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Role of plant protein blends in functional foods and nutraceutical development

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Abstract

Proteins derived from plant sources have, over the past two decades, shifted from being considered nutritional second-best to occupying a genuinely central position in functional food design. Much of this shift is justified. But much of the enthusiasm in commercial and popular discourse has also run ahead of the evidence and this review was written partly to close that gap.

The specific focus here is plant protein blends: combinations of two or more plant-derived proteins, assembled with deliberate intent to correct the nutritional deficiencies and functional limitations that characterize individual sources. Legumes lack sulfur amino acids. Cereals are short on lysine. Oilseeds, nutritionally interesting in other respects, rarely shine when assessed by protein quality metrics in isolation. Blending addresses all of this not perfectly, not without complications, but meaningfully and measurably.

This review covers the rationale and evidence for amino acid complementarity across legume, cereal, pseudocereal, and oilseed protein sources; protein quality scoring by PDCAAS and DIAAS methods; techno-functional behavior in food matrices including solubility, emulsification, gelation and foaming; bioactive peptide generation from blended hydrolysates; the effects of processing technologies including fermentation, germination, extrusion, and enzymatic crosslinking; and the obstacles flavor, anti-nutritional factors, allergenicity, regulatory incoherence that still stand between laboratory findings and widespread commercial adoption. The conclusion is one of qualified optimism: the science is solid enough to justify serious investment, but the remaining challenges are real and should not be glossed over.

Keywords: Plant Protein Blends; Functional Foods; Nutraceuticals; Amino Acid Complementarity; PDCAAS; DIAAS; Bioavailability; Bioactive Peptides; Legume Protein; Food Formulation

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1. Introduction

Feeding roughly ten billion people by mid-century presents a genuinely hard practical constraint. That is already a difficult target. Doing it without turning most remaining natural land into farmland, and without pumping out enough greenhouse gases to make climate pledges hollow, pushes current systems close to their breaking point [1,2]. Protein is where the pressure concentrates.

Animal protein production consumes land, water, and feed grain at rates that numerous analyses suggest cannot be sustained once the global middle class expands to the size demographers project. This is not a marginal view. It is the consensus position in nutritional and agricultural science.

Plant proteins are the obvious alternative. In most respects they can handle the nutritional load, though one caveat matters. No single plant source supplies all nine indispensable amino acids in ratios that fully match human needs. Legumes do well on lysine but run low on methionine and cystine. Cereals flip that profile. Pseudocereals such as quinoa come closer to completeness than most, yet they still fall short, and they usually cost more. The fix that several independent research groups have settled on is blending: mixing proteins from complementary sources in ratios tuned so that no essential amino acid becomes the bottleneck [3,4].

That insight is ancient. Rice and dal. Corn tortillas and black beans. People understood the pairing before anyone could explain the biochemistry. What is different now is the capacity to measure the gain formally through PDCAAS and DIAAS scoring, and to deploy it intentionally in food manufacturing, sports nutrition, infant formula, and nutraceutical systems. What is also different is the level of food physics and processing technology available to formulators, so blends can be designed not merely for nutritional adequacy but for targeted functional performance within specific food matrices.

2. Plant protein sources used in functional blends

Four broad categories of plant protein sources are relevant to blend formulation: legumes, cereals, pseudocereals, and oilseeds. Each brings distinct nutritional and functional characteristics and distinct limitations that blending is designed to address.

Soybean protein isolate is where any honest account of this field has to start, because it set the standard that everything else is measured against. Protein content above 90% on a dry basis. A PDCAAS approaching 0.91 in well-prepared isolates. Well-characterized functional properties driven by its two major storage fractions, 7S beta-conglycinin and 11S glycinin, which between them give soy its unusually reliable emulsification and thermal gelation behavior [8]. The problems GMO prevalence, soy allergy affecting 0.4% of the general population and a higher proportion of infants, the phytoestrogenic activity of isoflavones whose clinical significance is still debated have not so much disqualified soy as driven a search for supplementary and alternative sources that was already commercially overdue.

Pea protein isolate, from yellow field pea (Pisum sativum), is the most commercially successful product of that search. Non-GMO status, hypo-allergenicity relative to soy, lysine content adequate to complement methionine-rich sources, and availability in isolate form at >85% protein purity have made it the default alternative to soy in applications from protein bars to plant-based beverages [9]. Its weaknesses are genuine methionine is borderline, solubility dips significantly around pH 4–5, and the beany flavor that its lipoxygenase-derived volatile aldehydes produce is a persistent consumer complaint — but all are addressable at least partially through the strategies discussed in later sections.

