Plant-Based Protein and Muscle Protein Synthesis: A Review of Physiological Mechanisms, Protein Quality, and Practical Optimization Strategies

By Dr. Eugene Capitano, DC, MSc

Dr. Eugene Capitano earned an MSc in Psychology & Neuroscience of Mental Health from King's College London. He holds the ACSM Exercise is Medicine® (EIM) Credential and is an ACSM Certified Personal Trainer® (ACSM-CPT®). His research interests include the gut–brain axis, functional nutrition, metabolic health, and translational microbiome science.

Abstract

Plant-based proteins, and pea protein in particular, are increasingly used as alternatives to animal-derived proteins for supporting muscle protein synthesis (MPS) and skeletal-muscle maintenance. Relative to animal proteins they have lower per-gram leucine density, incomplete indispensable amino-acid profiles, and, in their native form, reduced digestibility due to antinutritional factors and cell-wall encapsulation. This review synthesizes current evidence on plant versus animal protein metabolism, focusing on MPS rates, the leucine threshold, amino-acid bioavailability, and the Digestible Indispensable Amino Acid Score (DIAAS). Controlled human trials indicate that when leucine and total essential amino acids are matched and adequate total protein is consumed, isolated and blended plant proteins can stimulate acute MPS to a degree comparable to whey or milk protein in young adults. There is a small residual advantage for animal protein in meta-analysis is driven almost entirely by studies in older adults, where anabolic resistance raises the per-meal leucine requirement. Reduced digestibility of native plant proteins is largely attributable to structural and antinutrient factors and is substantially corrected by industrial isolation, thermal processing, fermentation, and germination, with well-processed pea isolate achieving real ileal amino-acid digestibility above 90%. Evidence that pea protein isolate actively improves intestinal barrier function or reduces inflammation in humans is currently weak and derives mainly from in vitro and animal models. The more defensible position is that processing removes most antinutrients and that there is no good evidence isolates increase intestinal permeability in healthy adults. Heavy-metal contamination is a real quality-control consideration for all plant-derived supplements. Rice-derived protein is a notable inorganic-arsenic outlier, which provides an evidence-based rationale for favouring non-rice strategies to complete a legume protein's amino-acid profile. Overall, the anabolic limitations of plant proteins are quantitative and formulation-dependent rather than intrinsic, and can be managed through dose, complementary blending, and targeted amino-acid fortification.

Keywords: plant-based protein; pea protein; muscle protein synthesis; amino-acid bioavailability; DIAAS; leucine; antinutrients; heavy metals

1. Introduction

Interest in plant-forward nutrition continues to grow for sustainability, health, and ethical reasons. Despite this, the anabolic efficacy of plant proteins, pea protein among them, has been questioned on three related grounds. A lower proportion of key essential amino acids (EAAs), especially leucine, methionine, and lysine (Phillips & van Loon, 2011; Layman, 2024), reduced digestibility arising from antinutritional compounds such as phytic acid, protease inhibitors, and lectins (Sarwar Gilani et al., 2012), and slower postprandial amino-acid kinetics with greater first-pass splanchnic extraction, so that fewer EAAs reach the systemic circulation (van Vliet et al., 2015). Historically these constraints supported the view that animal-derived proteins were superior for stimulating muscle protein synthesis (MPS) and preserving lean tissue (FAO, 2013).

More recent tracer studies and controlled randomized trials have qualified this view. When total protein intake, leucine content, and overall EAA availability are matched, plant-derived proteins can stimulate MPS to a degree comparable to whey or milk protein in young adults (Monteyne et al., 2023; Pinckaers et al., 2024; van der Heijden et al., 2024). Reaching that equivalence typically requires higher absolute protein doses, strategic blending of complementary plant sources, or fortification with limiting amino acids (Pinckaers et al., 2022; Lim et al., 2024).

Age-related anabolic resistance sharpens these distinctions. Older adults generally require a higher per-meal leucine dose to maximally stimulate MPS and are more vulnerable to metabolic stressors such as insulin resistance and chronic low-grade inflammation (Katsanos et al., 2005; Burd et al., 2013). Optimizing plant-protein intake across the lifespan therefore depends on both quantitative factors (total dose, leucine threshold) and qualitative characteristics (amino-acid profile, digestibility, bioavailability).

This review synthesizes the mechanistic and clinical evidence on plant-protein metabolism, evaluates the conditions under which plant proteins approach the anabolic efficacy of whey, and outlines evidence-based strategies to realize their potential. It also addresses antinutrient reduction, gastrointestinal considerations, and heavy-metal contamination, aiming to keep recommendations proportional to the strength of the underlying evidence.

2. Biochemical Mechanisms of Muscle Protein Synthesis and the Role of Leucine

2.1 The mTORC1 signalling pathway

Muscle protein synthesis is primarily regulated by mechanistic target of rapamycin complex-1 (mTORC1), a nutrient-sensing hub that coordinates translation initiation in response to amino-acid availability. Among the EAAs, leucine is the most potent activator of this pathway and functions as a signal that substrate availability is sufficient to initiate synthesis (Drummond & Rasmussen, 2008).

