placed on the application of proteins in beverage formulations.

3.1. Protein quantity vs protein quality

One of the most effective nutritional strategies to prevent or decelerate sarcopenia is adequate protein intake, both in quantity and quality. Regarding protein quantity, the current Recommended Dietary Allowance (RDA) for protein in healthy adults is 0.8 g per kilogram (g/kg) of body weight per day (Landi et al., 2016). The exact proportion is depending on age, weight, gender, height, and activity level (Egan, 2016). However, this level is primarily intended to prevent protein deficiency rather than promote optimal health or preserve muscle mass in older individuals (Beaudart et al., 2019; Ganapathy & Nieves, 2020). Thus, in elderly with sarcopenia, this amount is insufficient to counteract the muscle degradation associated with aging (Beaudart et al., 2019). Instead, clinical guidelines recommend higher intakes, 1.2–1.7 g protein/kg body weight/day for older adults with or at risk of sarcopenia (Calvani et al., 2023; K. Smith et al., 2024). To date, there is still no established reference value for protein intake in sarcopenic patients, highlighting a critical gap in research.

Additionally, merely meeting daily protein targets is not enough to reach a muscle maintenance status. Protein distribution across meals significantly affects muscle protein synthesis (MPS), especially in older adults with anabolic resistance. An even intake of 25–30 *g* protein per meal, or 0.25–0.40 g protein/kg body weight, is recommended to maximize MPS (Egan, 2016). For instance, a woman weighing 60 kg should consume 72 to 90 *g* of protein per day, with approximately one-third of her daily intake (24–30 *g*) at each main meal. Factors like protein source, meal timing, distribution pattern, and nutrient intake around exercise also influence effectiveness of protein absorption (Hudson et al., 2020).

The quality of protein is just as important as the quantity. High-quality proteins are characterised by their content of essential amino acids (EAAs), with leucine recognised as a key trigger for MPS in older adults (Layman, 2024; Phillips, 2017). Yet, recent studies suggest that the other branched-chain amino acids (BCAAs), isoleucine and valine, also contribute meaningfully to maintaining muscle mass and function. Therefore, ensuring an adequate intake of all three BCAAs may enhance the effectiveness of dietary protein in mitigating the effects of sarcopenia (Evans et al., 2017; Fatahuddin & Niam, 2024; Ko et al., 2020; Rondanelli et al., 2021).

According to the World Health Organization (WHO), the daily requirement of BCAA for a healthy adult is 39 mg/kg of body weight for leucine, 20 mg/kg of body weight for isoleucine and 26 mg/kg of body weight for valine. However, specific recommendations of BCAAs for the elderly population are currently lacking at European level (FAO, 2007). The current daily requirements from the WHO (2007) are relatively outdated and may not fully reflect the increased needs of older adults, who often require higher intakes, as widely discussed in the literature (Garlick, 2021). Controversially, assuming an excessive amount of BCAAs might not be the most accurate perspective. The work of Solon-Biet et al. (2019) shows that adverse effects arise from an imbalanced dietary consumption of BCAAs in form of dietary supplements. These include metabolic syndrome, characterized by obesity, insulin resistance, hypertension, and dyslipidaemia. These side effects are linked to impaired BCAA metabolism and subsequent metabolic disruptions. The same outcomes are reported by Liu et al. (2022) and Hutson et al. (2005), expressing concerns about neural dysfunction and negative cardiovascular effects.

Although a tolerable upper intake level (UL) for BCAAs has not been established in Europe yet, some countries have their own guidelines. For example, the Italian Ministry of Health has established that the daily intake of BCAAs should not exceed 5 g/day (as the sum of the three) and suggests a ratio of 2:1:1 between leucine, isoleucine and valine, respectively (Italian Ministry of Health, 1999).

Ko et al. (2020) demonstrated that elderly individuals with sarcopenia who received a daily supplement containing 1.04 g of leucine, 0.86 g of isoleucine, and 0.72 g of valine showed significant improvements in muscle health. Similarly, Takeuchi et al. (2019) reported beneficial outcomes in sarcopenic patients treated with a daily supplement of 10 g of protein, including 2.5 g of BCAAs. This further reinforce the already known properties of BCAAs as demonstrated in other studies where they play a pivotal role in diets for enhancing muscle synthesis (Bai et al., 2021; Hernández-Conde et al., 2021; Mohta et al., 2022; Peng et al., 2022). Taking these values as a hypothetical upper limit, daily requirements of BCAAs for the elderly still rely on theoretical studies that have been conducted instead of outcomes of intervention studies.

The actual impact of dietary interventions is determined not only by the amino acid profile of the consumed protein, but also by the

bioavailability of these amino acids during digestion (Reid-McCann et al., 2022). This also consider the digestibility of complex proteins, which can be affected by factors such as processing methods (Qin et al., 2022). Until recently, protein quality was assessed using the Protein Digestibility Corrected Amino Acid Score (PDCAAS). PDCAAS is simply calculated as mg of limiting amino acid in 1 g of tested protein/ mg of the same amino acid in 1 g of reference protein all multiplied for the true digestibility (Joye, 2019). However, experts have recommended a more accurate scoring system known as the Digestible Indispensable Amino Acid Score (DIAAS) (Phillips, 2017). The DIAAS is based on the ileal digestibility of individual amino acids rather than overall protein digestibility, providing a more precise assessment of protein quality and emphasising limited amino acids based on the recommended daily amino acid intake (Xie et al., 2023). Therefore, optimizing dietary strategies for muscle health in the elderly not only requires attention to the amount and balance of BCAAs, but also to the selection of protein sources with high digestibility and bioavailable amino acids, as determined by PDCAAS and DIAAS values.

3.2. Plant protein sources in protein beverages

Addressing sarcopenia involves multiple nutritional factors, with protein being a key component. This subsection explores the range of plant-based proteins and their nutritional characteristics that may help support the maintenance of muscle mass.

There is a diverse portfolio of plant-based proteins used for the production of protein beverage (Fig. 2). These proteins are grouped into five distinct categories that represents sources suitable for plant-based beverages at the moment: 1) cereals (e.g., wheat, corn, oat, rice, barley); 2) legumes (e.g., soy, peas, chickpeas, lentils); 3) oil seeds (e.g., sunflower, sesame); 4) nuts (e.g., almond, cashew, walnut); 5) edible seeds. Fig. 2 also includes prospective sources that may become viable with future technological advancements, including pseudocereals, tubers, algae, as well as other emerging alternatives such as spirulina and moringa (Xie et al., 2023).

When selecting protein ingredients, it is essential to consider techno-functionality of the ingredients and nutritional value. For the application of plant proteins in beverages, techno-functional properties, such as solubility, emulsification, and impact on rheological parameters, like viscosity, need to be assessed.

The most common sources of protein in plant-based beverages intended for sarcopenia and MPS are peas, soy, and oat (Chughtai et al., 2022). These ingredients are frequently used due to their relatively high protein content, functional suitability and growing consumer acceptance (Xie et al., 2023).

Soy protein is so far, the most studied plant protein in muscle health. It is a complete protein, containing all nine essential amino acids, with a leucine content (~8%) comparable to that of animal proteins (Phillips, 2016). Moreover, quality of soy protein has recently reached significative values due to advances in food processing. Soy protein isolate has an *in vitro* protein digestibility score of 95–98%, while whey protein isolates range from 98 to 100%, further reinforcing that differences between plant and dairy proteins often depend on the protein source and form (Qin et al., 2022; Santos-Sánchez et al., 2024). Furthermore, soy contains isoflavones, which have been associated with antioxidant and anti-inflammatory effects that may support muscle preservation indirectly. Soy isoflavones may contribute to muscle preservation by attenuating oxidative stress and lowering the risk for inflammation, thereby helping to limit catabolic signalling associated with age-related muscle loss as already demonstrated by multiple human interventional studies (Prokopidis et al., 2023). However, due to processing, the presence of isoflavone in soy protein isolate might be limited in protein isolates and concentrates (Qin et al., 2022). One of the most relevant concerns regarding soy protein is its distinctive flavour, often attributed to lipid oxidation, as well as its potential allergenicity (Xie et al., 2023).