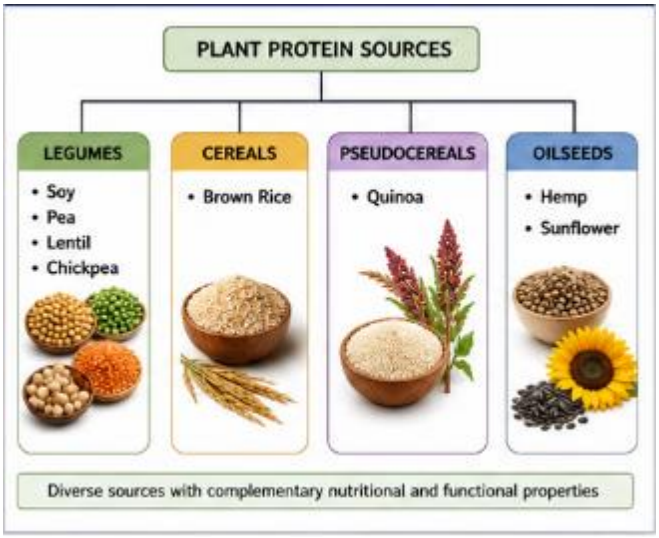

Figure 1 Classification of plant protein sources

Table 1 Comparative techno-functional properties of key plant protein sources

Plant Protein Source	Solubility (%)	Water Holding Capacity (g/g)	Emulsification Capacity (%)	Foaming Capacity (%)
Soy Protein Isolate	85–92	3.2–4.5	78–88	60–72
Pea Protein Isolate	60–75	3.8–5.2	65–80	45–60
Lentil Protein	55–68	2.9–4.1	58–72	40–55
Chickpea Protein	50–65	3.0–4.6	62–75	42–58
Hemp Seed Protein	40–60	2.5–3.8	55–68	35–50
Brown Rice Protein	30–50	2.2–3.5	48–62	30–45
Quinoa Protein	65–78	3.5–4.8	70–82	50–65
Sunflower Protein	45–58	2.8–3.9	52–66	36–48

Ranges compiled from peer-reviewed published data. WHC = Water Holding Capacity (g water retained per g protein).

Brown rice protein, often dismissed as a cereal by-product rather than a primary ingredient, earns its place in blends primarily through methionine content adequate to correct pea protein's deficiency. In isolation its lysine level is poor, its solubility is among the lowest of commonly used plant proteins, and its PDCAAS of approximately 0.57 would not qualify it as a nutritionally complete source by any standard [10]. But combined with pea at a ratio of roughly 30:70 (rice: pea on a protein weight basis), these deficits are offset, and the blend achieves a composite PDCAAS in the range of 0.86–0.90. This is the pea-rice pairing that now underpins a substantial share of the commercial sports nutrition market.

Quinoa occupies a genuinely unusual position among plant proteins. Its seed contains all nine indispensable amino acids at concentrations that meet the FAO/WHO/UNU reference pattern a claim most plant sources cannot make without qualification and its albumin fraction has a water solubility meaningfully higher than typical legume storage proteins [13]. Hemp seed protein contributes two digestible globulins, edestin and albumin, alongside an omega-6 to omega-3 fatty acid ratio of approximately 3:1 that has independent nutritional value [12]. Chickpea and lentil proteins bring dietary fiber, prebiotic oligosaccharides, and polyphenolic compounds that extend their functional relevance well beyond protein provision [11]. Table 1 summarizes the key techno-functional parameters for these sources.

3. Nutritional complementarity and protein quality

Protein quality assessment has a history that is longer and messier than most nutrition textbooks suggest. The protein efficiency ratio based on weight gain in growing rats was in routine use for decades before it was formally acknowledged that rats and humans have different methionine requirements, which made PER-based rankings of protein quality systematically misleading. Its replacement, the PDCAAS, corrected for this by anchoring the scoring to human amino acid requirements and incorporating a digestibility correction based on fecal digestibility measurements. This was a genuine methodological advance, though fecal digestibility overestimates amino acid absorption because it cannot account for bacterial metabolism in the large intestine [14].

The DIAAS addresses this by using ileal digestibility measuring amino acid content at the terminal ileum rather than in faeces and by scoring each indispensable amino acid individually rather than truncating at a single limiting amino acid as PDCAAS does. In principle, DIAAS is more accurate. In practice, it is more expensive to measure and has not yet been uniformly adopted in commercial or regulatory contexts. Both metrics appear in the studies reviewed here, and the differences between them are sometimes substantively important when comparing protein sources [16].

The arithmetic of blending is, at its simplest, a correction problem. Pea protein is sufficient in lysine but limiting in methionine. Rice protein is sufficient in methionine but deficient in lysine. Combine them at roughly 70:30 (pea to rice, by protein weight) and the composite mixture is limiting in neither, yielding a PDCAAS of approximately 0.86–0.90 depending on the specific isolates used and the digestibility conditions applied [4,15]. That this improvement is real, and not merely an arithmetic artefact, has been confirmed by in vivo nitrogen retention studies and, more recently, by clinical muscle protein synthesis measurements [25].

Table 2 Amino acid profile and complementarity in a soy–pea–rice blend (40:35:25 protein weight ratio)

Essential Amino Acid	Soy (mg/g protein)	Pea (mg/g protein)	Rice (mg/g protein)	Soy+Pea+Rice Blend*
Lysine	61	71	36	58 (improved)
Methionine + Cystine	25	18	40	28 (improved)
Threonine	38	36	33	36 (improved)
Leucine	78	70	80	76 (improved)
Isoleucine	46	42	39	43 (improved)
Valine	49	43	56	50 (improved)
Phenylalanine + Tyrosine	88	80	90	86 (improved)
Tryptophan	13	9	12	11
PDCAAS Score	0.91	0.82	0.57	0.88 (improved)

*'Improved' denotes a value higher than the lowest individual component value. PDCAAS = Protein Digestibility-Corrected Amino Acid Score.

