R&D priorities in crop optimisation for smart protein applications

Enhancing the nutritional & functional properties of Indian crops for smart protein applications

About the Good Food Institute India

The Good Food Institute India (GFI India) is the leading expert on India's emerging smart protein sector—the ecosystem of plant-based, cultivated, and fermentation-derived meat, eggs, and dairy. As part of an international network of organisations across the U.S., Brazil, Europe, Israel, Japan, and APAC, we work at the intersection of science, business, and public sector engagement to accelerate the R&D, technical know-how transfer, industrialisation, and commercialisation of smart proteins in India. We endeavour to unlock the knowledge and resources needed to transform how meat is made—satisfying rising food demand in ways that accelerate climate progress, protect animals and ecosystems, and strengthen public health. Drawing on India's unique strengths—including indigenous crops, a strong agrarian economy, low-cost technologies and infrastructure, an abundant talent pool, and biomanufacturing prowess—GFI India provides strategic market intelligence, ecosystem development support, and sector-focused advisory to help advance smart protein innovation and market readiness.

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Executive summary

For over seven decades, agriculture has remained the backbone of the Indian economy, ensuring food security, generating employment, and supporting national economic development.[1] In recent years, India's agricultural policy discourse has increasingly emphasised the need for crop diversification, value addition, climate-resilient farming systems, and improved farmer incomes. Within this evolving landscape, smart proteins (globally referred to as alternative proteins),[#2] which began gaining traction in India around 2017, present a complementary pathway that aligns with these priorities. The smart protein sector is often analysed through the triple-bottom-line framework: people, planet, and profit, as it simultaneously advances environmental sustainability, economic opportunity, and health and nutritional outcomes. By creating new demand for protein-rich crops such as pulses, millets, and oilseeds, smart protein innovation also supports the development of value-added agricultural markets. These crops can serve as key ingredients for plant-based meat, egg, and dairy alternatives, thereby expanding commercial opportunities beyond conventional food uses and strengthening market linkages between farmers, food processors, and emerging agri-food industries. Strengthening R&D efforts that connect crop science, breeding, and ingredient functionality for smart protein innovation will be critical to diversifying the ingredient base for India's plant-based sector while reinforcing the role of agriculture in driving sustainable food systems.

India's agricultural innovation ecosystem provides a strong foundation for advancing smart protein solutions. During the Green Revolution (1960s–1990s), major agricultural initiatives led to the development of high-yielding crop varieties and national self-sufficiency in food grains. In subsequent decades, attention shifted towards nutrition-sensitive agriculture, owing to growing recognition of micronutrient deficiencies, often termed 'hidden hunger.' In response, the Indian Council of Agricultural Research (ICAR) integrated nutritional enhancement into its R&D agenda, leading to the development of crop varieties enriched with protein and key micronutrients such as iron, zinc, and vitamin C.[3] Government investments have continued to strengthen this ecosystem: budget allocations to the agricultural sector increased from ₹11,915 crore in 2008–09 to ₹1,22,528 crore in 2024–25, while public funding for agricultural R&D has grown nearly sixfold since the early 1980s.[4] Recent initiatives include the establishment of a Global R&D Hub for Millets with a ₹250 crore allocation (2023–2026)[5] and the six-year Mission for Aatmanirbharta in Pulses, which focuses on crops such as pigeon pea, black gram, and lentils through efforts to develop climate-resilient seeds, enhance protein content, improve productivity and post-harvest management, and ensure remunerative prices for farmers.[6] Similarly, government support is also emerging to accelerate the scale, commercial viability, and mainstream adoption of smart proteins. Notably, in August 2024, the Union Cabinet approved the 'BioE3' policy (Biotechnology for Economy, Environment and Employment), India's first biotechnology policy under the Department of Biotechnology's (DBT) 'Fostering High-Performance Biomanufacturing' initiative, which identifies 'functional foods and smart proteins' as one of six implementation verticals. The policy is accompanied by funding schemes from DBT and the Biotechnology Industry Research Assistance Council (BIRAC) that are either dedicated to or include smart proteins in their scope.[7] One such funding call focused on utilising untapped crops for sustainable protein extraction, highlighting the policy's emphasis on advancing novel protein sources for smart protein applications.[8] Several other funding calls instituted by the Government of India and international organisations support research initiatives focused on crop optimisation.