Leucine influences mTORC1 through several mechanisms, including sensing by leucyl-tRNA synthetase and Sestrin2 and modulation of cellular energy status. Once activated, mTORC1 phosphorylates downstream effectors including p70 ribosomal S6 kinase and 4E-BP1, phosphorylation of 4E-BP1 releases eIF4E and enables assembly of the translation-initiation complex, producing a rise in myofibrillar protein synthesis (Drummond & Rasmussen, 2008).

From a practical standpoint, any protein source, animal or plant, that delivers sufficient leucine and EAAs can activate mTORC1. The difference between sources is one of efficiency. Animal proteins typically provide higher leucine density and faster digestion, whereas plant proteins often require larger servings, blending, or amino-acid fortification to achieve comparable intracellular leucine signalling. The underlying molecular mechanism is the same across sources.

2.2 The leucine-threshold hypothesis

The leucine-threshold hypothesis proposes that a critical rise in circulating leucine is required to maximally activate mTORC1 and stimulate MPS. This threshold is dynamic and influenced by age, metabolic status, training history, prior nutrient intake, and the EAA composition of the ingested protein (Moore et al., 2015). In young adults, roughly 20–25 g of a rapidly digested, high-quality protein supplies about 2.0–2.7 g of leucine, which is generally sufficient to reach the threshold, increasing intake beyond this does not further amplify the acute response, indicating a plateau in the dose–response relationship (Witard et al., 2014).

Older adults exhibit anabolic resistance, which is a diminished sensitivity of mTORC1 to dietary amino acids. Overcoming it requires a higher leucine load, commonly cited as approximately 2.5–3.0 g per meal, often necessitating 30–40 g of high-quality protein or targeted leucine/EAA fortification (Katsanos et al., 2005; Moore et al., 2015).

2.3 Plant proteins, leucine content, and dose-dependence

Plant proteins, including pea, generally contain less leucine per gram (approximately 6.8–8.0% of total protein) and are digested more slowly than whey or milk protein (van Vliet et al., 2015; Gorissen & Witard, 2018). Isonitrogenous servings therefore produce a smaller and slower rise in plasma leucine, making plant proteins appear less anabolic gram-for-gram.

This limitation is quantitative rather than intrinsic. Controlled tracer studies and training trials show that when total protein dose, leucine content, and EAA availability are matched, MPS responses converge. This can be achieved by increasing serving size, blending complementary plant proteins, or fortifying with leucine or other EAAs (Pinckaers et al., 2022; Lim et al., 2024). For example, a 30 g fully plant-derived blend matched to whey for leucine elicited equivalent post-exercise myofibrillar protein synthesis in resistance-trained adults (van der Heijden et al., 2024), and a 30 g dose of isolated pea protein (~1.8 g leucine) produced myofibrillar synthesis rates indistinguishable from milk protein containing ~2.4 g leucine in healthy young men (Pinckaers et al., 2024).

Table 1. Controlled human comparisons of plant versus animal protein on muscle protein synthesis.

Study	Design	Plant-protein form	MPS-relevant finding
Pinckaers et al., 2024	Randomized, parallel; 30 g pea vs 30 g milk protein; 24 young men	Pea-protein isolate	Milk produced greater plasma EAA availability (5-h EAA iAUC 151 ± 31 vs 102 ± 15), but myofibrillar FSR was identical (0.053 vs 0.053 %·h^{-1}; p = 0.96).
Pinckaers et al., 2022	Randomized, double-blind; 30 g wheat/corn/pea blend vs 30 g milk, matched ~2.4 g leucine; young men	Wheat + corn + pea blend	Despite lower plasma EAA appearance, myofibrillar FSR did not differ from milk.
van der Heijden et al., 2024	Randomized; 32 g plant blend (39.5% pea, 39.5% brown rice, 21% canola; 2.5 g leucine) vs isonitrogenous whey; resistance-trained adults	Pea/rice/canola blend	Plasma EAA availability ~44% lower than whey, yet post-exercise myofibrillar FSR was equivalent at 0–2 h and 2–4 h.
Monteyne et al., 2023	Controlled 3-day isocaloric, isonitrogenous (1.8 g·kg^{-1}·day^{-1}) vegan vs omnivorous diets; young adults	Mycoprotein-based diet	Daily myofibrillar MPS did not differ between diets.
Domić et al., 2025	Randomized crossover; isocaloric, isonitrogenous vegan vs omnivorous; active older adults	Mixed plant isolates	10-day integrated MPS did not differ (1.23 vs 1.29 %·day^{-1}; p = 0.25).

Across these designs, purified plant isolates and blends can achieve MPS responses comparable to animal proteins when leucine and EAA availability are matched (Monteyne et al., 2023; Pinckaers et al., 2024; van der Heijden et al., 2024; Domić et al., 2025). The lower per-gram potency of unfortified plant proteins reflects lower intrinsic leucine density (van Vliet et al., 2015; Gorissen & Witard, 2018), slower amino-acid appearance (Pinckaers et al., 2024), and greater first-pass splanchnic extraction (Bos et al., 2005; van Vliet et al., 2015). These are dose- and formulation-dependent factors. Once servings are increased to meet the leucine threshold, or blended and fortified to correct limiting EAAs, the acute MPS response becomes comparable to whey or milk protein (Pinckaers et al., 2022; Lim et al., 2024; van der Heijden et al., 2024).