Pea protein, derived primarily from yellow split peas (*Pisum sativum*), is rich in BCAAs, especially lysine and arginine, though it is limited in methionine (Babault et al., 2015). Despite this, pea has demonstrated efficacy in supporting muscle maintenance when consumed in appropriate amounts (Banaszek et al., 2019). Emerging evidence indicates

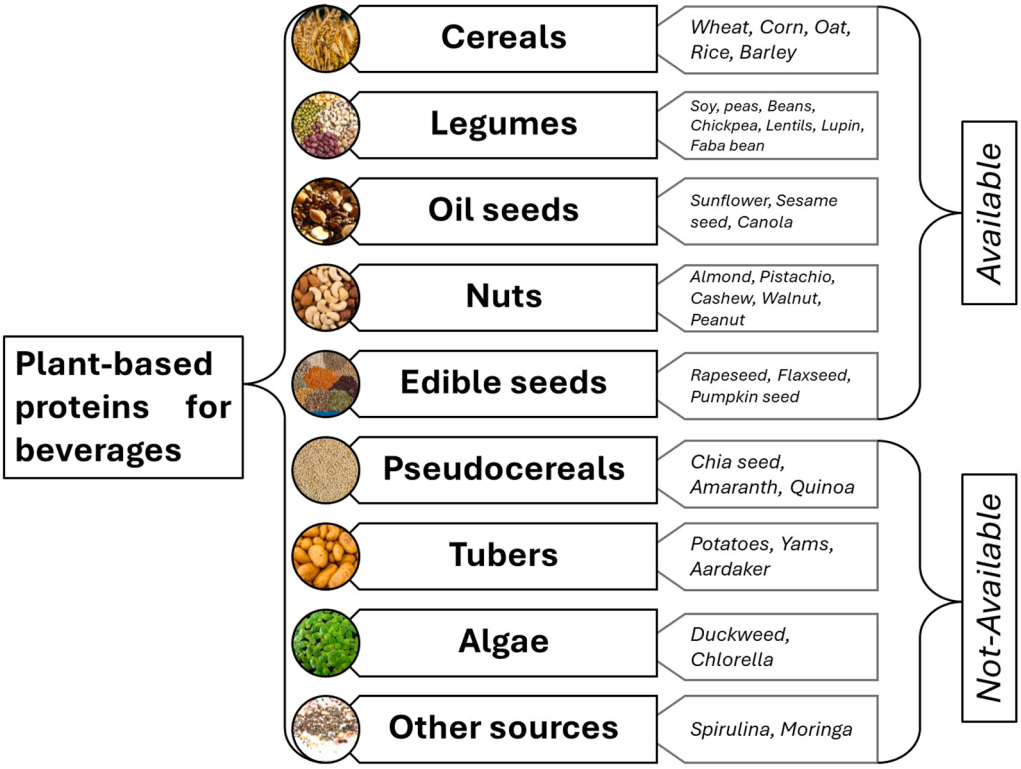


Fig. 2. Classification of protein ingredients suitable for beverage production. Adapted from Akharume et al. (2021), Xiao et al. (2023) and Xie et al. (2023).

that even pea protein is comparable to whey protein in promoting muscle thickness and strength gains in resistance-trained individuals (Babault et al., 2015; Banaszek et al., 2019). Its high digestibility (close to animal-protein) and hypoallergenic nature make it particularly attractive for older populations with dietary restrictions (Pandey et al., 2025). Pea protein-enriched beverages also show emulsifying property, facilitating palatability and emulsion stability in functional beverage formulation (Quintieri et al., 2023).

Considering cereals, oat protein, primarily sourced from *Avena sativa*, is increasingly recognized for its favourable amino acid profile and functional properties (Boukid, 2021). Although relatively low in lysine, it is rich in essential amino acids such as threonine and methionine (Holopainen-Mantila et al., 2024). The protein digestibility of oat protein concentrate is generally lower than that of soy or pea, but higher than other cereals, such as wheat. The advantage of incorporating oats into the diet goes beyond their protein digestibility; oats can be considered as gluten-free under appropriate agronomic conditions, rich in beta-glucans and possess a mild flavour making them well-suited for the use in functional foods and beverage formulations (Boukid, 2021; Joye, 2019). Oat protein techno functionality remains a limiting factor, as oat proteins typically exhibit low solubility and poor emulsification stability (Boukid, 2021). However, emerging processing methods, such as acylation and enzymatic treatments, have been shown to enhance protein solubility, foaming capacity, emulsification performance, and gelling properties (Boukid, 2021; Holopainen-Mantila et al., 2024).

Literature highlights that other plant protein sources also hold nutritional and functional promise, including lupin, chickpea, cowpea, and faba bean (Chughtai et al., 2022). Lupin stands out with a protein content of up to 44% and is commonly used in fermented and milk-substitute formulations due to its high nutritional density and functional potential (Córdova-Ramos et al., 2020). Chickpeas and faba beans offer hight sensory acceptability, with digestibility values ranging between 0.70 and 0.78, making them suitable for dairy alternatives (Lizarazo et al., 2015; Tavano et al., 2016). Nonetheless, chickpeas, like oats, are limited by low protein purity, as the maximum protein content achievable in their isolates, due to technological constraints, is approximately 50%, compared to about 80% for other protein sources (Chughtai et al., 2022).

All these legumes are generally rich in lysine but limited in sulphur-containing amino acids, whereas cereals, including rice, wheat, and oats, are high in methionine and cysteine but low in lysine. By strategically pairing these protein sources, it is possible to achieve complementary amino acid coverage, thereby enhancing overall protein quality and supporting nutritional requirements for muscle maintenance and general health (Nasrabadi et al., 2021). Legumes and cereals are frequently combined in solid plant-based foods, such as meat alternatives, to produce a more complete amino acid profile (Xiao et al., 2023). However, plant-based beverages containing cereal and legumes together are scarce (Chughtai et al., 2022). A bibliometric analysis included in Section 6 will further reveal the most recent findings on plant protein ingredients and their associated challenges for sarcopenia management.

Emerging sources such as duckweed and quinoa offer promising nutritional profiles for future product development; however, their distinctive characteristics, such as respectively strong flavours and bitterness, present sensory challenges that currently limit their widespread industrial application (Quintieri et al., 2023).

3.3. Techno-functional and nutritional limitations of plant protein ingredients compared to animal proteins

The potential of plant-based protein ingredients to preserve muscle health and mitigate sarcopenia remains underrecognized, partly because eating patterns are strongly shaped by cultural food traditions in different populations (Pandey et al., 2025).

Another contributing factor is longstanding scientific assumptions that have underestimated plant-based proteins. Plant proteins have traditionally been regarded as nutritionally inferior to animal proteins because they often contain lower levels of certain essential amino acids. For instance, legumes tend to be limited in methionine and cysteine, while cereals are generally deficient in lysine and tryptophan (Xiao et al., 2023). Animal-derived proteins are often regarded as "high--quality" because they provide all nine essential amino acids in adequate amounts and exhibit higher bioavailability (Pandey et al., 2025). In contrast, plant proteins generally have reduced bioavailability, influenced by their structural properties and the presence of antinutritional factors, such as tannins and phytic acid, which can impede protein absorption (Reid-McCann et al., 2022).

