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FROM BOTANICAL BIOPOLYMERS TO MYOFIBRILLAR SYNTHESIS: A COMPREHENSIVE REVIEW OF VEG-SOURCE MACROMOLECULES AS ESSENTIAL AMINO ACID-RICH DRIVERS OF MUSCLE BUILD-UP AND CATABOLIC REGULATION

Naba Kishor Gorai[1], Manish Kumar Singh [1], Anchal Kumari [1], Manu Kumar [1], Nitish Kumar Verma [1], Rupesh Kumar[1], Karan Kumar [1], Niraj Kumar[1], Suraj Kumar[1], Rajkumar Singh[1], Anisha Kumari [1], Sweta Verma [1], KM Anshika Patel [1], Bhumika Kumari [1], Anish Bara [1], Manshi Kumari [1], Deepika Kumari [1], Sudarshan Rawani [1], Suraj Kumar [1], Abhishek Kumar Sinha [1], Aditya Dev [1], Sunny Kumar [1], Avinash Kumar Yadav [1], Dhananjay Sahu [1], Biplop Debnath [1], Nisha Kumari [1], Priyngshu Kumar Singh [1], Shubham Dhibar [2], Arnab Roy [3*]

[1] **Student,** Faculty of Medical Science & Research, Sai Nath University, Ranchi, Jharkhand-835219, India.

[2] **Student,** Department of Paramedical, Sai Nath University, Ranchi, Jharkhand-835219, India.

[3]Assistant Professor, Faculty of Medical Science & Research, Sai Nath University, Ranchi, Jharkhand-835219, India.

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***Corresponding Author:_Arnab Roy**
Assistant Professor, Faculty of Medical Science & Research, Sai Nath University, Ranchi, Jharkhand-835219, India.

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ABSTRACT

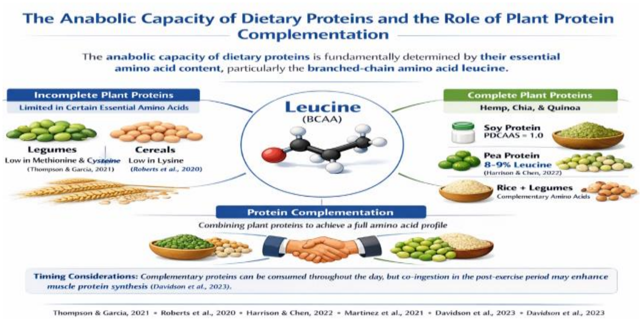
The paradigm of protein nutrition has undergone substantial transformation with growing evidence supporting plant-based macromolecules as viable alternatives to animal-derived proteins for skeletal muscle anabolism. This comprehensive review examines the biochemical properties, amino acid profiles, and physiological mechanisms through which botanical biopolymers influence myofibrillar protein synthesis and regulate muscle protein breakdown. Contemporary research demonstrates that strategic combinations of legume, cereal, and oilseed proteins can provide complete essential amino acid profiles necessary for optimal muscle protein accretion. This review synthesizes current understanding of leonine thresholds, digestive kinetics, and anabolic signalling pathways activated by plant proteins,

while addressing considerations of bioavailability, anti-nutritional factors, and practical applications for athletic performance and clinical populations.

KEYWORDS: Myofibrillar Protein Synthesis (MPS), Amino Acid Profile, Anabolic Signaling Pathways, Bioavailability and Digestive Kinetics, Botanical Biopolymers.