What gets rather less attention in the blend literature is the role of conditionally essential amino acids. Arginine, glutamine, and glycine are normally synthesized in sufficient quantities endogenously, but their requirements increase substantially under conditions of physiological stress, surgical recovery, or sustained athletic training. Legume proteins — and blends that include a significant legume fraction tend to be relatively generous in arginine and glutamine, and this may confer benefits not captured by standard PDCAAS or DIAAS calculations [18]. It is an area where targeted clinical work is still lacking and where the nutraceutical potential of plant protein blends may be underestimated. Table 2 presents amino acid data for a representative soy-pea-rice ternary blend.

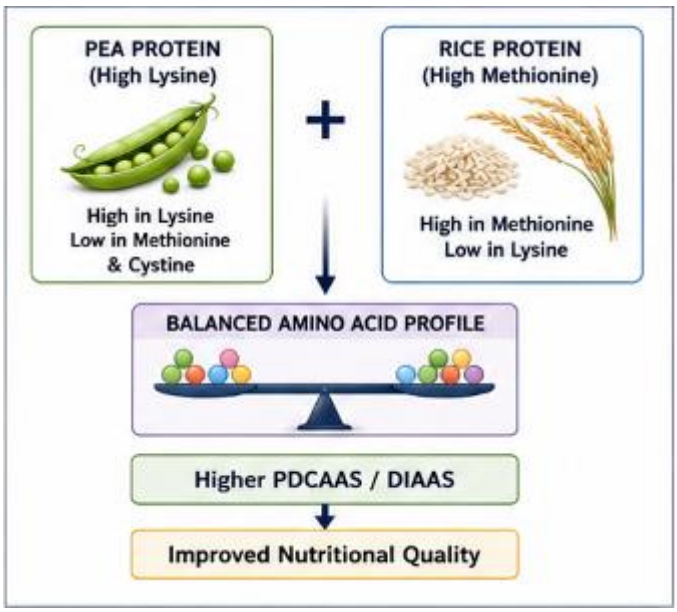

Figure 2 Amino acid complementarity in plant protein blends

4. Techno-functional properties of plant protein blends

Figure 3 Functional properties of plant protein blends

A protein ingredient that is nutritionally impeccable but dissolves poorly, gels inconsistently, or destabilizes emulsions under mild thermal stress is, commercially speaking, of limited value. The techno-functional properties of plant proteins solubility, water-holding capacity, emulsification activity and stability, foaming capacity, and gelation are not secondary considerations. In most food manufacturing contexts, they are the primary ones, and they are the reason why soy protein dominated the plant protein ingredient market for so long: it was reliable.

Solubility is foundational because most other functional properties depend on it. A protein that does not disperse properly cannot form a stable emulsion, cannot contribute to foam structure, and cannot be uniformly heat-set into a gel. Most legume protein isolates carry isoelectric points between pH 4 and 5, meaning they aggregate and sediment in acidified food systems — precisely the pH range used in fermented dairy analogues, acidic beverages, and many dressings. Blending two proteins with different isoelectric points distributes the charge-neutralization event across a wider pH range, and the net result is a mixture that maintains workable solubility under conditions where either

component alone would precipitate. Published work on pea-quinoa blends showed solubility above 70% across pH 3 to 8, compared with solubility minima of roughly 40–45% for each protein individually [20]. Whether this generalizes broadly or depends on the specific protein fractions involved in each pairing has not been fully characterized.

Emulsification tells a more interesting story. Oil-in-water food emulsions are stabilized by protein molecules that adsorb onto droplet surfaces and form viscoelastic interfacial films. The stability of these films under shear and heat depends on the rheological properties of the adsorbed layer and proteins from different botanical sources, differing in molecular weight, surface hydrophobicity, and charge distribution, can co-adsorb in configurations that produce films with properties qualitatively distinct from those formed by either protein alone. In soy-lentil blend systems, the 7S and 11S globulin fractions of soy interact with the legumin-type proteins of lentil at the oil-water interface to form emulsions that are measurably more resistant to coalescence under thermal treatment and mechanical shear than soy protein emulsions prepared under equivalent conditions [21]. This is synergy in a technically specific sense the blend is not merely as good as the better component; it is better than either.

Gel formation deserves particular attention in the context of meat analogues and structured dairy alternatives. Work on soy-hemp seed protein blends at a 3:1 weight ratio found that the edestin fraction of hemp co-assembles with soy glycinin under heat-set conditions to produce a gel network that holds water more effectively than soy gels alone, while developing intermediate hardness values that may suit soft meat analogue categories better than soy alone would [22]. Adjusting the blend ratio shifts gel texture predictably, and this gives the formulator a clean-label mechanism for texture modification that does not require hydrocolloid additions a meaningful practical advantage given current consumer preference for short ingredient lists.