The digestibility of plant-based proteins is generally lower than that of animal-derived proteins (Reid-McCann et al., 2022). However, this gap is not insurmountable. Emerging strategies, such as combining complementary plant protein sources, enhancing amino acid profiles, and improving processing techniques, can increase the nutritional quality and bioavailability of plant proteins. In fact, a lot of plant-based protein isolates, and concentrates have protein digestibility rate close to animal protein sources (Akharume et al., 2021; Nasrabadi et al., 2021). From a functional food formulation perspective, plant-based proteins present several technical challenges that can hinder their effective incorporation into dietary interventions designed to improve muscle health. One of the main issues is poor solubility, particularly in aqueous systems, which makes them difficult to use in nutritional beverages and other liquid formulations (Akharume et al., 2021). This limitation is attributed to the physicochemical properties of the proteins' intrinsic amino acid composition and sequence (Gao et al., 2024). The latter depends on the number of non-polar amino acids that are hydrophobic (Xiao et al., 2023). Therefore, a common approach to improving protein solubility is to replace the most hydrophobic residue on the surface with a charged or polar residue (Akharume et al., 2021). Hydrophilic amino acid residues tend to move towards the solvent interface in water, while most hydrophobic residues are buried inside the protein to minimise free energy (Gao et al., 2024). Additionally, the solubility of plant proteins presents a U-shaped curve at varying pH levels, with their lowest solubility being at their isoelectric point. Moreover, heating, drying and other preparation treatments during extraction and storage can have an impact on the solubility of proteins and can cause changes compared to the native/unprocessed proteins (Akharume et al., 2021; Gao et al., 2024; Xiao et al., 2023). Another concern connected to protein solubility is the maximum inclusion level that can be achieved in a beverage matrix without causing severe viscosity or mouthfeel issues (Liu et al., 2021; Manassero et al., 2020; Štreimikytė et al., 2020). This may limit the maximum protein content achievable in beverage formulations.

In addition to solubility concerns, plant proteins are often associated with undesirable sensory properties. Many exhibit strong off-flavours commonly described as bitter, earthy, or beany that result from the presence of compounds such as saponins, alkaloids, and oxidized lipids (Mittermeier-Kleßinger et al., 2021). Off flavours are mostly derived from small peptides, hydrophobic amino acid and oxidative degradation of fats. Small peptides and hydrophobic amino acid are the result of enzymatic hydrolysis from proteolytic enzymes (Akharume et al., 2021). Considering the degradation of fats, linear-chain saturated fatty acids undergo oxidation, forming flavour compounds including short-chain or medium-chain fatty acids, aldehydes, alcohols, esters, lactones, and methyl ketones. The oxidation reactions of unsaturated fatty acids, such as linoleic acid and linolenic acid, yield various aldehydes, alcohols, and esters (Xie et al., 2023). Texture is another important factor; plant protein powders frequently produce a gritty or chalky mouthfeel, which further detracts from palatability (M. S. Kim et al., 2025). These characteristics can persist even after conventional processing and may negatively impact consumer acceptance, particularly among older adults who are already vulnerable to changes in taste perception (Xiao et al., 2023; Xie et al., 2023). In contrast, animal-derived proteins typically offer better emulsification properties and a smoother, more desirable texture resulting in a more pleasant appeal for consumer (Kim

et al., 2025).

4. The role of other nutrients to maintain muscle mass during aging

Besides dietary protein, other macro- and micronutrients can counteract muscle loss in elderly. This section highlights the function of lipids, dietary fibre, vitamins and minerals for maintaining muscle mass.

4.1. Lipids and dietary fibre

Given the complex aetiology of sarcopenia and the different factors affecting its development, addressing only energy balance and protein intake might be a very simplistic approach (Fielding et al., 2011).

Oxidative stress has been identified as a key contributor to the physiological mechanisms underlying sarcopenia (Cannataro et al., 2021). Hence, antioxidants have been suggested to combat the development of sarcopenia by inhibiting the generation of reactive oxygen species (ROS). Following the recognition of the need to suppress oxidative stress, polyunsaturated fatty acids (PUFAs) show promising potential to support skeletal muscle health through anti-inflammatory effects, thereby maintaining muscle mass and strength (Ganapathy & Nieves, 2020; Robinson et al., 2018). Among these, the omega-3 fatty acids eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) have gained significant attention for their potential to maintain skeletal muscle health, and thus support muscle mass and strength (Cailleaux et al., 2024; Calvani et al., 2023). Omega-3 fatty acids, a class of long-chain PUFAs, have long been associated with anti-inflammatory effects, which may be particularly pertinent to sarcopenia-related research. Recently, their positive impact on muscle mass has been highlighted as potentially beneficial for sarcopenic individuals (Cailleaux et al., 2024). However, a cross-sectional study involving 363 people aged 60 and above found that while dietary fish oil intake was positively associated with frailty status in younger participants (below 70), it had little effect on those over 70 years of age (Ganapathy & Nieves, 2020), suggesting that the evidence remains controversial.

Recently also dietary fibres were investigated as key contributors to increase skeletal muscle mass in adults. Elevated dietary fibre intake has been linked to reductions in fat mass and gains in lean body mass. Greater fibre consumption is also correlated with enhanced glucose regulation and increased skeletal muscle strength (Frampton et al., 2021). A recent paper of Kao et al. (2023) highlighted how dietary fibres influence the bioavailability and the absorption of nutrients. The study by Montiel-Rojas et al. (2020) further reinforces this thesis, showing beneficial effects on MPS in older adults after a high dietary intake treatment.

Considering dietary fibres, β-glucans' properties stand out among the others. β-glucans' beneficial effects rely on their ability to slow glucose absorption, improve insulin sensitivity, and reduce systemic inflammation, which together can limit the metabolic stress and protein catabolism that contribute to age-related muscle loss (Zabriskie et al., 2020; Zhang et al., 2023). The supplementation of this fibre has been shown to enhance muscle strength and endurance in athletes, with improvements observed in grip and triceps strength following a four-week intervention (Wang et al., 2022). The study from Zhang et al. (2023) highlight the therapeutic potential against muscle wasting conditions associated with inflammation and oxidative stress, typically associated with sarcopenia. Moreover, β-glucans may modulate immune function and reduce inflammation, potentially supporting muscle recovery and overall physical performance (Wang et al., 2022). The importance of β-glucans further reinforces the need for sustainable plant sources, such as oats, that can provide these valuable nutrients (Zhang et al., 2023).

4.2. Key micronutrients for muscle health

Micronutrient adequacy represents another critical factor contributing to muscle health and the management of sarcopenia.

Among these, vitamin D plays a pivotal role in muscle function and calcium homeostasis, thereby contributing to the maintenance of strength and the reduction of fall risk (Rondanelli et al., 2016). However, evidence based on supplementation trials remains inconclusive, with studies reporting mixed effects on muscle mass and strength. While higher doses improved muscle mass in some vitamin D-deficient sarcopenic individuals, results varied depending on weight status, gender, dose, and duration (Bauer et al., 2015; Rondanelli et al., 2016). Overall, nowadays, it is still unclear which factors determine the effectiveness of vitamin D for muscle health (Ganapathy & Nieves, 2020; Robinson et al., 2018). The vitamin D receptor (VDR) and the mitochondrial enzyme 25 (OH) D-1-alpha hydroxylase, both found in muscle tissue, are believed to play a crucial role in maintaining muscle health (Calvani et al., 2023; Liu et al., 2024; Robinson et al., 2018). Research indicates that mice without VDR have smaller and fewer muscle fibres (Robinson et al., 2018). Since in humans, the expression of VDR in muscle tissue decreases with age, additional vitamin D supplements might compensate this derangement (Calvani et al., 2023). Even though recommendations for vitamin D intake in sarcopenic patients are still not clearly defined, nutritional claims can support its optimal intake in the general population. Recent studies have proposed supplementation with vitamin D at doses of 20 μg/day (800 IU) as a potential therapy against muscle loss in elderly with positive results (Bauer et al., 2015; Kim et al., 2016; Rondanelli et al., 2016; Takeuchi et al., 2019).