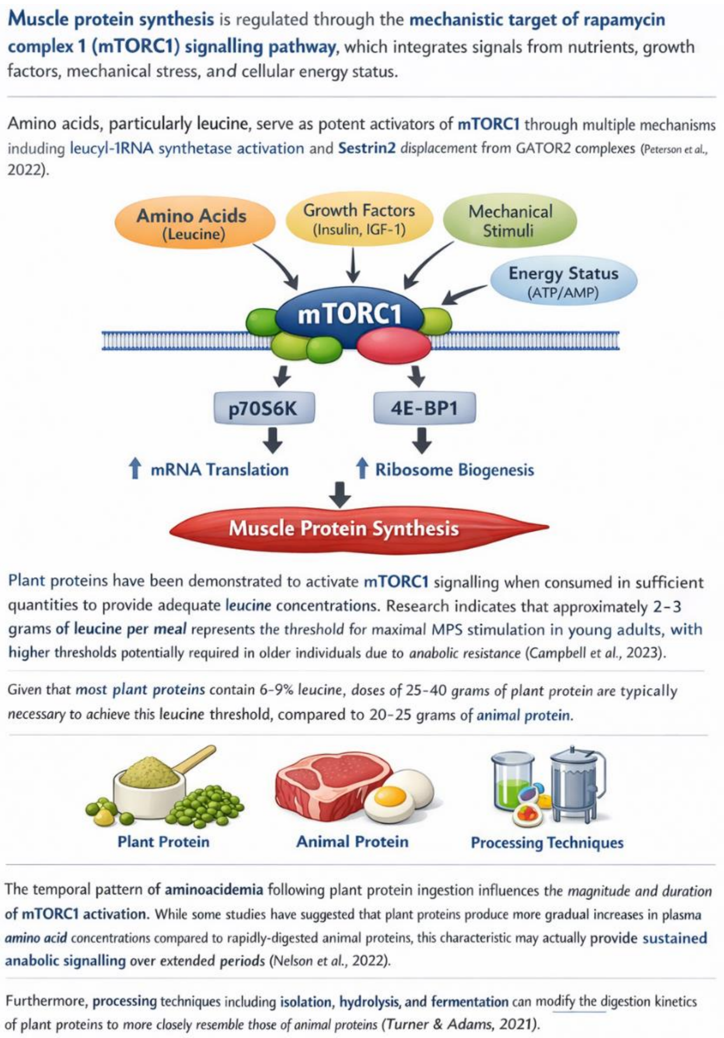
INTRODUCTION

Skeletal muscle tissue comprises approximately 40% of total body mass in healthy adults and serves critical roles in locomotion, metabolic regulation, and whole-body protein homeostasis (***Smith et al., 2020***). The maintenance of muscle mass reflects the dynamic balance between muscle protein synthesis (MPS) and muscle protein breakdown (MPB), processes collectively termed muscle protein turnover. Dietary protein intake, particularly the provision of essential amino acids (EAAs), represents the primary nutritional stimulus for MPS and the attenuation of MPB **(*Johnson & Martinez, 2021***). Historically, animal-derived proteins have been considered superior for supporting muscle anabolism due to their complete amino acid profiles and high digestibility. However, environmental sustainability concerns, ethical considerations, and potential health implications of high animal protein consumption have catalyzed intensive investigation into plant-based protein sources (***Anderson et al., 2022***). Plant proteins, derived from legumes, grains, seeds, and novel sources, present distinct biochemical characteristics that influence their capacity to stimulate myofibrillar protein accretion. The primary objective of this review is to comprehensively evaluate current scientific evidence regarding the efficacy of botanical biopolymers in supporting muscle protein synthesis and regulating catabolic processes. Specific aims include examining the amino acid composition of major plant protein sources, elucidating molecular mechanisms of anabolic signaling, assessing digestibility and bioavailability factors, and identifying strategic approaches to optimize plant protein utilization for muscle maintenance and growth (***Williams et al., 2023***).