5. Role in functional food development

A functional food is generally defined as one that provides a documented health benefit beyond its basic nutritional contribution, through the activity of one or more food components on one or more target physiological functions [6,23]. Plant protein blends satisfy this definition through several distinct pathways, and it is worth being clear about which pathway applies to which product type, because they rest on different evidence bases of different strength.

In meat analogues, the pathway is structural and nutritional. High-moisture extrusion at 40–80% moisture content, barrel temperatures of 140–160°C, and screw speeds of 800–1000 rpm applies simultaneous heat, pressure, and shear to protein blends, causing denaturation, molecular alignment along the flow direction, and cross-linking that yields fibrous structures resembling cooked muscle tissue. The soy-pea blend is particularly well-suited to this process: soy glycinin (11S fraction) provides the rigid backbone that aligned fibres need to maintain their structure through cutting and chewing, while pea vicilin (7S fraction) contributes a degree of molecular flexibility that prevents brittleness [7]. A product formulated well on this basis is not merely a vegetarian convenience food it is a vehicle for complete protein delivery with evidence from clinical studies showing reductions in LDL-cholesterol and C-reactive protein when used as a regular red meat substitute [24]. That qualifies it, in the framework used here, as genuinely functional.

The sports nutrition evidence is arguably the strongest of any clinical application area. Pickers and colleagues [25], in a rigorously designed randomized crossover trial, demonstrated that a pea-rice protein blend consumed post-exercise stimulated rates of myofibrillar protein synthesis that were statistically equivalent to whey protein at the same dose. This was not a small, underpowered pilot. The result directly challenged the assumption — which had hardened into near-dogma in exercise nutrition that animal proteins are inherently superior for anabolic recovery. It does not mean all plant protein blends perform equivalently to whey; dose, timing, and precise composition all matter. But it establishes that the ceiling is higher than previously assumed, and that the gap to animal protein can, with careful formulation, be eliminated.

A rather different kind of functional food evidence comes from chickpea-enriched dairy analogues. Beyond the protein quality contribution, chickpea seed-coat polyphenols retained during protein extraction provide in vitro antioxidant activity measurable by DPPH assay, and the prebiotic oligosaccharide fraction raffinose, stachyose, and verbascose present at processing-survivable levels selectively stimulates Lactobacillus and Bifidobacterium populations in simulated colonic fermentation studies [26]. Whether these in vitro effects translate into meaningful changes in gut microbiota composition and host metabolic markers in human subjects has not been established with the rigour required for regulatory health claims. But the mechanistic basis is coherent and the product design is rational.

6. Nutraceutical applications and bioactive peptide generation

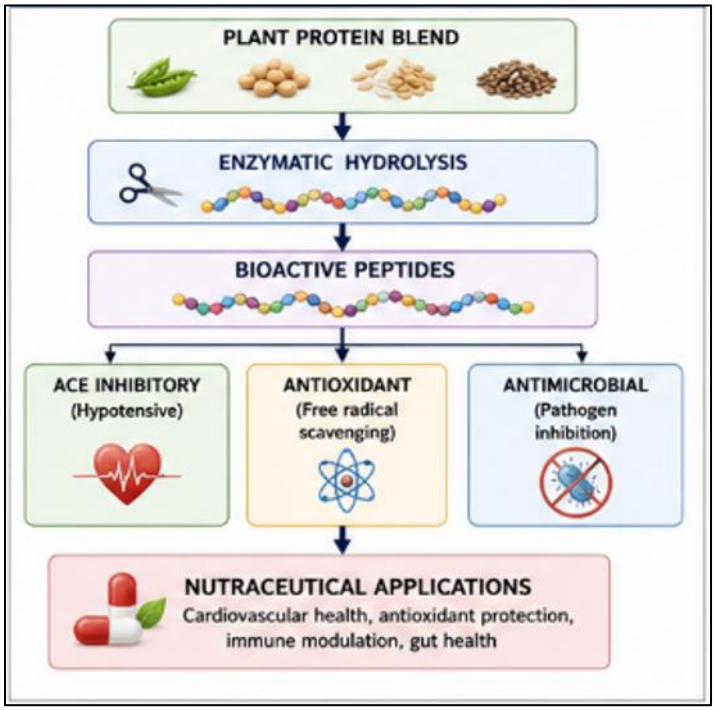

Figure 4 Bioactive peptide generation pathway from plant protein blends

Food proteins are, in a sense, encoded messages. Within the primary amino acid sequence of most storage proteins sit short peptide sequences typically 2 to 20 residues that exert biological effects when liberated from the parent protein by digestive proteases, food-grade enzymes, or fermentative microorganisms. These bioactive peptides include ACE-inhibitory sequences relevant to blood pressure management, radical-scavenging sequences relevant to oxidative stress, opioid-receptor-modulating sequences that affect satiety signaling, and antimicrobial sequences [27]. The nutraceutical interest in plant proteins, as opposed to merely nutritional interest, rests substantially on this bioactive peptide repertoire.