As mentioned above, oxidative stress is one of the key contributors to causing sarcopenia. Therefore, dietary antioxidant vitamins including vitamins A, C, E and carotenoids appear to be promising candidates for preventing and treating age-related loss of muscle mass and function (Robinson et al., 2018). Vitamin C is particularly significant because it plays a crucial role in regenerating vitamin E within cell membranes, effectively reducing the vitamin E radicals that are produced (Welch et al., 2020). However, since ROS have both physiological and pathological roles, simply suppressing their activity might not improve age-related declines in muscle mass and function (Cannataro et al., 2021; Ganapathy & Nieves, 2020; Srivastava et al., 2024; Thornton et al., 2024). In fact, some evidence was shown in a recent trial that investigated the impact of vitamin C (500 mg/day) and E (117.5 mg/day) supplementation on muscle mass and strength in older men (aged 60 to 81) during a 12-week period of strength training. Follow-up assessments revealed that the group taking supplements experienced a smaller increase in total lean mass (1.4%vs. 3.9%) and smaller gains in rectus femoris muscle thickness (Robinson et al., 2018; Thornton et al., 2024). Nevertheless, other research suggests that a higher dietary intake of these antioxidant vitamins, particularly vitamin C, could help preventing the loss of muscle mass and strength during ageing, and might be valuable for preventing and treating frailty and sarcopenia (Srivastava et al., 2024).

Plant-based ingredients such as cereals and legumes are naturally rich in these antioxidant vitamins. Among cereals and legumes, yellow maize and green peas represent the richest natural sources of provitamin A carotenoids, as yellow maize is the only cereal crop accumulating considerable amounts of β-carotene, while green peas provide meaningful levels among common legumes (Abdel-Aal et al., 2013; Trono, 2019). Regarding vitamin E content, soybeans and blue lupines provide approximately 6.5 and 1.1 mg of α-tocopherol per 100 g, respectively (Helmut and Erbersdobler, 2017).

In contrast, dairy-based sources remain comparatively limited in these antioxidant vitamins, with whey protein, for instance, providing negligible amounts of vitamin C and A (U.S. Department of Agriculture, 2026). Therefore, incorporating plant-based ingredients into functional beverages may provide additional nutritional value beyond protein supplementation for older adults, notably through their antioxidant activity, which has been associated with reduced oxidative stress and inflammation in ageing populations (Dobroslavska et al., 2024).

Additionally, B vitamins, like vitamin B6 (pyridoxine) and vitamin

B12 (cobalamin), may offer protective effects against sarcopenia and frailty. Although they represent key cofactors in the metabolic pathways for MPS of branched-chain amino acids BCAAs, further research is still needed to define the precise correlation between these vitamins and muscle health improvement (Ganapathy & Nieves, 2020). Soybeans and faba beans are good sources of pyridoxine, with respective contents of 1.1 and 0.37 mg per 100 g (Helmut and Erbersdobler, 2017). While dairy-based protein sources are naturally rich in vitamin B12, plant-based sources such as legumes and cereals generally contain negligible amounts of this vitamin (Bryant, 2022; U.S. Department of Agriculture, 2026).

Considering the overall health of muscle tissue, minerals play a vital role in muscle contraction, protein synthesis, and cellular repair (Ogawa et al., 2024). Magnesium and selenium have demonstrated clear benefits in enhancing muscle mass and strength when included as part of sarcopenia treatment, further underscoring their importance (Thornton et al., 2024). However, recent studies suggest that their effectiveness in promoting muscle growth may be limited when used in isolation (Ogawa et al., 2024; van Dronkelaar et al., 2023).

In symbiosis with vitamin D, calcium plays an essential role in muscle health (Calvani et al., 2023; Landi et al., 2016; Srivastava et al., 2024). As already discussed in previous paper, muscle contraction and overall muscle health depend on calcium (Calvani et al., 2023; Landi et al., 2016; Srivastava et al., 2024). However, a recent systematic review by Ogawa et al. (2024) suggests that the benefits of calcium may be more pronounced for bone health rather than directly impacting muscle strength or sarcopenia management.

Given the clear scientific consensus that sarcopenia has a multifactorial aetiology, several studies have investigated the effects of combining protein supplements with the already discussed nutrients, generally reporting positive outcomes, as summarized in Table 1.

Among the five case studies reviewed in Table 1, none relied on a plant-based beverage as a protein supplement. This further emphasize the limited attention of the scientific community into the practical adoption of non-animal protein sources in sarcopenia trials. However, a recent study compared animal and plant protein in MPS and highlighted remarkably similar outcomes for both sources (Reid-McCann et al., 2022). Four studies of the ones listed in Table 1 reported a significant increase in muscle health outcomes when protein supplementation was combined with micronutrients and exercise (Bauer et al., 2015; Li et al., 2021; Maltais et al., 2016; Rondanelli et al., 2016). These findings suggest that the synergistic effect of these interventions may play a meaningful role in the prevention and management of sarcopenia. Additionally, among the five studies in Table 1, only one focused exclusively on women, while the remaining four included mixed-sex cohorts, highlighting the need to better address potential sex-related differences in sarcopenia research (Kim et al., 2016).

5. Advantages of plant-based proteins for the development of functional beverages for muscle health

Plant-based ingredients offer several advantages, including a lower environmental footprint compared to animal-derived proteins, contributing to more sustainable food systems (McTernan et al., 2026). They also provide a diverse range of phytochemicals compounds, such as dietary fibre, vitamins, and phytochemicals, which can further counteract muscle loss (Robinson et al., 2018). In addition, plant-based sources are particularly suitable for vulnerable groups affected by sarcopenia, including individuals with lactose intolerance, milk allergies, or specific dietary preferences, thereby expanding the accessibility of protein-enriched products (Štreimikytė et al., 2020; Wochenschr & Morley, 2016).

However, as mentioned above, there are challenges which need to be addressed, such as the impact of plant protein ingredients on beverage quality (functionality, sensory) and nutritional adequacy. The following section highlights promising processing techniques and regulations for nutrition claims.

5.1. Processing techniques to counteract the limitations of plant proteins

The use of plant-based protein ingredients in beverages can be challenging due to their limitations as highlighted above. Various processing techniques can facilitate the modulation and integration of the ingredients within the beverage mimicking their animal-based counterpart.

To overcome inferior textural properties compared to dairy products, plant-based beverages include, beside proteins, carbohydrates (starches and gums) to increase viscosity and stability. This mimics structural

Table 1
Human intervention studies and observational studies investigating the effects of protein-based beverages, alone or combined with other supplements, on muscle mass, strength, and function in older adults.