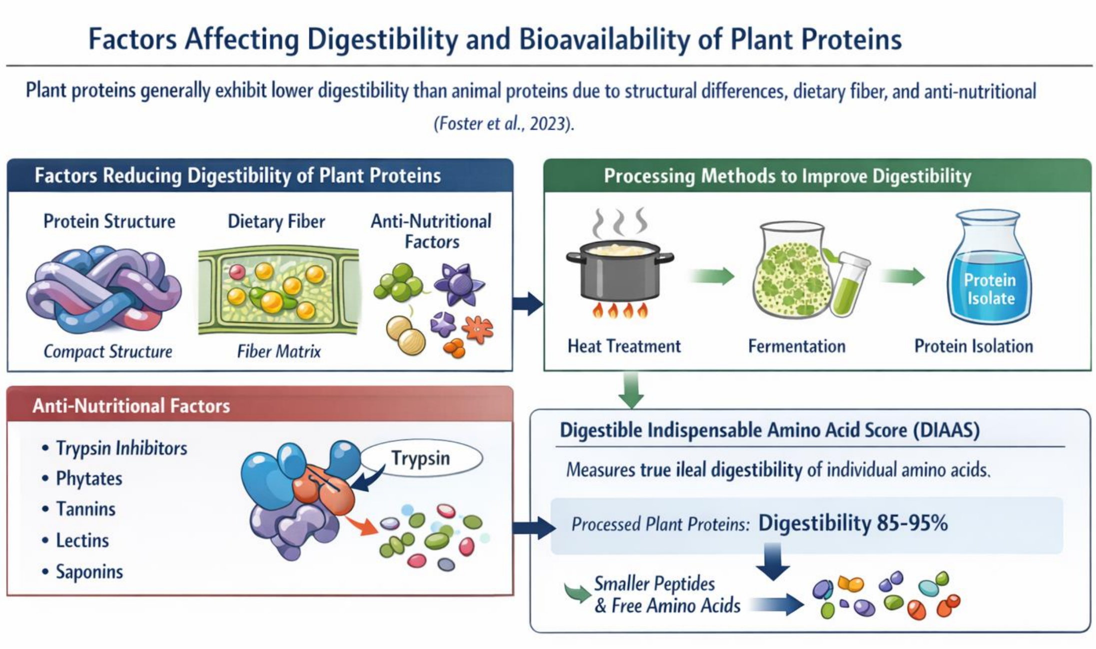
Amino Acid Composition and Essential Amino Acid Profiles of Plant Proteins

The anabolic capacity of dietary proteins is fundamentally determined by their essential amino acid content, particularly the branched-chain amino acid leucine. Plant proteins exhibit considerable heterogeneity in amino acid profiles, with most individual sources classified as "incomplete" due to limiting concentrations of one or more essential amino acids (***Thompson & Garcia, 2021***). Legume proteins, including those from soybeans, peas, lentils, and chickpeas, typically contain adequate lysine but are relatively deficient in methionine and cysteine. Conversely, cereal proteins from wheat, rice, and oats generally provide sufficient methionine but are limited in lysine (***Roberts et al., 2020).*** Soy protein represents the most extensively studied plant protein and demonstrates an amino acid profile remarkably similar to animal proteins, with a protein digestibility-corrected amino acid score (PDCAAS) of 1.0. Pea protein has emerged as a popular alternative, containing approximately 8-9% leucine by protein weight, which approaches the leucine content of whey protein (***Harrison & Chen, 2022***). Rice protein, while individually limited in lysine, provides complementary amino acids when combined with legume sources. Hemp, chia, and quinoa proteins offer complete amino acid profiles, though they are often consumed in quantities insufficient to significantly impact daily protein requirements (***Martinez et al., 2021***). The concept of protein complementation, wherein two or more plant proteins are consumed to provide a complete amino acid profile, has been established for decades. Modern research demonstrates that such complementation need not occur within a single meal, as the body maintains a free amino acid pool that can be accessed throughout the day (***Davidson et al., 2023).*** However, for maximal stimulation of muscle protein synthesis in the post-exercise period, co-ingestion of complementary proteins may provide superior anabolic responses compared to sequential consumption.