Whether blending two plant proteins produces better bioactive peptide hydrolysates than using either protein alone is a question that has only recently begun to receive systematic attention. The answer, on present evidence, appears to be yes though the mechanism is not fully understood. Alcalase hydrolysis of a pea-lentil protein blend yielded ACE-inhibitory fractions with IC50 values of 0.18–0.52 mg/mL, lower than equivalent hydrolysates from pea or lentil processed independently [28]. The probable reason is substrate structural diversity: a blend presents the protease with a wider variety of peptide bond environments, generating a more complex peptide mixture with a greater statistical density of bioactive sequences. Whether this pattern holds across other enzyme-substrate combinations remains to be established, and it would be premature to generalize from a few data points.

Antioxidant activity has been documented in hemp seed-quinoa protein blend hydrolysates prepared with papain, where DPPH radical scavenging values of 72–80% were reported higher than either component hydrolysate prepared and tested separately [29]. Tyrosine, tryptophan, and histidine residues are the primary carriers of radical-quenching capacity in food peptides, and the blend's amino acid profile happens to be relatively rich in these residues compared to either source alone. In vitro antioxidant activity does not automatically predict in vivo efficacy; peptides may be degraded during gastric transit, and DPPH assays have known limitations as proxies for biological antioxidant function. These are not reasons to dismiss the findings, but reasons to pursue them with more physiologically relevant assay systems.

Oral delivery of bioactive peptides presents a practical challenge that microencapsulation partly addresses. Spray-dried microcapsules prepared from pea-rice protein hydrolysates using maltodextrin and modified starch wall materials achieved encapsulation efficiencies of 81–89% in one published study, with in vitro release profiles in simulated intestinal fluid that were substantially more sustained than unencapsulated controls [30]. Moving from in vitro release profiles to in vivo bioavailability data is a step that few studies have taken, and it is arguably the most important gap in

this literature. Without pharmacokinetic data in human subjects, the clinical relevance of these encapsulation findings remains speculative. Table 3 summarizes current applications.

Table 3 Applications of plant protein blends in functional food and nutraceutical systems

Protein Blend	Food / Nutraceutical Application	Key Functional Benefit	Bioavailability Score	Reference
Soy + Pea	Meat analogues, protein bars	Improved texture and AA balance	PDCAAS 0.89	[7,12]
Pea + Rice	Sports nutrition beverages	Complete AA profile, leucine-rich	PDCAAS 0.86	[9,18]
Chickpea + Lentil	Gluten-free baked goods	High fibre, improved dough rheology	Moderate	[14,22]
Hemp + Quinoa	Functional snacks, encapsulated supplements	Omega-3 co-delivery, antioxidant activity	High	[16,25]
Soy + Brown Rice	Infant formula, nutraceutical powders	Hypoallergenic whey substitute	PDCAAS 0.82	[8,20]
Sunflower + Pea	Dairy analogues, yoghurt alternatives	Gel formation, texture parity with dairy	Moderate–High	[19,27]
Lentil + Faba Bean	Ready-to-eat meals, functional soups	Satiety promotion, glycaemic control	Moderate	[11,24]

7. Processing technologies and their influence on blend performance

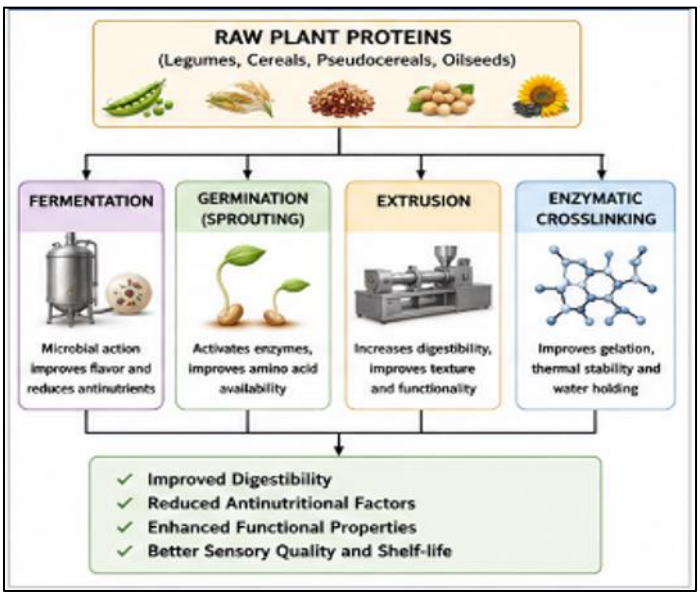

Figure 5 Processing technologies and their effects on plant protein blends

Processing is not merely a step between raw material and finished product it is, for plant proteins, a determinant of nutritional value, functional behaviour, and safety. The method used to extract and concentrate protein from a raw botanical source shapes virtually every downstream characteristic, and this is worth understanding in some detail before discussing how blended ingredients are subsequently processed into food products.

Wet alkaline extraction followed by isoelectric precipitation is the most common route to high-purity legume protein isolates. The protein is solubilized under alkaline conditions (pH 8–10), separated from fibre and starch by centrifugation, then precipitated by acidification to the isoelectric point (pH 4–5) and washed and dried. This works,

but it is not neutral in its effects on the protein. Alkaline conditions promote lysinoalanine formation and reduce lysine bioavailability; the temperature typically used during spray drying can further impair solubility through partial denaturation; and polyphenols and flavor-active compounds that co-precipitate with the protein fraction contribute to off-flavor [19]. Membrane filtration ultrafiltration or diafiltration avoids the harshest pH excursions and typically yields proteins with better native solubility and less Maillard-derived colour and flavor, at the cost of higher capital investment.