Author/ Study	Sample & Intervention	Protein	Micronutrient	Exercise	Results
Rondanelli et al. (2016)	$n = 130$, age $\geq$ 65 years; two groups: supplement group vs. isocaloric placebo for 12 weeks	22 g whey protein	100 IU VitD	20-min exercise sessions daily, 5 times/week for 12 weeks	Significant increase in fat-free mass, relative skeletal muscle mass, and handgrip strength in the intervention group.
Bauer et al. (2015)	$n = 297$, age $\geq$ 65 years; two groups: supplement group vs. isocaloric placebo for 13 weeks	20 g whey protein, 3 g leucine	800 IU VitD	No	Experimental group showed significantly better chair-stand performance and greater appendicular muscle mass gains compared to placebo.
Kim et al. (2016)	$n = 139$, age $\geq$ 70 years women; four groups: (1) Exercise + Nutrition (Ex+N) with daily amino acid and catechin-fortified tea, (2) Exercise only (Ex), (3) Nutrition only (N), (4) Control; 12 weeks	EAA supplement	20 μg VitD + tea fortified with 540 mg catechins daily	Aerobic and resistance training included for Ex+N and Ex groups (60-min classes twice weekly)	No significant improvements in muscle mass or combined variables were observed in any group.
Maltais et al. (2016)	$n = 26$, age $\geq$ 65 years, three groups: (1) milk-based protein (12 g protein, 7 g EAA), (2) EAA supplement (12 g protein, 7 g EAA), (3) rice milk control; 12 weeks	12 g protein (7 g EAA)	No	All groups performed 3 weekly 1-hour resistance training sessions for 4 months	All groups increased muscle mass (1.8% in fat-free mass); resistance training alone increased muscle mass, but 12 g protein post-exercise was insufficient to add benefits.
Li et al. (2021)	$n = 241$, age $\geq$ 60 years; four groups: (1) Nutr (nutrition only), (2) Ex (exercise only), (3) Nutr+Ex (nutrition + exercise), (4) Control; 12 weeks	10 g whey protein powder, taken three times daily	EPA (300 mg) + DHA (200 mg) + VitD3 (250 IU), taken as capsules twice daily	Ex and Nutr+Ex: 30 min aerobic + resistance training, three times/ week	Improved muscle mass and grip strength vs. controls; muscle mass increased 4.7% (Nutr), 2.2% (Ex), 3.5% (Nutr+Ex), controls slightly decreased.

Abbreviations: VitD, vitamin D; EAA, essential amino acids; Ex, exercise; Nutr, nutrition; EPA, eicosapentaenoic acid; DHA, docosahexaenoic acid.

features of animal products, like oil droplets, air particles, and fat crystals (George et al., 2024). Kim et al. (2025) provided a comprehensive sensory profiling of plant-based protein beverages, showing that soy protein isolate has distinct textural and mouthfeel properties significantly affected by enzyme treatment. Their findings revealed that these textural characteristics are inherent to the type of protein rather than protein concentration (Kim et al., 2025). Improving the texture of plant-based protein beverages can be achieved by using techniques like high hydrostatic pressure (HHP), which modifies protein techno-functionality to create a desirable texture, and adding emulsifiers such as glucomannan to enhance mouthfeel. Additionally, ultrasound treatment is gaining attention for its ability to modify and improve the functional properties of plant protein concentrates and isolates, further enhancing beverage texture (George et al., 2024; Lim & Baik, 2025; Munekata et al., 2020).

The primary challenge for scaling up plant-based proteins beverages remains to be their solubility. To address this, a wide range of physical, chemical, and enzymatic strategies have been developed to modify protein structure and improve their solubility and functionality. These approaches are summarised in Table 2. Techniques such as microwave heating, high-pressure processing, enzymatic treatments, and cold plasma offer diverse mechanisms to enhance solubility, each with specific advantages and limitations. Technological advancements further demonstrate as plant-based protein beverages could represent an effective prevention against muscle loss and sarcopenia (Nasrabadi et al., 2021).

Besides the techno-functional limitations of native plant-proteins, they can carry off-flavours. Mitigating off-flavours in plant-based protein beverages involves identifying and reducing key odorants and bitter compounds through advanced techniques like sensomics and sensoproteomics, which help pinpoint flavour-causing molecules (Nasrabadi et al., 2021). Processing methods such as enzymatic hydrolysis, fermentation, and the removal of secondary metabolites can minimize undesirable “green” or “beany” notes and bitterness (Mittermeier-Kleßinger et al., 2021).

However, the most important consideration for the development of protein beverages for treating sarcopenia is their nutritional profile tailored to the requirements for elderly. First and foremost, based on protein quality, blending cereals and legumes with the priority of reaching a complete protein and increasing the amounts of BCAAs is key for the base formulation. Although plant proteins also tend to have lower digestibility compared to animal proteins, recent studies indicate these differences are clinically insignificant when a variety of plant-based sources are consumed (Akharume et al., 2021; Bryant, 2022). Moreover, processing techniques, such as heat treatment, sonication or enzymatic treatments can increase protein digestibility (Akharume et al., 2021; Bryant, 2022; Nasrabadi et al., 2021; Xiao et al., 2023). On this matter, the work of Kim et al. (2023) demonstrated as enzymatic hydrolysis increases ileal amino acid release, improving DIAAS scores from 0.75 to 0.92 for pea protein isolates. Moreover, high-moisture extrusion enhances PDCAAS by 15–20% through protein denaturation (Hall & Moraru, 2022), while high-pressure processing preserves native structure for optimal gastric digestion (de Boer et al., 2026). Thus, processing further bridges solubility and texture gains with nutritional efficacy required for sarcopenia management.

Fortification with essential macro- and micronutrients to maintain muscle health, which are listed above, can also have an impact on beverage quality such as techno-functionality, sensory, and nutritional quality like protein digestibility. To the best of the authors’ knowledge research investigating interactions between these macro- and micronutrients and plant proteins is scarce.

Compared to solid foods, the use of a beverage matrix has some implications. Liquid protein beverages accelerate gastric emptying compared to solid foods, delivering amino acids to the small intestine 20–30% faster and producing higher peak plasma concentrations within 30–60 min post-ingestion (Calvez et al., 2021). This rapid delivery elevates amino acid oxidation rates by 15–25% versus slower solid protein digestion, potentially lowering net muscle protein synthesis efficiency despite greater leucine spikes (Witard et al., 2026). However, beverages timed post-exercise may optimize MPS, while their utility shines for frail patients with dysphagia balancing kinetics with compliance advantages (Ganapathy & Nieves, 2020; Štreimikytė et al., 2020).

5.2. Ingredient selection

To meet the nutritional requirements for sarcopenia management, food products should supply amino acids (either free or in form of protein), antioxidants, anti-inflammatory compounds, and other components supporting muscle contraction. A list of ingredients highly recommended for beverage formulations to mitigate sarcopenia is summarized in Table 3.

Accordingly, high-protein ingredients are needed, such as whey

Table 2
Technological treatments to enhance plant protein solubility, adapted from Gao et al. (2024), Kim et al. (2025), Nasrabadi et al. (2021), Munekata et al. (2020), Rojas et al. (2022) and Xie et al. (2023).

Technique	Mechanism	Effects on Protein	Notes
Microwave Heating	Dielectric heating using electromagnetic waves	Disrupts disulfide and non-covalent bonds; enhances solubility	Preserves flavour/nutrition; effective as pretreatment
High-Intensity Ultrasound (HIUS)	Cavitation and microstreaming	Disrupts structure, reduces particle size, disaggregates complexes	Lab scale: excessive use can cause aggregation
High-Pressure Homogenization (HPH)	Shear forces and cavitation (150–200 MPa)	Reduces particle size; enhances protein–solvent interaction	May cause aggregation if pressure is too high
High Hydrostatic Pressure (HHP)	Compression of protein structures (100–1000 MPa)	Reversible denaturation improves solubility; high pressure may cause aggregation	Enhances enzymatic hydrolysis (e.g., soy protein)
Glycation	Maillard reaction or enzymatic cross-linking	Adds carbohydrates to proteins; increases hydrophilicity	Combined with ultrasound; may reduce lysine; lab-scale
pH-Shifting	Extreme pH exposure and neutral refolding	Exposes sulfhydryl and hydrophobic groups; enhances solubility	Alkaline shifts + ultrasound effective (e.g., rapeseed protein)
Enzymatic Treatments (Proteolytic)	Proteases (e.g., trypsin, alcalase)	Cleave peptide bonds, loosen structure, expose hydrophilic groups	Depends on enzyme type and time
Enzymatic Treatments (Non-proteolytic)	Cross-linking by TG, laccases, peroxidases	Alters molecular weight, charge, hydrophobicity; enhances solubility	Can be combined with hydrolysis
Enzymatic Glycation	Enzymatic carbohydrate and protein linking	Introduces hydrophilic groups, improves solubility	Often paired with physical methods; reduces lysine; lab-scale
Amino Acid Modulation	Substitution of surface residues	Replaces hydrophobic residues with charged/polar (e.g., Asp, Ser)	Common in pharma; potential for plant proteins
Cold Plasma Treatment	Non-thermal reactive species modification	Induces mild structural changes; enhances water interactions	Retains nutritional quality, promising for food applications

Table 3
Key components required for plant-based protein beverages formulation suited for sarcopenia treatments. Nutrients, their RDI, UL, and relevant notes refer to a 60 kg post-menopausal woman. Data sourced from the European Food Safety Authority (Bresson et al., 2016; EFSA Panel on Dietetic Products, 2012).