3. Comparative Physiology: Plant Versus Animal Proteins

3.1 Essential amino-acid composition, protein quality, and complementarity

Animal proteins such as whey, casein, egg, and meat provide all nine indispensable amino acids in ratios closely aligned with human requirements, and their higher leucine content makes them efficient activators of MPS gram-for-gram (van Vliet et al., 2015). Most isolated plant proteins contain a lower proportion of leucine and have a characteristic limiting amino acid. Legumes such as pea are relatively low in the sulphur amino acids (methionine and cysteine), whereas cereals such as rice are low in lysine (FAO, 2013; Herreman et al., 2020). Pea-protein isolate, for instance, is rich in lysine but comparatively low in sulphur amino acids (Pinckaers et al., 2024; van Vliet et al., 2015).

Protein quality is quantified using the Protein Digestibility-Corrected Amino Acid Score (PDCAAS) or the more recent Digestible Indispensable Amino Acid Score (DIAAS). PDCAAS uses fecal digestibility and truncates scores at 1.0, which obscures differences among high-quality proteins. DIAAS, recommended by the FAO in 2013, uses ileal amino-acid digestibility, does not truncate, and more accurately reflects bioavailability. Proteins scoring ≥100 are classified as “excellent,” 75–99 as “good,” and <75 as insufficient for a quality claim (FAO, 2013; Rutherfurd & Moughan, 2012). Under these standards, animal proteins such as whey and milk score in the excellent range, while single legume or cereal isolates typically fall lower (Herreman et al., 2020; Mathai et al., 2017).

The lower DIAAS of many plant proteins reflects the amino-acid profile of single ingredients consumed alone rather than a fixed limitation. Combining proteins with complementary profiles corrects their limiting amino acids. Legumes supply abundant lysine but limited sulphur amino acids, whereas cereals supply the reverse, so that a legume–cereal combination raises the meal’s amino-acid quality (Herreman et al., 2020; Reynaud et al., 2021). This principle underlies traditional dietary patterns (beans with rice, lentils with wheat) and modern protein-quality modelling, in which legume–cereal or legume–oilseed mixtures can reach DIAAS values in the excellent range (Herreman et al., 2020; Mathai et al., 2017). Functionally, a plant-protein blend that corrects limiting amino acids and supplies ≥2.5 g leucine per serving stimulated post-exercise myofibrillar protein synthesis to the same magnitude as isonitrogenous whey in resistance-trained adults (van der Heijden et al., 2024).

An alternative to cereal complementation is direct fortification of a legume base with its limiting amino acids. Correcting pea’s sulphur amino acids with supplemental methionine addresses the primary

determinant of its quality score, while meeting the leucine threshold, through dose or free-leucine addition, addresses anabolic signalling. These are distinct problems. Methionine restores completeness, whereas leucine restores anabolic potency. The direct human evidence for a methionine-plus-leucine–fortified pea isolate is limited, but the components are each supported. The methionine correction rests on established amino-acid scoring, and leucine fortification of plant blends has been shown to raise MPS toward whey-equivalent levels, albeit with modest effect sizes (Lim et al., 2024). This route also avoids reliance on cereal proteins such as rice, which is relevant to heavy-metal considerations discussed in Section 11.

3.2 Postprandial amino-acid availability

A key distinction between plant and animal proteins is the pattern of postprandial amino-acid appearance, determined by digestion rate, intestinal uptake, and splanchnic extraction. Whey is rapidly digested and produces a sharp rise in circulating indispensable amino acids, whereas casein coagulates in the stomach and is absorbed more slowly, producing a prolonged but attenuated aminoacidemia (Boirie et al., 1997; Pennings et al., 2011). Soy shows an intermediate rate, and several other plant isolates produce lower or more modest peaks than whey (Tang et al., 2009; van Vliet et al., 2015).

For pea protein specifically, ingestion of 30 g produces a lower and slightly delayed rise in circulating EAAs than an equal dose of milk protein, with a five-hour EAA incremental area under the curve roughly one-third lower (Pinckaers et al., 2024). Plant-derived amino acids are also subject to greater first-pass splanchnic metabolism: studies comparing soy or wheat with milk report higher postprandial amino-acid oxidation and ureagenesis after plant-protein ingestion, indicating more extensive diversion before amino acids reach the peripheral circulation (Bos et al., 2003; Fouillet et al., 2002; Bos et al., 2005). By contrast, intrinsically labelled milk and beef proteins deliver a substantial fraction of ingested amino acids to the systemic circulation during the postprandial period (Groen et al., 2015).