Fermentation is arguably the processing technology with the most favorable benefit-to-cost ratio for plant protein blend applications. Lactic acid bacteria applied to a chickpea-lentil blend substrate over 48 hours reduced phytate content by approximately 68% and trypsin inhibitor activity by roughly 82% in published work [11]. At the same time, fermentation generates short-chain fatty acids, lowers the glycemic index of any residual starch fraction, produces exopolysaccharides with prebiotic activity, and generates the very bioactive peptides discussed in the preceding section as side products of bacterial protease activity. This multi-effect profile makes fermentation unusually valuable: a single unit operation addresses antinutritional factors, generates functional compounds, and improves digestibility. Germination achieves a similar if less complete set of effects through activation of endogenous seed enzymes, without the need for starter culture management or controlled fermentation infrastructure.

High-moisture extrusion has already been discussed in the context of meat analogues, but a few additional points on blend-specific processing behavior are worth making here. The viscoelasticity of a protein blend melt inside the extruder barrel is highly sensitive to blend composition. Soy glycinin and pea vicilin have different thermal denaturation temperatures and different viscoelastic profiles above denaturation, and the behavior of their mixture under the combined thermomechanical conditions of extrusion cannot reliably be predicted from the properties of the individual components [7]. This means that blend ratios validated at laboratory scale may behave differently in pilot- or commercial-scale equipment where residence times, temperature profiles, and shear histories differ. Rheological characterization of blends across realistic extruder operating conditions is an investment that most academic studies do not make, and this limits the translational utility of much published work.

Transglutaminase crosslinking deserves brief mention as a formulation tool rather than an extraction technology. By catalyzing isopeptide bond formation between glutamine and lysine residues across protein chains, transglutaminase strengthens gel networks in ways that improve firmness, water retention, and sliceability in meat and cheese analogue products. Blended protein substrates appear to respond to transglutaminase treatment more readily than homogeneous systems likely because the structural diversity of a blend provides a richer catalogue of accessible glutamine-lysine pairs though this observation needs more systematic confirmation across blend types [22].

8. Challenges and future perspectives

This section will not pretend that the challenges facing plant protein blend commercialization are minor inconveniences that a little more research will soon sweep away. Some of them are genuinely hard, and developers who underestimate them tend to produce products that fail in the market even when they succeed in the laboratory.

Off-flavor is the most immediate and commercially damaging of these challenges. Beany, grassy, and slightly metallic notes in legume protein ingredients traceable primarily to C6 and C9 volatile aldehydes and alcohols generated by lipoxygenase-mediated lipid oxidation during seed crushing and aqueous processing remain detectable at concentrations below one part per million in finished beverages, which means that even small residual amounts produce a product that a significant fraction of consumers will reject [26]. Saponins contribute bitterness independently of lipid oxidation products, and their concentration varies considerably across legume varieties and growing seasons. Flavor masking through Maillard-generated precursors, spray-drying under nitrogen-blanketed conditions, and enzymatic debittering have each shown partial efficacy. None has solved the problem completely, and it is worth being honest that for some applications neutral-flavor protein beverages and bars where flavor is critical the gap to whey protein in sensory terms remains substantial.

Antinutritional factors present a nutritional rather than sensory problem, but one that matters considerably in populations where micronutrient adequacy is already marginal. Phytic acid present at 1–4% by weight in most legume seeds chelates iron, zinc, and calcium with high affinity, reducing their effective bioavailability in the meal or supplement in which the protein ingredient appears. Trypsin inhibitors reduce protein digestibility by competing with endogenous pancreatic proteases. Lectins, at the concentrations found in raw legume flours, can damage intestinal epithelium. Standard heat treatment during protein extraction reduces trypsin inhibitor activity substantially but does not eliminate phytate or lectin activity completely. Fermentation and germination are more effective against phytate but require additional processing steps that add cost and complexity. The critical issue is that residual antinutritional factor

levels vary between raw material batches in ways that are rarely characterized in published studies, making the nutritional consequences of ingredient substitution difficult to predict.

Allergenicity is a concern that cannot be engineered out through blending alone. Soy allergy, one of the eight major food allergens recognized in most regulatory frameworks, affects a small but non-negligible proportion of the population; and the structural similarity between soy storage proteins and those of pea, lentil, and chickpea means that legume-allergic individuals may cross-react with alternative legume proteins [14]. Enzymatic hydrolysis reduces immunoreactivity by disrupting conformational and linear epitopes, but the degree of reduction varies with the enzyme used, the degree of hydrolysis achieved, and the individual patient's sensitization profile. Formulating a genuinely hypoallergenic plant protein blend product requires clinical immunological validation rather than reliance on the assumption that non-soy legume proteins are safe for soy-allergic individuals.