Component	Recommended Specification	Purpose
Protein	20–30 g per serving	Stimulate MPS; combat age-related muscle loss aligns with 1.2–1.5 g/kg/day target intake.
BCAAs	~2.5 g leucine; 1–1.5 g isoleucine; 1–1.5 g valine	Essential for MPS; shown to improve muscle mass and strength
Vitamin D	15–20 μg (600–800 IU) per day	Enhances muscle function, strength, and reduces fall risk; within safe upper limit (100 μg/day).
Vitamin C + E	Vitamin C: ~90 mg/day; Vitamin E: ~13 mg/day (men), 11 mg/day (women)	Antioxidant defence against oxidative muscle damage
Omega-3 (EPA/DHA)	>250 mg/day from plant-compatible source (e.g., algal oil, linoleic sunflower oil)	Anti-inflammatory; supports muscle mass and function
Minerals	Magnesium, Calcium, Selenium (within safe limits)	Aid in muscle contraction and protein metabolism
Protein Source Type	Isolate/concentrate blends of pea, soy, faba, oat, chickpea	Improve digestibility and amino acid completeness
Technological Enhancements	High-pressure, enzymatic hydrolysis, or ultrasound treatment	Improve solubility, bioavailability, and sensory properties
Fat Source	Moderate MUFAs or PUFAs (e.g., flaxseed or rapeseed oil)	Improves fatty acid profile providing omega 3 s fatty acids
Additives	Minimal; clean label; no artificial sweeteners or gums unless essential	Aligns with consumer preference for natural and transparent ingredients
Portion Format	~200–250 ml single-serve bottle	Practical for elderly users; allows even protein distribution across meals
Regulatory Compliance	Meets EU nutrition/health claim guidelines (EC 1924/2006, 1169/2011)	Ensures safety, credibility, and legal marketability

Abbreviations: MPS: Muscle Protein Synthesis; BCAA: Branched-Chain Amino Acids; MUFA: Monounsaturated Fatty Acid; PUFA: Polyunsaturated Fatty Acid; EPA: Eicosapentaenoic Acid; DHA: Docosahexaenoic Acid.

protein isolates or, as a more sustainable alternative, pulse protein isolates in combination with cereal-based proteins. Complementary blends of pulses and cereals can improve overall protein quality by increasing amino acid complementarity and digestibility, making them a useful strategy for plant-based sarcopenia products (Messina et al., 2025). Overall, in light of the technological advances discussed in Chapter 5.1, it is reasonable to assume that sarcopenia-targeted products can now be developed using more sustainable plant-based ingredients. Innovative processing technologies such as high-pressure treatment (Vogelsang-O'Dwyer et al., 2022), enzymatic hydrolysis (Kim et al., 2023), or ultrasound (Rojas et al., 2022) effectively enhance protein solubility, nutrient bioavailability, and sensory properties while maintaining a clean-label, palatable beverage suitable for older adults.

As presented in Table 3, vitamins C and E may contribute to antioxidant functionality, which is particularly relevant in liquid matrices, where oxidative reactions are more likely to occur (Calvani et al., 2023; Witard et al., 2026). Anti-inflammatory ingredients are also important for supporting muscle protein synthesis and recovery and may be provided by sources such as omega-3 rich oils (Ganapathy & Nieves, 2020). In addition, minerals relevant to muscle contraction, such as selenium and magnesium, should be considered (Ogawa et al., 2024).

In addition to nutritional design, formulation and market positioning aspects must also be considered. Additives should be minimal to ensure a clean-label profile, avoiding artificial sweeteners or gums unless essential, in line with consumer preferences for natural and transparent ingredient lists (Rovai et al., 2025). The portion format should favour practicality, such as ~200–250 ml single-serve bottles, which are particularly convenient for elderly users and support even protein distribution across meals. Finally, the price for ingredients need to be considered. Setting a price target of $\leq$ €10 per litre of formulation would promote broad accessibility and help avoid niche pricing, making such products affordable and appealing for targeting older population (Bruyère et al., 2022; Chughtai et al., 2022; Robinson et al., 2018).

5.3. Regulations and product claims

Compliance with European regulatory frameworks is essential to ensure safety, transparency, and accurate communication of health benefits of plant-based protein beverages. According to Regulation (EC) No 1924/2006, any health claim, such as supporting muscle health, must be scientifically substantiated and authorized by EFSA (EFSA Panel on Dietetic Products, 2012; European Parliament & Council, 2006).

Nutritional labelling must comply with the Food Information to Consumers (FIC) Regulation (EU) No 1169/2011, which requires clear presentation of energy value, macronutrients, and relevant micronutrients per serving. Allergen information and transparent ingredient lists, especially for protein sources such as pea or soy, are mandatory to help consumers make informed choices (European Parliament & Council, 2011). Several core consumer concerns influence the acceptance of plant-based beverages, including ingredient transparency, taste, and nutritional profile (Kim et al., 2025). Recent research shows that consumers prioritize the amount and type of protein in beverages (Rovai et al., 2025a). Natural sweeteners are preferred, and additives like gums and phosphates are generally rejected (Aschemann-Witzel & Peschel, 2019). These preferences align with the growing clean label trend, where consumers seek simple and recognizable ingredients (Aschemann-Witzel & Peschel, 2019; Rovai et al., 2025). For plant-based beverages targeting muscle health in older adults, success will depend not only on delivering high nutritional value but also on fostering consumer trust through ingredient transparency, familiarity, and the strategic use of well-perceived protein sources such as pea and soy (Xie et al., 2023).

As highlighted above, key nutrients to counteract muscle loss are protein and vitamin D, among others. Nutrient and fortification claims must meet EU criteria; a "high protein" claim requires the product to contain at least 20% of its energy values from protein. Similarly, for a "high in vitamin D" claim, the product must provide at least 1.5 μg per 100 g or 100 ml (30% of the RI). Claims regarding added vitamin D must adhere to specific levels and labelling rules to accurately reflect their role in muscle health (EFSA Panel on Dietetic Products, 2012).

Furthermore, marketing claims must avoid suggesting the product can prevent or cure diseases unless specifically approved by EFSA (EFSA Panel on Dietetic Products, 2012). Therefore, claims relating to sarcopenia should be carefully worded and supported by robust scientific evidence to avoid misleading consumers. Adhering to these regulatory and labelling requirements not only ensures consumer protection but also helps build trust and credibility for plant-based beverages in a competitive market (Domínguez Díaz et al., 2020). Building on this framework, plant-based protein beverages may legitimately display claims such as "protein contributes to a growth in muscle mass" or "protein contributes to the maintenance of muscle mass", provided they meet the compositional thresholds set by EU law. In addition, if fortified appropriately, they may also carry claims like "vitamin D contributes to normal muscle function", offering further support to consumers concerned with muscle synthesis and health.