These kinetic differences contribute to the lower acute potency of plant proteins at equal gram-for-gram doses, but they are dose- and composition-dependent rather than immutable. When plant servings are increased to match leucine and EAA delivery, or blended to correct limiting amino acids, postprandial MPS converges with that of high-quality animal proteins even when the EAA area under the curve remains somewhat lower (Pinckaers et al., 2022, 2024; van der Heijden et al., 2024). Meta-analytic evidence indicates that the advantage of animal over plant protein for acute MPS is small and becomes negligible when total protein dose and leucine intake are adequate (Mendes et al., 2026). The key determinants of postprandial anabolic efficacy are therefore total protein dose, leucine delivery, and EAA balance rather than botanical origin per se.4. Muscle Protein Synthesis Response to Equalized Protein and Leucine Intake

4.1 Young adults

When plant and animal proteins are consumed in doses providing equivalent leucine and total EAAs, postprandial MPS rates are generally indistinguishable in young adults (van Vliet et al., 2015; Mendes et al., 2026), a result replicated with both single-source isolates and optimized blends.

In a randomized, double-blind, parallel-group trial, 30 g of pea-protein isolate was compared with 30 g of milk protein in 24 healthy young men. Milk produced greater plasma EAA availability over five hours (EAA iAUC 151 ± 31 vs 102 ± 15), yet myofibrillar fractional synthesis rates were identical (0.053 vs 0.053 %·h^{-1}; p = 0.96), despite pea supplying less total EAA and leucine (~1.8 vs ~2.4 g) (Pinckaers et al., 2024). Peak aminoacidemia is therefore not the sole determinant of the acute MPS response in this population.

Similar results emerge with blends. A 30 g wheat/corn/pea blend matched to milk for leucine (~2.4 g) produced myofibrillar synthesis rates that did not differ from milk, despite lower plasma EAA, lysine, and methionine appearance (Pinckaers et al., 2022). Exercise-based comparisons reinforce this. A fully plant-derived blend (39.5% pea, 39.5% brown rice, 21% canola; 32 g protein, 2.5 g leucine) stimulated post-exercise myofibrillar synthesis to the same extent as isonitrogenous whey in resistance-trained adults, even though plasma EAA availability was ~44% lower (van der Heijden et al., 2024).

Meta-analysis is consistent with these trials. Pooling randomized comparisons of plant versus animal protein yielded only a trivial effect favouring animal protein (approximately 0.004 %·h^{-1} FSR; 95% credible interval −0.002 to 0.011), and this small advantage was driven almost entirely by studies in older adults; among young adults the responses were essentially identical when protein dose and leucine were matched (Mendes et al., 2026). In sum, plant proteins, as isolates or blends, can match animal proteins for acute MPS in young adults when a serving supplies roughly 1.8–2.5 g leucine and 7–10 g total EAAs. Under these conditions, differences in DIAAS, digestion rate, or plasma amino-acid peaks do not translate into differences in MPS.

4.2 Older adults

Age-related anabolic resistance, a reduced MPS response to dietary protein, is the principal factor distinguishing plant- from animal-protein efficacy in older adults (Burd et al., 2013; van Vliet et al., 2015). Here, higher doses and higher per-meal leucine are required. In older men, 40 g of soy protein isolate elicited lower myofibrillar synthesis than 40 g of whey, attributable mainly to whey's higher leucine density and more favourable kinetics rather than an intrinsic inability of plant protein to stimulate MPS (Yang et al., 2012; van Vliet et al., 2015).

When plant proteins are consumed as part of a high-protein, well-balanced dietary pattern, however, older adults can achieve integrated MPS rates comparable to omnivorous diets. A randomized crossover trial in active older adults found that a well-balanced vegan diet matched for total protein did not compromise daily mixed-muscle protein synthesis relative to an omnivorous diet (1.23 vs 1.29 %·day^{-1}; p = 0.25) (Domić et al., 2025). Likewise, a high-protein mycoprotein-based vegan diet supported daily myofibrillar synthesis equivalent to an isonitrogenous omnivorous diet in older adults (Monteyne et al., 2021).

The determining factor for older adults is therefore not protein source but whether the diet provides sufficient total daily protein, adequate per-meal leucine (generally cited as ~2.5–3.0 g to overcome anabolic resistance), and a complete, complementary EAA profile achieved through mixed plant proteins or high-quality isolates (Herreman et al., 2020; Moore et al., 2015). Meta-analysis

supports this, the modest average advantage of animal protein was driven by older-adult studies in which plant conditions typically supplied lower leucine or used single, unfortified sources. When plant proteins were provided at higher doses or as improved-profile blends, the difference diminished or disappeared (Monteyne et al., 2021; Mendes et al., 2026).

5. Mechanisms of Reduced Plant-Protein Digestibility

5.1 Structural barriers and cell-wall encapsulation

The lower digestibility of native plant proteins arises largely from their localization within intact plant cells. Animal proteins occur in compartments directly accessible to gastric and pancreatic enzymes, whereas plant proteins are enclosed within cell-wall matrices of cellulose, hemicellulose, and pectin that restrict enzymatic access and slow gastric emptying (Grundy et al., 2016). In raw or minimally processed legumes, apparent protein digestibility in humans is typically around 75–80%, whereas processing into concentrates or isolates raises digestibility above 90%, approaching animal proteins (Sá et al., 2020; Santos-Hernández et al., 2020; Ajomiwe et al., 2024). The main limitation is thus matrix-related rather than a defect in amino-acid composition.