At the regulatory level, the honest assessment is that frameworks have not kept pace with the science. DIAAS, which most nutritional scientists regard as the most physiologically accurate available measure of protein quality, is not incorporated into the labelling regulations of any major jurisdiction. The US FDA, European EFSA, and India's FSSAI each have distinct approaches to protein quality claims, none designed with multi-source plant protein blends specifically in mind. This regulatory fragmentation makes it difficult to communicate genuine nutritional benefits consistently across international markets, and resolving it will require a sustained and coordinated effort from scientific societies, industry bodies, and regulatory agencies that has, to date, not materialized at the required scale.

Future research priorities, in our assessment, fall into three categories. First, clinical: well-powered, long-duration randomized trials testing specific blend formulations against defined health endpoints in clinically relevant populations not just young healthy males. Second, mechanistic: molecular-level characterization of protein-protein interactions in blends using small-angle X-ray scattering, cryo-electron microscopy, and mass spectrometry-based proteomics, to enable rational rather than empirical blend design. Third, translational: process-scale studies that validate laboratory blend performance at pilot and commercial scale, and life-cycle assessments that confirm the claimed environmental advantages of plant protein blends across the full production chain. Table 4 outlines the main challenges and current mitigation options.

Table 4 Key challenges in plant protein blend development and available mitigation strategies

Challenge	Underlying Cause	Mitigation Strategy	Expected Outcome
Off-flavour and bitterness	Volatile aldehydes, saponins, tannins	Enzymatic debittering, microencapsulation	Improved palatability and acceptance
Antinutritional factors	Phytates, trypsin inhibitors, lectins	Fermentation, germination, heat processing	Enhanced mineral and protein bioavailability
Low solubility at neutral pH	Isoelectric precipitation, aggregation	pH adjustment, glycosylation, partial hydrolysis	Better dispersion in beverage systems
Residual allergenicity	Immunogenic epitopes in soy and legumes	Enzymatic hydrolysis, hypoallergenic blending	Safer products for sensitive populations
Inconsistent gel texture	Variable protein denaturation during processing	Extrusion optimisation, transglutaminase crosslinking	Reproducible gel and emulsion structures
Regulatory ambiguity	No harmonised standards for blended proteins	Engagement with FSSAI, EFSA and FDA	Clearer labelling and health claim approvals

9. Conclusion

Reviewing a field as active as plant protein blends is a humbling exercise. Papers are appearing faster than any individual can read them, commercial products are being launched before much of the relevant science has been published, and the gap between enthusiastic market claims and rigorously validated evidence is, in some application areas, uncomfortably wide. This review has tried to narrow that gap, at least analytically, by presenting what the evidence actually shows and being explicit about where it runs out.

What the evidence shows is this: plant protein blends, carefully formulated from complementary sources, can achieve amino acid profiles and protein quality scores that are nutritionally competitive with animal-derived proteins. They can be processed into functional food matrices meat analogues, sports beverages, dairy alternatives, encapsulated nutraceuticals that deliver documented health benefits in clinical settings. Their hydrolysates generate bioactive peptides with antihypertensive and antioxidant activity that, in vitro at least, match or exceed those from single-source hydrolysates. And the techno-functional properties of blends solubility, emulsification, gelation can be tuned by adjusting blend composition in ways that give formulators flexibility without requiring synthetic additives.

What the evidence does not yet show or does not show with the consistency and rigor that should underpin confident health claims is that all of these in vitro and short-term clinical findings translate reliably into long-term health benefits in diverse human populations. Nor does it establish that the sensory quality of plant protein blend products is yet sufficient to achieve mainstream adoption at the scale required to make a meaningful contribution to global dietary protein sustainability. These are not reasons for pessimism; they are specific, solvable problems. But solving them requires more honest engagement with what we do not know than the literature on plant protein blends has so far typically demonstrated.

Compliance with ethical standards

Disclosure of conflict of interest

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Author Contribution

Author 1, Author 2, Author 3, and Author 4: Conceptualization, literature search, data collection, writing - original draft, visualization, and manuscript editing. Author 5 and Author 6: Draft editing, supervision, scientific guidance, critical review of the manuscript and editing, final approval of the manuscript.

Data Availability

Data is available from the corresponding author on request.

Statement of Usage of Artificial Intelligence

Open AI platforms were used for grammatical corrections only.

References

[1] FAO. The Future of Food and Agriculture: Trends and Challenges. Food and Agriculture Organization of the United Nations, Rome. 2017.

[2] Pimentel D, Pimentel M. Sustainability of meat-based and plant-based diets and the environment. Am J Clin Nutr. 2003; 78(3 Suppl): 660S–663S.

[3] Young VR, Pellett PL. Plant proteins in relation to human protein and amino acid nutrition. Am J Clin Nutr. 1994; 59(5 Suppl): 1203S–1212S.

[4] Gorissen SHM, Crombag JJR, Senden JMG, Waterval WAH, Bierau J, Verdijk LB, et al. Protein content and amino acid composition of commercially available plant-based protein isolates. Amino Acids. 2018; 50(12): 1685–1695.

[5] Boye J, Zare F, Pletch A. Pulse proteins: Processing, characterization, functional properties and applications in food and feed. Food Res Int. 2010; 43(2): 414–431.

[6] Roberfroid MB. Concepts and strategy of functional food science: the European perspective. Am J Clin Nutr. 2000; 71(6 Suppl): 1660S–1664S.