6. Research gaps and recommendation for future plant-based beverages to counteract muscle loss – a bibliometric analysis

The section reveals the outcome of a bibliometric analysis of recent scientific literature on plant-based protein sources and their relationship

with muscle health in the elderly population conducted following the PRISMA methodology based on Appicciutoli et al. (2025) and Krzywonos and Piwowar-Sulej (2022). The methodology used is outlined in Supplementary Material (S1). Briefly, the process involved the development of a refined search strategy, systematic selection of relevant articles, and the application of bibliometric mapping techniques to uncover thematic patterns and research gaps within the field. Peer-reviewed studies (2015-March 2026) were retrieved from Scopus and Web of Science using: ('sarcopenia' OR 'muscle health') AND ('nutrition' OR 'dietary intervention' OR 'protein intake') AND ('older adults' OR 'elderly') AND ('muscle mass' OR 'muscle strength'). Articles were screened by title and abstract based on predefined inclusion and exclusion criteria, and the selection process is illustrated using an adapted PRISMA-style flow diagram in Supplementary Material (S1). Papers outside the initial search string were also included to ensure comprehensive coverage and to incorporate the latest research progress.

Considering the general distribution of publications over the years, the trend from 2015 to 2025 reflects a gradual increase in attention toward the relationship between plant-based proteins and muscle health in older adults. The overall trajectory showed to growing interest ($n = 7$ in 2015), particularly evident from 2020 onward, with a noticeable peak in 2023 ($n = 13$). To assess the significance of these contributions, the number of citations of each research article was considered. Citation analysis serves as a key indicator of scientific impact and helps to identify the most recognized and foundational studies within a given research area (Appicciutoli et al., 2025). Highly cited publications often represent turning points or milestone contributions, shaping the direction of subsequent investigations and highlighting the central themes that have garnered sustained academic attention in this field. The following five studies, ranked by their citation counts, represent the most influential contributions in accordance with the research string presented in Supplementary Material (S1) since 2015.

The most cited study, presented by van Vliet et al. (2015) revealed that the intake of plant-based proteins, like soy and wheat, lead to a lower muscle protein synthesis response compared to animal proteins such as whey, milk, and beef. This is attributed to lower digestibility, suboptimal amino acid profiles, and reduced leucine content in plant proteins. The study represents the first critical assessment of plant-based proteins, paving the way for subsequent studies aimed at challenging or addressing its findings.

The review by Berrazaga et al. (2019) stands out as the second most cited publication. The study critically explores the challenges of plant proteins, which are less effective in stimulating muscle protein synthesis. The study suggests that strategies tested on younger individuals should be explored in older populations to prevent muscle loss linked to aging or chronic diseases.

The work of Lonnie et al. (2018), is a multidimensional review that connects factors such as protein intake to public health nutrition, the sustainability of plant-based proteins, and aging physiology. The review also explores hunger, satiety, and appetite mechanisms, suggesting that the currently recommended protein intake for aging adults may be insufficient for maintaining muscle mass and strength. The review highlights how plant-based proteins can help address this issue while also supporting healthy weight management and preventing overweight-related diseases.

Paddon-Jones et al. (2015) further contextualize protein consumption within functional aging, introducing the “protein per meal” concept to address the risk of sarcopenia. The article emphasizes that evenly distributed, high-quality protein intake (25–30 g per meal), combined with regular physical activity, may help prevent or slow sarcopenia in older adults. It highlights the role of leucine in muscle protein synthesis and identifies breakfast as a key opportunity to improve protein intake.

With a more clinical tone, Landi et al. (2016) elaborate the importance of sufficient and high-quality protein intake for maintaining muscle health in older adults. Central to their argument is the inadequacy of the current RDA for older individuals, advocating for higher intake levels and leucine-enriched sources. By acknowledging anabolic resistance in ageing muscle, the paper contributes to the ongoing discussion about updating dietary guidelines.

Together, these five key studies provide a comprehensive view of the evolving dialogue between protein sources, aging, and environmental sustainability. They represent important milestones for future research and serve as historical evidence of how, over the past decade, the scientific approach toward plant-based alternatives has significantly shifted.

A co-occurrence analysis of keywords was performed to highlight the most prominent themes and research trends in the field. The results of the ‘thematic analysis’ and the ‘keyword analysis’ are illustrated in Fig. 3. The network visualization in Fig. 3a identified three main thematic clusters that reflect both the development and current directions of the literature related to the use of plant-based proteins for muscle health and sarcopenia. The blue cluster reflects a methodological and translational advance in the field, with a strong focus on clinical trials, resistance training, and functional performance metrics. Research in this domain investigates the effectiveness of dietary protein interventions in combination with physical activity to improve muscle mass, strength, and overall physical function. The frequent co-occurrence of terms related to lean body mass, grip strength, and randomized controlled trials suggests a growing interest in practical applications aimed at preserving mobility and independence in aging individuals. The green cluster revolves around the biological and nutritional quality of different protein types and their relationship with muscle preservation. Here, studies delved into the anabolic potential of specific plant protein isolates, such as soy or pea. An emphasis lied on essential amino acid content, particularly leucine demonstrating, again, the importance of this amino acid for muscle health. Sarcopenia occurred as one of the central themes of this cluster. The red cluster predominantly captures studies focused on population characteristics and dietary habits, reflecting early research efforts aimed at understanding how age, sex, caloric intake, and habitual consumption of various protein sources influence muscle-related outcomes in older adults. The increasing interest of animal-based to plant-based dietary patterns could be defined considering the dimension of the animal protein and plant protein items on the map. Interestingly, the terms "male" and "female" show similar levels of occurrence in this cluster, which is misleading given that women are generally more prone to sarcopenia than men (Narici & Maffulli, 2010). This suggests a gap in sex-specific analyses and representation in scientific literature on sarcopenia management.

Evidence indicates that women face a higher risk of sarcopenia, with menopause emerging as a key driver of this disparity. Menopause is independently linked to muscle decline and is often accompanied by reductions in physical activity and diet quality (Narici & Maffulli, 2010). Oestrogen deficiency after menopause contributes to reductions in muscle strength and quality (Messier et al., 2011). During the peri- and postmenopausal stages, women commonly reduce their intake of protein and fat while experiencing increased appetite, which can negatively impact body composition. Additionally, some women may intentionally cut calories to prevent menopause-related weight gain, potentially leading to nutrient deficiencies (Thornton et al., 2024). Moreover, recent studies demonstrate a decline in muscle mass of 0.6% per year after menopause (Messier et al., 2011).

Although menopause and dietary behaviours are closely linked to the development of sarcopenia in women, there is still limited evidence on effective diet-focused interventions during the menopausal transition and later life (Thornton et al., 2024). This may be attributed to the complex interplay of hormonal changes during menopause, individual variability in dietary patterns and lifestyle factors, and a lack of long-term, well-controlled intervention studies specifically targeting women in the menopausal transition and later life (Messier et al., 2011).