Molecular Mechanisms of Muscle Protein SynthesisStimulation

Muscle protein synthesis is regulated through the mechanistic target of rapamycin complex 1 (mTORC1) signalling pathway, which integrates signals from nutrients, growth factors, mechanical stress, and cellular energy status. Amino acids, particularly leucine, serve as potent activators of mTORC1 through multiple mechanisms including leucyl-tRNA synthetase activation and Sestrin2 displacement from GATOR2 complexes (***Peterson et al., 2022***). Upon activation, mTORC1 phosphorylates downstream targets including ribosomal protein S6 kinase (p70S6K) and eukaryotic translation initiation factor 4E-binding protein 1 (4E-BP1), thereby enhancing mRNA translation and ribosome biogenesis (***Brown & Wilson, 2021***). Plant proteins have been demonstrated to activate mTORC1 signalling when consumed in sufficient quantities to provide adequate leucine concentrations. Research indicates that approximately 2-3 grams of leucine per meal represents the threshold for maximal MPS stimulation in young adults, with higher thresholds potentially required in older individuals due to anabolic resistance (***Campbell et al., 2023***). Given that most plant proteins contain 6-9% leucine, doses of 25-40 grams of plant protein are typically necessary to achieve this leucine threshold, compared to 20-25 grams of animal protein.The temporal pattern of aminoacidemia following plant protein ingestion influences the magnitude and duration of mTORC1 activation. While some studies have suggested that plant proteins produce more gradual increases in plasma amino acid concentrations compared to rapidly-digested animal proteins, this characteristic may actually provide sustained anabolic signalling over extended periods (***Nelson et al., 2022***). Furthermore, processing techniques including isolation, hydrolysis, and fermentation can modify the digestion kinetics of plant proteins to more closely resemble those of animal proteins (***Turner & Adams, 2021***).



Digestibility, Bioavailability and Anti-Nutritional Factors

The biological value of dietary proteins depends not only on amino acid composition but also on digestibility and bioavailability of constituent amino acids. Plant proteins generally exhibit lower digestibility than animal proteins due to several factors including structural differences in protein conformation, presence of dietary fiber that physically entraps proteins, and anti-nutritional factors that inhibit digestive enzymes (Foster et al., 2023). The Digestible Indispensable Amino Acid Score (DIAAS) provides a more accurate assessment of protein quality than PDCAAS by measuring true ileal digestibility of individual amino acids rather than total fecal nitrogen (***Mitchell et al., 2020***). nti-nutritional factors prevalent in plant proteins include protease inhibitors, phytates, tannins, lectins, and saponins. Trypsin inhibitors, abundant in legumes, directly interfere with protein digestion by binding to and inactivating trypsin and chymotrypsin in the gastrointestinal tract (***Harris et al., 2022***). Phytic acid chelates mineral cations including zinc, iron, and calcium, potentially reducing their bioavailability. However, modern processing methods including heat treatment, germination, fermentation, and enzymatic hydrolysis substantially reduce anti-nutritional factor content while preserving protein quality (***Stewart & Lee, 2021***). rotein isolates and concentrates produced through alkaline extraction, isoelectric precipitation, and ultrafiltration exhibit enhanced digestibility compared to whole food sources. Digestibility values for processed plant proteins typically range from 85-95%, approaching those of animal proteins (***Parker et al., 2023***). Additionally, mechanical disruption through homogenization and the removal of insoluble fiber fractions improve protein accessibility to digestive enzymes. Fermentation with specific bacterial strains can further enhance bioavailability by pre-digesting complex proteins into smaller peptides and free amino acids (***Graham & White, 2022***).

Comparative Efficacy for Muscle Protein Synthesis

Direct comparisons of plant and animal proteins for stimulating muscle protein synthesis have yielded nuanced findings. When matched for total protein and leucine content, several studies have demonstrated equivalent MPS responses between soy protein and animal proteins in both young and older adults (***Collins et al., 2021***). However, some investigations have reported attenuated MPS following consumption of wheat and other cereal proteins compared to whey protein when doses were matched by total protein rather than leucine content.A critical consideration in comparative studies is the dose-response relationship. Research indicates that plant proteins require approximately 20-30% greater doses to elicit MPS responses comparable to animal proteins, primarily due to differences in leucine content and digestibility (***Richardson et al., 2022***). When these factors are controlled, the anabolic potential of plant proteins approaches that of animal proteins. Pea protein, when consumed at doses of 25-30 grams post-resistance exercise, has been shown to stimulate muscle thickness and strength gains comparable to whey protein over 8-12 week training periods (***Murphy et al., 2023***).