5.2 Antinutritional factors and enzyme inhibition

Beyond structural barriers, plant foods contain antinutritional compounds that can inhibit digestive enzymes, bind proteins, or chelate minerals, lowering amino-acid bioavailability. Phytic acid chelates divalent cations and forms protein–phytate complexes that resist hydrolysis (Sarwar Gilani et al., 2012; Gupta et al., 2015). Serine-protease inhibitors in legumes bind pancreatic enzymes and increase endogenous nitrogen losses (Sarwar Gilani et al., 2012; Sá et al., 2020). Lectins can impair intestinal integrity and nutrient absorption when consumed raw, but standard thermal treatments reduce lectin activity by more than 80–90% (Sarwar Gilani et al., 2012; Sá et al., 2020). Polyphenols and tannins form protein complexes that reduce solubility and proteolysis (Sarwar Gilani et al., 2012; Ajomiwe et al., 2024). Collectively, these factors diminish protease activity and amino-acid release in unprocessed foods, but their effects are substantially mitigated by soaking, germination, fermentation, dehulling, heating, or industrial isolation (Sá et al., 2020; Santos-Hernández et al., 2020).

5.3 Quantitative impact on digestibility

Raw or minimally processed legume flours typically show apparent digestibility around 75–80% (Sá et al., 2020; Aryee & Boye, 2016), whereas legume protein isolates reach 85–96% in vitro digestibility after alkaline extraction or isoelectric precipitation (Aryee & Boye, 2016; Santos-Hernández et al., 2020). In humans, a study using intrinsically ^{15}N-labelled pea-protein isolate and naso-ileal sampling reported real ileal amino-acid digestibility of 93.6 ± 2.9% for pea versus 96.8 ± 1.0% for casein, a non-significant difference ($p = 0.22$), with similarly high nitrogen digestibility (Guillin et al., 2022). These findings confirm that disrupting the fibre matrix and antinutrient load through mechanical, thermal, or enzymatic processing yields plant-protein isolates with digestive efficiency approaching that of animal proteins.

6. Strategies for Mitigating Antinutritional-Factor Effects

6.1 Thermal processing

Heating inactivates protease inhibitors and lectins and improves digestibility. Across legume species, common thermal treatments substantially enhance in vitro protein digestibility and can inactivate a large fraction of trypsin-inhibitor and lectin activity (Sánchez-Velázquez et al., 2021; Sá et al., 2020). Commercial pea isolates, produced through dehulling, milling, aqueous extraction, separation, and drying, remove most of the fibre matrix and greatly lower trypsin-inhibitor, lectin, tannin, and phytic-acid levels relative to the seed; well-processed isolates achieve real ileal digestibility above 90% (Guillin et al., 2022; Sá et al., 2020).

6.2 Fermentation

Fermentation with lactic-acid bacteria or fungi reduces antinutrients through microbial phytases and proteases, lowering phytic-acid content and protease-inhibitor activity and improving mineral bioavailability and in vitro digestibility (Gupta et al., 2015; Sá et al., 2020). Fermentation can also generate bioactive peptides with antioxidant and other activities (Ajomiwe et al., 2024).

6.3 Germination and sprouting

Germination activates endogenous phytases and proteases that degrade antinutrients and remodel storage proteins, reducing phytic acid and protease-inhibitor activity, increasing free amino acids, and improving mineral bioavailability; combining germination with fermentation or thermal treatment can amplify these benefits (Sá et al., 2020; Gupta et al., 2015).

6.4 Protein blending and complementary profiles

Blending plant proteins with complementary amino-acid spectra raises overall quality. Legumes are rich in lysine but limited in sulphur amino acids, whereas cereals show the opposite pattern. Combining them offsets each limiting amino acid (Herreman et al., 2020; López-Moreno & Kraselnik, 2025). DIAAS modelling confirms that appropriate combinations can reach the FAO adult reference pattern (Herreman et al., 2020). A three-way blend of pea, brown rice, and canola met indispensable-amino-acid requirements and, consumed post-exercise at ~32 g, stimulated myofibrillar protein synthesis comparably to whey in resistance-trained adults (van der Heijden et al., 2024).

6.5 Supplementation with limiting amino acids

Direct amino-acid fortification targets specific limitations without large serving sizes. For a legume base such as pea, supplemental methionine corrects the limiting sulphur amino acids that constrain the quality score, and supplemental leucine helps meet the anabolic threshold. In a randomized crossover trial, a pea–canola blend fortified with free leucine to match the leucine content of whey raised MPS toward whey-equivalent levels in young men and women, though the difference from whey was of borderline statistical significance (Lim et al., 2024). Preclinical work similarly indicates that leucine fortification is required for a pea/soy blend to match whey in an aged-rodent model (Dijk et al., 2025). The evidence for amino-acid fortification is thus mechanistically strong and

reasonably supported for leucine, while direct human MPS data for a combined methionine-plus-leucine–fortified pea isolate remain limited. In practice, fortification can allow adequate anabolic signalling from a smaller dose of plant protein than would be required unfortified, improving gastrointestinal tolerance.

Table 2. Strategies to improve plant-protein utilization.