Fig. 3b presents the overlay visualization of the keyword co-occurrence network. While it shares the structural layout of the standard network visualization, it adds a temporal dimension by color-

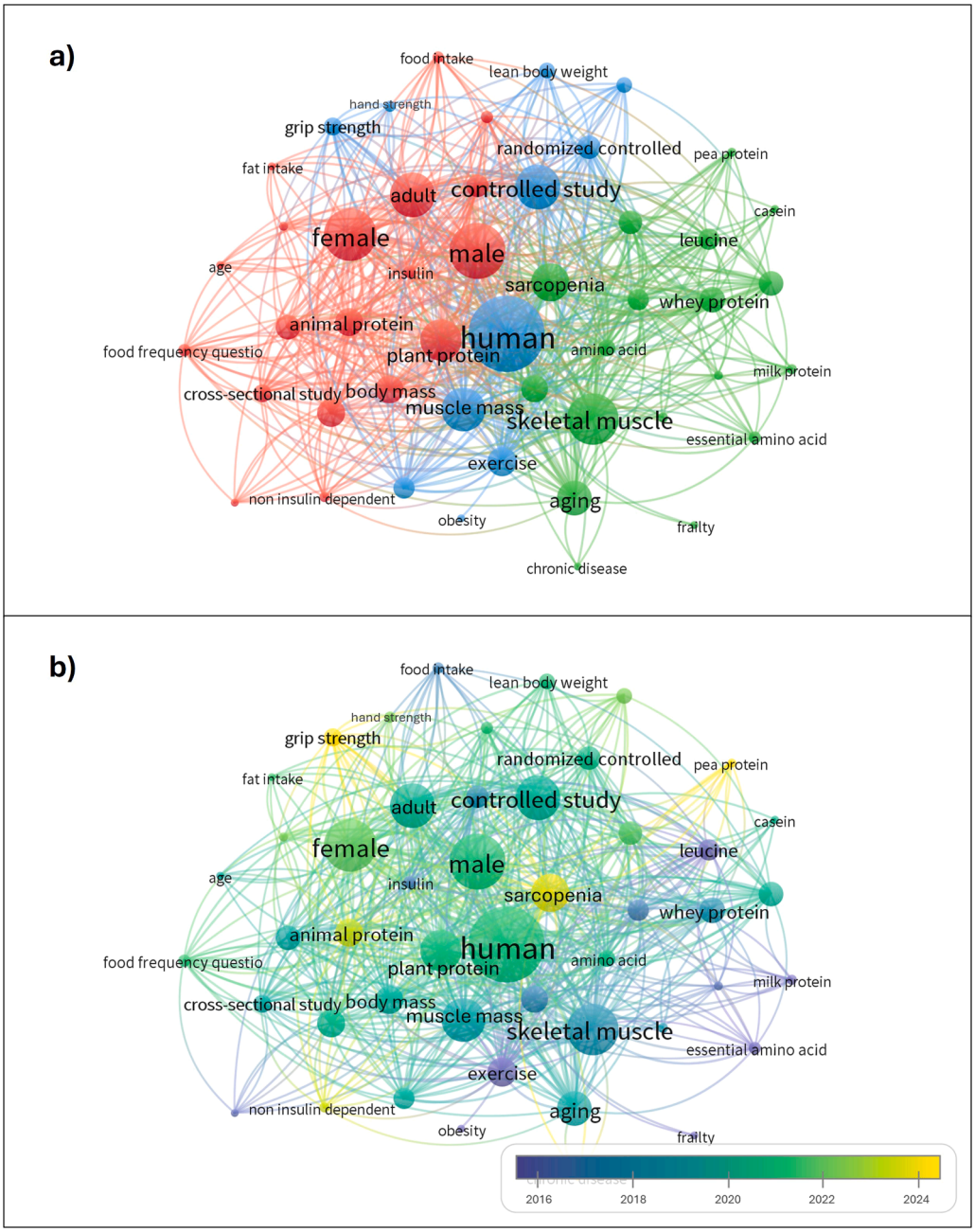


Fig. 3. Network visualization of keyword co-occurrence (minimum occurrence = 5). (a) Clustered network visualization showing three distinct thematic clusters. The size of each circle represents the frequency of a keyword's occurrence, while the lines between them indicate the strength of co-occurrence across the reviewed documents. Only keywords appearing at least five times were included, resulting in a network of 48 terms grouped into three distinct clusters. (b) Overlay visualization of the same network, where darker colours indicate earlier research topics and brighter colours highlight more recent areas of focus. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

coding the terms according to their average publication year. In this context, darker shades (e.g., blue) correspond to earlier research topics, while lighter shades (green to yellow) highlight more recent areas of focus. Analysis of the overlay network visualization indicates that certain terms have only recently gained prominence. Notably, 'pea' and 'sarcopenia' represent emerging areas of investigation, underscoring the increasing scientific interest in plant-based dietary components and the relatively recent recognition of sarcopenia as a significant clinical and public health issue within the last decade. While insulin-dependent mechanisms, obesity, and frailty have long formed the background of research interest, sarcopenia has now been more extensively investigated in recent studies, demonstrating its recognition as a real and impactful health problem.

Overall, these clusters illustrate a clear trajectory in the literature. The central positioning of terms such as human, muscle, and sarcopenia indicates an integrated research focus, with dietary protein increasingly viewed as a strategic component in interventions for age-related muscle decline.

A hypothetical formulation for a plant-based beverage targeting sarcopenia should focus on scientifically supported nutrients essential for muscle maintenance and recovery. It must provide a balanced combination of protein, branched-chain amino acids, antioxidants, vitamins, minerals, and polyunsaturated fatty acids. The formulation should also ensure digestibility and bioavailability, while considering sensory acceptability and affordability. The product must align with established intake guidelines for the elderly, drawing on clinical trial

evidence to support safe and effective nutrient levels. Additionally, the portion format should allow for protein intake to be distributed throughout the day, and the price must be affordable. Table 3 summarizes the key components and specifications that define this hypothetical beverage, aligning with both current clinical recommendations and consumer expectations. However, as no human trials have tested plant-based beverages (Table 1), the formulation's clinical efficacy, bioavailability, and tolerability remain speculative until validated through targeted intervention studies.

7. Conclusion

After identifying high-protein plant-based beverages as a powerful tool for preventing and mitigating sarcopenia, this review highlights a fundamental disconnect between the potential of plant-based beverages and how they are currently positioned in both scientific research and the commercial market. While numerous studies confirm the role of protein, especially high-quality sources rich in BCAAs like leucine, in supporting muscle health, the evidence around plant-based beverages remains limited. Most clinical trials still focus on whey or milk protein, and plant-based options are rarely included or sufficiently tested in elderly populations.

Nutritionally, it is clear that plant-based beverages can reach the required standards if properly formulated. Combining complementary protein sources, fortifying with essential micronutrients like vitamin D, and including functional lipids like omega-3 s can significantly enhance their muscle-supportive potential. From a technological perspective, advancements in processing methods like enzymatic treatments, ultrasound, and protein blending, are promising in improving solubility, digestibility, and taste. These innovations are essential to overcome the well-known challenges of using plant proteins in functional drinks.

The regulatory landscape highlights how health claims need to be backed by solid evidence, and the lack of clinical trials involving plant-based beverages tailored for sarcopenia limits what can legally be communicated to consumers. At the same time, there is a growing demand for transparency and simplicity in ingredient lists, which many current products ignore.

Notably, to the best of the authors' knowledge, there are no established recommended daily doses for protein intake in older adults, nor are there clear guidelines specifically addressing protein intake for counteracting sarcopenia. There is a lack of sex-specific recommendations, highlighting a critical gap in current research and dietary guidelines.

Perhaps most importantly, this review identifies a scarcity of studies focused specifically on vulnerable subgroups, like postmenopausal women, who are most affected by sarcopenia. This is a critical oversight, considering how hormonal changes, diet, and lifestyle in this group directly affect muscle loss. Addressing this oversight should be a priority for future research. Moreover, current works remain largely confined to theoretical discussions and isolated nutrient analyses. Future studies should aim to develop integrated, evidence-based, and cost-effective plant-based beverages specifically designed to prevent or mitigate sarcopenia, translating nutritional insights into practical, real-world interventions.

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Ethical statement - studies in humans and animals

Ethical approval was not required for this study.

CRediT authorship contribution statement

Diego Appicciutoli: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Aylin W. Sahin:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.fhfh.2026.100288.

Data availability

Data will be made available on request.

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