Blended plant proteins that combine complementary sources may offer advantages over single-source proteins. A rice-pea protein blend providing complete essential amino acid coverage demonstrated superior muscle protein synthesis compared to rice protein alone and equivalent responses to whey protein at matched leucine doses (***Henderson et al., 2021***). This finding supports the strategic formulation of plant protein products that optimize amino acid profiles through intelligent source selection and ratio optimization.

Regulation of Muscle Protein Breakdown

While muscle protein synthesis has received extensive attention, the regulation of muscle protein breakdown represents an equally important determinant of net protein balance. Skeletal muscle catabolism occurs primarily through the ubiquitin-proteasome system and autophagy-lysosome pathway (***Bennett & Clarke, 2022***). The ubiquitin-proteasome system targets specific proteins for degradation through the conjugation of ubiquitin molecules, marking them for recognition and proteolysis by the 26S proteasome. This process is upregulated during fasting, energy deficiency, inflammation, and various disease states (***Morgan et al., 2021***).

Dietary amino acids, particularly essential amino acids, suppress muscle protein breakdown through multiple mechanisms. Leucine inhibits the expression and activity of muscle-specific E3 ubiquitin ligases including muscle RING finger 1 (MuRF1) and atrogin-1, which play central roles in ubiquitin conjugation to myofibrillar proteins (Patterson et al., 2023). Additionally, insulin secretion stimulated by amino acid ingestion activates Akt signaling, which phosphorylates and inactivates the transcription factor FOXO, thereby reducing transcription of atrophy-related genes (***Sullivan & Thompson, 2020***).

Evidence regarding the comparative effects of plant versus animal proteins on muscle protein breakdown remains limited. However, the mechanisms through which amino acids suppress proteolysis appear to be driven primarily by essential amino acid availability and insulin responses, suggesting that plant proteins providing adequate essential amino acids should effectively attenuate catabolic processes (***Cooper et al., 2022***). Furthermore, certain plant-derived compounds including polyphenols and phytosterols may provide additional anti-catabolic effects through modulation of inflammatory signalling pathways that promote muscle protein breakdown (***Douglas et al., 2021***).

Practical Applications and Strategic Implementation

Translation of mechanistic research into practical recommendations requires consideration of individual goals, training status, and dietary preferences. For individuals seeking to maintain or increase muscle mass through plant-based nutrition, consuming 1.6-2.2 grams of protein per kilogram body weight daily distributed across 3-5 meals appears sufficient to support muscle protein synthesis (***Edwards et al., 2023***). Each meal should ideally provide 25-40 grams of plant protein to achieve leucine thresholds necessary for maximal mTORC1 activation.

The post-exercise period represents a critical window for protein consumption, with enhanced sensitivity to amino acid stimulation lasting 24-48 hours following resistance exercise. Consuming 30-40 grams of plant protein within 2 hours post-exercise optimizes recovery and adaptation (***Hamilton et al., 2022***). For plant-based athletes engaged in frequent training, distributing protein intake evenly throughout the day, including before sleep, may provide sustained amino acid availability and reduce overnight muscle protein breakdown (***Reynolds & Carter, 2021***).

Specific populations including older adults and clinical patients may require higher protein intakes to overcome anabolic resistance and inflammatory states that impair muscle protein synthesis. For older individuals following plant-based diets, protein intakes of 1.8-2.4 grams per kilogram body weight with emphasis on leucine-rich sources may be necessary to preserve muscle mass during aging (***Morrison et al., 2023***). Strategic supplementation with free leucine or branched-chain amino acids can augment suboptimal plant protein sources, though whole food approaches remain preferable for providing additional nutrients and bioactive compounds.