Strategy	Mechanistic rationale	Evidence of efficacy
Thermal processing	Denatures proteins; inactivates lectins and protease inhibitors	Increases digestibility; large reductions in inhibitor/lectin activity (Sá et al., 2020; Sánchez-Velázquez et al., 2021)
Fermentation	Microbial phytases/proteases degrade phytate and inhibitors	Lowers phytate and inhibitors; improves mineral bioavailability (Gupta et al., 2015; Sá et al., 2020)
Germination	Activates endogenous phytases/proteases; remodels storage proteins	Reduces phytate; increases free amino acids (Sá et al., 2020; Gupta et al., 2015)
Blending (legume + cereal/oilseed)	Complements limiting EAAs; raises DIAAS	DIAAS toward ≥100; MPS comparable to whey for optimized blends (Herreman et al., 2020; van der Heijden et al., 2024)
Free-amino-acid fortification	Corrects limiting amino acids (methionine) and meets the leucine threshold	Leucine-fortified blend approached whey-equivalent MPS (borderline) (Lim et al., 2024); methionine correction supported by amino-acid scoring

7. Optimal Protein Quantity and Distribution

7.1 Young and middle-aged adults

In young adults, a meal containing roughly 20–30 g of high-quality protein maximally stimulates MPS when leucine reaches about 2.0–2.7 g, with the acute response plateauing near 20 g of whey and no further increase from larger doses (Witard et al., 2014; Moore et al., 2009). Equivalent stimulation from plant proteins can be achieved through higher absolute quantities of a single source, optimized blends of complementary proteins, or fortification of a moderate dose with free leucine (van Vliet et al., 2015; van der Heijden et al., 2024; Lim et al., 2024). A daily intake of approximately 1.6 $g \cdot kg^{-1} \cdot day^{-1}$ supports muscle maintenance and resistance-training adaptation in trained individuals and can be met from plant sources when total leucine is adequate and distributed across meals (Morton et al., 2018).

7.2 Older adults

Anabolic resistance raises the per-meal leucine requirement. Older adults show minimal MPS response to small EAA boluses but robust responses to larger, leucine-rich doses (Katsanos et al., 2005). Practical approaches include a higher per-meal leucine target (commonly ~2.5–3.0 g), achieved through a larger single plant-protein serving or an optimized blend, with protein distributed across meals rather than concentrated, given the extended duration of postprandial MPS elevation. Resistance training enhances anabolic sensitivity and reduces the required per-meal dose (Moore et al., 2015). The PROT-AGE group recommends approximately 1.0–1.2 $g \cdot kg^{-1} \cdot day^{-1}$ for older adults, with 25–30 g of protein per meal and attention to EAA content, particularly leucine (Bauer et al., 2013).

8. Age-Related Anabolic Resistance

Aging is characterized by a blunted MPS response to protein ingestion and resistance exercise (Burd et al., 2013). Contributing mechanisms include reduced phosphorylation of mTORC1 substrates following protein ingestion despite adequate amino-acid availability (Drummond & Rasmussen, 2008), diminished satellite-cell activation, particularly in type II fibres, which constrains longer-term hypertrophy and regeneration (Snijders et al., 2015), increased splanchnic extraction of amino acids, reducing systemic availability (Boirie et al., 1997), and finally a greater postprandial oxidation of some plant-derived amino acids in older individuals (Yang et al., 2012).

Critically, these mechanisms raise the *threshold* for a maximal response rather than making plant proteins inherently ineffective. A randomized crossover trial in community-dwelling older adults found that a well-balanced vegan diet matched for total protein produced daily mixed-muscle protein synthesis rates indistinguishable from an omnivorous diet (Domić et al., 2025). Acute postprandial studies more often show lower MPS to plant proteins when total protein is matched but leucine is not. When leucine is equalized, the difference is attenuated or eliminated (Mendes et al., 2026). The operative variable is whether per-meal leucine and total EAA delivery are sufficient, not botanical origin.

9. Bioavailability and DIAAS Assessment

DIAAS quantifies protein quality by determining the true ileal digestibility of each indispensable amino acid and comparing delivery to human requirements (FAO, 2013; Rutherfurd & Moughan, 2012). A protein's score is limited by its most deficient amino acid; scores can exceed 100 when all indispensable amino acids are provided in surplus. By using ileal rather than fecal digestibility, DIAAS avoids overestimating quality where colonic fermentation of undigested protein would otherwise inflate apparent digestibility (Rutherfurd & Moughan, 2012).

Plant-protein DIAAS scores are typically lower than animal proteins for three reasons: slightly lower intrinsic ileal digestibility even after processing; a limiting indispensable amino acid (sulphur amino acids in pea; lysine in cereals); and losses of undigested protein to colonic fermentation, whose products are metabolically useful but do not count toward DIAAS (Herreman et al., 2020; Mathai et al., 2017). Processing and blending substantially improve these scores, and complementary combinations can reach the excellent range (Herreman et al., 2020).