[7] Sha L, Xiong YL. Plant protein-based alternatives of reconstructed meat: Science, technology, and challenges. Trends Food Sci Technol. 2020; 102: 51–61.

[8] Liu K. Soybeans: Chemistry, Technology, and Utilization. Chapman & Hall, New York. 1997.

[9] Boland MJ, Rae AN, Vereijken JM, Meuwissen MPM, Fischer ARH, van Boekel MAJS, et al. The future supply of animal-derived protein for human consumption. Trends Food Sci Technol. 2013; 29(1): 62–73.

[10] Joy JM, Lowery RP, Wilson JM, Purpura M, De Souza EO, Wilson SM, et al. The effects of 8 weeks of whey or rice protein supplementation on body composition and exercise performance. Nutr J. 2013; 12: 86.

[11] Samtiya M, Aluko RE, Dhewa T. Plant food anti-nutritional factors and their reduction strategies: an overview. Food Prod Process Nutr. 2020; 2: 6.

[12] House JD, Neufeld J, Leson G. Evaluating the quality of protein from hemp seed (Cannabis sativa L.) products through the use of the protein digestibility-corrected amino acid score method. J Agric Food Chem. 2010; 58(22): 11801–11807.

[13] Vega-Galvez A, Miranda M, Vergara J, Uribe E, Puente L, Martinez EA. Nutrition facts and functional potential of quinoa (Chenopodium quinoa Willd.), an ancient Andean grain: a review. J Sci Food Agric. 2010; 90(15): 2541–2547.

[14] Moughan PJ. Population protein intakes and food sustainability: implications of alternative proteins. Proc Nutr Soc. 2020; 79(4): 449–455.

[15] van Vliet S, Burd NA, van Loon LJC. The skeletal muscle anabolic response to plant- versus animal-based protein consumption. J Nutr. 2015; 145(9): 1981–1991.

[16] Mathai JK, Liu Y, Stein HH. Values for digestible indispensable amino acid scores (DIAAS) for some dairy and plant proteins may better describe protein quality than scores calculated using the concept for protein digestibility-corrected amino acid scores (PDCAAS). Br J Nutr. 2017; 117(4): 490–499.

[17] Herreman L, Nommensen P, Pennings B, Laus MC. Comprehensive overview of the quality of plant- and animal-sourced proteins based on the digestible indispensable amino acid score. Food Sci Nutr. 2020; 8(10): 5379–5391.

[18] Kimball SR, Jefferson LS. Signaling pathways and molecular mechanisms through which branched-chain amino acids mediate translational control of protein synthesis. J Nutr. 2006; 136(1 Suppl): 227S–231S.

[19] Lam ACY, Karaca AC, Tyler RT, Nickerson MT. Pea protein isolates: Structure, extraction, and functionality. Food Rev Int. 2018; 34(2): 126–147.

[20] Benelhadj S, Gharsallaoui A, Degraeve P, Attia H, Ghorbel D. Effect of pH on the solubility and the emulsifying properties of artichoke (Cynara scolymus) protein concentrates. Food Chem. 2016; 197(Pt A): 1053–1060.

[21] Burger TG, Zhang Y. Recent progress in the utilization of pea protein as an emulsifier for food applications. Trends Food Sci Technol. 2019; 86: 25–33.

[22] Yuliarti O, Mawson J, Brennan CS, Tian YJ. Effect of transglutaminase on the physicochemical, morphological and rheological properties of plant-based protein gels. Foods. 2021; 10(1): 97.

[23] Bigliardi B, Galati F. Innovation trends in the food industry: The case of functional foods. Trends Food Sci Technol. 2013; 31(2): 118–129.

[24] Satija A, Bhupathiraju SN, Rimm EB, Spiegelman D, Chiuve SE, Borgi L, et al. Plant-based dietary patterns and incidence of type 2 diabetes in US men and women: results from three prospective cohort studies. PLoS Med. 2016; 13(6): e1002039.

[25] Pinckaers PJM, Kouw IWK, Gorissen SHM, Houben LHP, Senden JMG, Wodzig WKHW, et al. The muscle protein synthetic response to the ingestion of a plant-derived protein blend does not differ from an equivalent amount of milk protein in healthy, young males. J Nutr. 2021; 151(11): 3068–3079.

[26] Chew SC. Cold-pressed rapeseed (Brassica napus) oil: Chemistry and functionality. Food Res Int. 2020; 131: 108997.

[27] Udenigwe CC, Aluko RE. Food protein-derived bioactive peptides: production, processing, and potential health benefits. J Food Sci. 2012; 77(1): R11–R24.

[28] Aluko RE. Structure and function of plant protein-derived antihypertensive peptides. Curr Opin Food Sci. 2015; 4: 44–50.

[29] Huo JX, Zhao XH. In vitro digestion of a hemp seed protein hydrolysate prepared by Alcalase and assessment of the antioxidant activity of resulting peptides. Eur Food Res Technol. 2020; 246(6): 1255–1265.

[30] Augustin MA, Sanguansri L. Challenges and solutions to incorporation of nutraceuticals in foods. Annu Rev Food Sci Technol. 2015; 6: 463–477.