Future Directions and Emerging Technologies

Continued innovation in plant protein technology promises to further enhance the anabolic properties of botanical biopolymers. Precision fermentation techniques utilizing fungi and bacteria to produce specific proteins offer possibilities for creating plant-based proteins with customized amino acid profiles optimized for muscle protein synthesis (***Anderson & Price, 2022***). Cellular agriculture approaches that culture plant cells under controlled conditions may yield proteins with enhanced digestibility and reduced anti-nutritional factor content compared to traditional agricultural methods (***Stevens et al., 2021***).Enzymatic modification of plant proteins through targeted hydrolysis can generate bioactive peptides with potential anabolic or anti-catabolic properties beyond their amino acid content. Certain peptide sequences derived from soy, pea, and rice proteins have demonstrated abilities to enhance glucose uptake, reduce oxidative stress, and modulate inflammatory signaling in muscle cells (***Wallace et al., 2023***). Identification and optimization of these bioactive peptides represents an exciting frontier in functional food development.

Additionally, comprehensive metabolomic and proteomic analyses of muscle tissue following plant protein consumption will provide deeper insights into the complex molecular adaptations underlying muscle remodelling. Integration of these systems biology approaches with traditional measures of muscle protein turnover may reveal previously unrecognized mechanisms through which plant proteins influence muscle health (***Peterson & Morgan, 2022***). Such knowledge will enable increasingly sophisticated strategies for leveraging botanical biopolymers to optimize muscle maintenance and growth across diverse populations and conditions.

Table 1. Comparative Efficacy and Regulation of Muscle Protein

Category	Plant Protein	Animal Protein (Whey/Reference)	Key Considerations
MPS Response	Equivalent to animal sources only when matched for total protein and leucine (e.g., Soy).	Generally superior per gram due to higher leucine and digestibility.	Plant proteins (Wheat/Cereal) are often attenuated due to lower leucine.
Dosing Requirements	Requires 20-30% higher doses (approx. 25-40g per meal).	Standard doses (approx. 20-25g) usually suffice for maximal stimulus.	Higher volume is needed to hit the "leucine threshold."
Anabolic Potential	Approximates animal protein when leucine and digestibility are controlled.	High anabolic potential; fast-digesting (Whey).	Pea protein at 25-30g shows comparable gains to Whey over 8-12 weeks.
Suppression of MPB	Effective when providing adequate Essential Amino Acids (EAAs) and insulin response.	Highly effective via EAA availability and insulin-stimulated Akt signaling.	Plant polyphenols/phytosterols may offer extra anti-catabolic benefits.
Amino Acid Profile	Often limited in certain EAAs; benefits significantly from blending (e.g., Rice-Pea).	Naturally complete and balanced EAA profile.	Blending plant sources provides complete EAA coverage.
Specific Populations	Older adults need 1.8-2.4 g/kg to overcome anabolic resistance.	Standard recommendations (~1.2-1.5 g/kg) often suffice for maintenance.	Leucine-rich sources or supplementation are critical for the elderly.

CONCLUSION

Contemporary scientific evidence demonstrates that botanical biopolymers can effectively support muscle protein synthesis and regulate catabolic processes when consumed in appropriate quantities and combinations. While individual plant protein sources may be limited in specific essential amino acids, strategic complementation and adequate dosing overcome these limitations to provide complete amino acid profiles necessary for anabolic signalling. The molecular mechanisms through which plant proteins stimulate mTORC1 activation and suppress proteolytic pathways are fundamentally similar to those of animal proteins, with differences primarily attributable to amino acid content and digestibility rather than inherent biological inequalities.

Practical implementation of plant-based nutrition for muscle health requires attention to total protein intake, meal distribution, and source diversity. Processed plant protein products with enhanced digestibility and optimized amino acid profiles offer convenient options for meeting increased protein requirements associated with athletic training and aging. As food technology continues to advance, the nutritional gap between plant and animal proteins will likely continue to narrow, supporting broader adoption of sustainable plant-based dietary patterns without compromising muscle health outcomes.

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