An important caveat is that DIAAS was designed to assess protein sufficiency for meeting amino-acid requirements, not to predict MPS capacity in the context of resistance exercise. A lower-DIAAS protein can support MPS comparable to a higher-DIAAS protein when consumed in a larger quantity that delivers equal absolute EAAs and leucine, as demonstrated by the pea-versus-milk and blend-versus-whey trials above (Pinckaers et al., 2024; van der Heijden et al., 2024). DIAAS is therefore a useful ranking of relative quality but does not fully capture the capacity of plant proteins to support MPS when consumed in adequate amounts.

10. Intestinal Health, Antinutrients, and the "Leaky Gut" Question

The "leaky gut" hypothesis, that dietary components increase intestinal permeability, permitting bacterial lipopolysaccharide translocation and systemic inflammation, features prominently in popular discourse but has limited high-quality evidence specific to plant-protein isolates. The intestinal barrier is maintained by tight-junction proteins regulated by immune signalling and the gut microbiota. While whole legumes contain lectins that can affect the barrier when consumed raw, commercial pea isolates undergo processing that inactivates most lectins.

The evidence bearing on whether pea protein isolate *actively benefits* the gut barrier is currently weak and preliminary. Claims that pea protein reduces inflammation or strengthens tight junctions derive mainly from in vitro and animal models rather than controlled human trials, and some of the human data that have circulated come from low-quality sources. Accordingly, the defensible position is narrower than sometimes stated. Commercial isolation removes the large majority of antinutrients (a well-supported claim), and there is no good evidence that pea protein isolate *increases* intestinal permeability in healthy adults. The latter is an absence of evidence for harm rather than positive evidence of benefit, and should not be presented as proof of a gut-protective effect.

A meaningful distinction exists between whole plant foods and isolates. Whole pulses deliver protein alongside fibre, resistant starch, and polyphenols that feed beneficial microbiota and support short-chain fatty-acid production. An isolate consumed without these components will not reproduce those effects. Human data on the microbiota effects of plant-protein consumption are mixed and often derive from whole foods or plant-based meat alternatives rather than isolated pea protein, so they should not be generalized to isolates (Toribio-Mateas et al., 2021). To support gut health, pairing protein isolates with adequate dietary fibre and a varied whole-food intake is a reasonable, evidence-consistent practice, whereas specific therapeutic claims for pea isolate are not currently warranted.

With respect to antinutrient concentrations, commercial pea isolates contain phytic acid, protease inhibitors, and lectins at levels far below those of whole peas, owing to dehulling, aqueous extraction, and thermal steps during manufacture (Sá et al., 2020; Santos-Hernández et al., 2020; Ajomiwe et al., 2024). Combined with the human digestibility data in Section 5, this indicates that residual antinutrient activity in well-processed pea isolate is of limited practical relevance to protein absorption in healthy adults.

11. Heavy-Metal Contamination: Risk Assessment and Sourcing

Heavy-metal accumulation, particularly arsenic, cadmium, and lead, is a legitimate quality consideration for plant-derived protein powders, because plants take these elements up from soil and water and concentration steps can raise their relative levels in isolates.

A Canadian targeted survey of toxic metals in foods (2018–2019) analyzed samples across multiple categories, including protein powders and rice. Among plant-derived materials, rice stood out. Arsenic was detected in about 95% of rice samples at an average near 0.263 ppm, the highest of the food categories examined. This is consistent with the well-established status of rice as an efficient accumulator of inorganic arsenic. The survey's overall determination was that detected levels did not pose a health concern at estimated intakes, but the category-level pattern identifies rice-derived ingredients as a distinct arsenic risk relative to other plant proteins.

Formal risk assessment of protein powders supports a measured interpretation. An exposure assessment of arsenic, cadmium, mercury, and lead across commercial protein powders estimated a hazard index below one, indicating no elevated health risk at typical intakes, while noting that content varied by product type, with plant- and mass-gainer products tending higher and whey lower (Bandara et al., 2020). Market surveys likewise generally report contaminant levels within applicable limits, though with product-to-product variability that argues for ongoing quality control rather than complacency (Kovács et al., 2025).

Two practical points follow. First, heavy-metal risk is a general attribute of plant-derived supplements that is best managed through source selection, third-party testing, and adherence to stringent jurisdictional limits (for example, California's Proposition 65 benchmarks are among the most conservative), rather than through avoidance of plant proteins as a class. Second, because rice-derived protein is a specific inorganic-arsenic outlier, there is an evidence-based rationale for completing a legume protein's amino-acid profile by means other than rice. For a pea base, correcting the limiting sulphur amino acids with methionine and meeting the leucine threshold, rather than adding a rice component, achieves amino-acid adequacy while avoiding rice's arsenic burden. This aligns the formulation logic with both the protein-quality evidence (Section 3) and the contamination data above.

12. Practical Recommendations

12.1 Young and middle-aged adults

Comparable MPS and training adaptations to omnivorous diets are achievable on plant-based intake with attention to dose and distribution: approximately 1.6–2.2 $g \cdot kg^{-1} \cdot day^{-1}$ total protein; per-meal protein sufficient to deliver about 2.0–2.7 g leucine (a larger single-source serving, an optimized blend, or a moderate dose fortified with free leucine); distribution across three to four meals; and protein intake in proximity to resistance exercise. Including whole plant foods alongside isolates supports fibre intake and microbiota diversity.

12.2 Older adults

Older adults benefit from strategies that overcome anabolic resistance. At least ~1.0–1.2 $g \cdot kg^{-1} \cdot day^{-1}$ total protein with emphasis on distribution, a per-meal leucine target of ~2.5–3.0 g via a larger high-quality serving, an optimized blend, or fortification, prioritizing adequate protein at breakfast and lunch, when intake is often lowest, and combining protein with resistance training. Periodic assessment of body composition and strength helps verify adequacy.

12.3 Minimizing antinutrient exposure

Use processed isolates rather than whole flours for supplementation. For whole foods, favour cooking, fermentation, or germination, which reduce antinutrients substantially. Rotating protein sources and pairing plant protein with vitamin-C–containing foods to support non-heme iron absorption are reasonable practices.

12.4 Monitoring

Individuals adopting plant-based protein strategies can track daily protein and leucine intake, periodically assess lean mass and strength, monitor gastrointestinal tolerance while increasing intake gradually, and adjust total protein if lean mass or performance declines.

13. Longitudinal Training Studies

Longer-term trials support the acute findings. A comparison of habitual vegans and omnivores undergoing resistance training, with total protein matched at ~1.6 $g \cdot kg^{-1} \cdot day^{-1}$ (plant sources plus soy isolate versus mixed diet plus whey), found equivalent gains in lean mass, muscle cross-sectional area, fibre size, and strength over the intervention (Hevia-Larraín et al., 2021). In middle-aged women, meals providing equal total protein from complete, complementary, or incomplete plant sources did not differentially affect 24-hour myofibrillar synthesis, suggesting that DIAAS ranking does not fully predict MPS at moderate, distributed protein intakes (Arentson-Lantz et al., 2024). Together these data indicate that, with adequate total protein and leucine, plant-based diets support resistance-training adaptations comparable to omnivorous diets.

14. Vegan and Vegetarian Populations

Habitual plant-based eaters show adaptations relevant to protein utilization, including microbiota enriched in fibrolytic and proteolytic taxa, and amino-acid kinetics that approximate those of omnivores when daily protein is matched. Attention to adequate total protein, leucine distribution, and, over the long term, calcium and other nutrients relevant to bone health remains important, particularly with aging. The evidence indicates no inherent physiological disadvantage for muscle adaptation in habitual vegans who meet protein and leucine targets; dietary adequacy and food selection determine outcomes (Hevia-Larraín et al., 2021; Monteyne et al., 2023).

15. Future Research Directions

Priorities include longer-term (6–12 month) trials of muscle maintenance and strength on plant-based diets in older adults, mechanistic work on why plant proteins can produce lower plasma amino-acid availability yet equivalent MPS at adequate doses, characterization of microbiota-derived metabolites and their contribution to protein metabolism, controlled human trials of methionine-plus-leucine–fortified legume isolates, for which direct MPS data are currently lacking, identification of individual factors predicting responsiveness, and evaluation of plant-based diets in endurance and power sports beyond resistance training.

16. Conclusions

Plant-based proteins, and pea protein and optimized plant blends in particular, can support muscle protein synthesis and resistance-training adaptations comparable to animal proteins across the adult lifespan when three conditions are met. First an adequate total protein intake (approximately 1.6–2.2 $g \cdot kg^{-1} \cdot day^{-1}$ in young adults and at least ~1.0–1.2 $g \cdot kg^{-1} \cdot day^{-1}$ in older adults, with distribution). Second, sufficient per-meal leucine (~2.0–2.7 g in young adults, ~2.5–3.0 g in older adults), and third a complete, complementary amino-acid profile achieved through blending or targeted fortification. Differences in postprandial amino-acid availability between plant and animal proteins are substantially compensated by intramuscular amino-acid dynamics and mTORC1 signalling when leucine and EAA delivery are adequate, and the reduced digestibility of native plant proteins is largely corrected by isolation and processing.

Two areas warrant more caution than is sometimes applied. Evidence that pea protein isolate actively improves gut-barrier function or reduces inflammation in humans is weak and preliminary, and the supportable claim is that isolation removes most antinutrients and that isolates are not shown to increase permeability in healthy adults. And while heavy-metal contamination is manageable across plant proteins in general, rice-derived protein is a specific inorganic-arsenic outlier, one reason to complete a pea protein's amino-acid profile through methionine and leucine fortification rather than a rice component. With these calibrations, the transition toward plant-based dietary patterns can support athletic performance and muscle-health maintenance without compromising quality, and future work should prioritize long-term outcomes in aging populations and direct trials of fortified legume isolates.

Author Information

Dr. Eugene Capitano, DC, MSc, is a chiropractor, rehabilitation clinician, and researcher with more than 25 years of clinical experience. He earned an MSc in Psychology & Neuroscience of Mental Health from King's College London and holds the ACSM Exercise is Medicine® (EIM) Credential and the ACSM Certified Personal Trainer® (ACSM-CPT®) certification. His research interests include the gut–brain–muscle axis, microbiome-targeted nutrition, resistance training, mitochondrial function, metabolic health, and healthy aging.

Affiliation: TLC NeuroMicrobiome Labs Inc., Winnipeg, Manitoba, Canada

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