These developments are particularly relevant to the plant-based smart protein sector. Many Indian plant-based meat manufacturers currently rely on expensive imported protein ingredients because domestically sourced crops often lack consistent functional properties or exhibit quality variability between batches. Enhancing the protein content, functionality, and sensory and nutritional qualities[9] of indigenous crops can therefore strengthen domestic supply chains for plant-based ingredients. Although processing technologies can improve these aspects of plant proteins, they often increase production costs and may require additives to achieve the desired texture and stability. Improving crop traits at the farm level can reduce the need for costly and energy-intensive downstream processing. Most plant-based products currently rely on a limited set of crops, particularly soy, wheat, and pea for meat alternatives, and soy, almond, coconut, oats, and millets for dairy alternatives. In addition, optimising crops and their residues as fermentation feedstocks could enable scalable and cost-effective smart protein production, but this potential remains untapped. Expanding research toward underexplored crops could broaden the ingredient landscape while creating new value chains for farmers.

This white paper outlines ten key R&D priorities to drive the sector forward, which collectively highlight the need for a holistic crop-to-ingredient innovation approach to support India's smart protein sector. Broadly, they emphasise expanding the diversity of crop inputs, improving the nutritional and functional characteristics of plant-based ingredients, and aligning crop breeding with the specific requirements of plant-based and fermentation-enabled food applications.

To realise these opportunities, targeted recommendations have been identified for stakeholders across the value chain (Fig. 1).

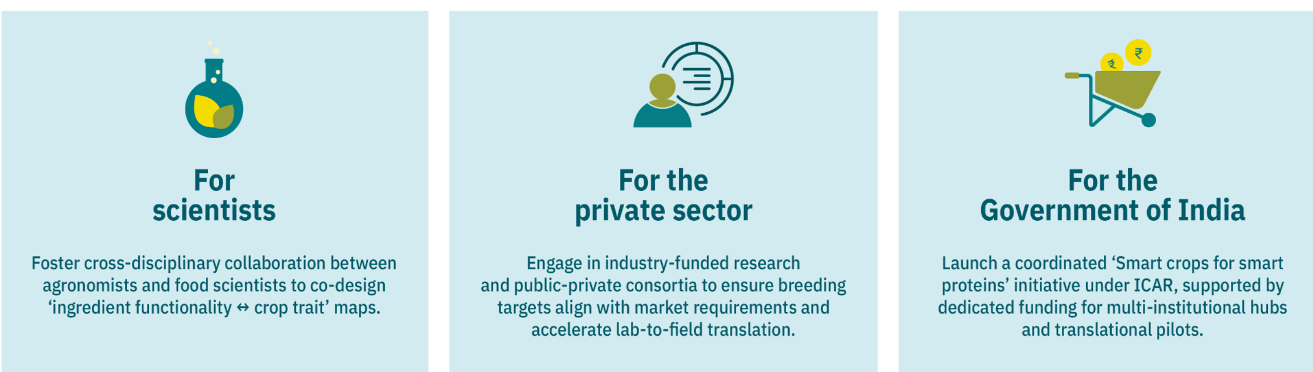

Figure 1. Stakeholder-aligned recommendations for implementing R&D opportunities

[#] *Please refer to the annexures for: (1) a glossary of smart protein and crop optimisation terms; (2) a directory of leading Indian research institutions and their focus areas in crop nutritional enhancement; and (3) a curated list of domestic and international R&D funding opportunities. Annexure-4 provides details on Indian crops and their specific ingredient applications across plant-based meat, egg, and dairy products.*

Table of contents

Deep dive: Research priorities in crop optimisation for smart protein applications

1. Tapping the ingredient potential of India's indigenous and underutilised crops for smart protein applications

Globally, only ~170 of the ~30,000 edible plant species are cultivated commercially for food, with rice, maize, wheat, and potato supplying nearly 60% of all calories.[10,11] Around 30 plant species supply ~95% of plant-derived proteins,[12] yet only a few, mainly soy, pea, and wheat gluten, are widely used in plant-based meat, egg, and dairy alternatives. More recently, mung bean and chickpea have begun gaining relevance for plant-based eggs. Consequently, the smart protein sector needs to diversify and localise protein sources to strengthen its ingredient supply chains. In India, the plant-based smart protein sector currently depends heavily on imported protein ingredients[13] from regions such as China and Europe. This reliance arises partly from the limited domestic availability of crops like pea, soy, and chickpea that meet the functional specifications required for food processing. High import tariffs and logistics costs further increase ingredient prices, affecting the cost competitiveness of plant-based products relative to animal-derived foods.

Exploring India's indigenous and underutilised crops offers an opportunity to diversify the ingredient basket for smart protein applications. India's biodiversity includes crops such as millets, pulses, and pseudocereals with promising nutritional profiles. Protein levels in legumes range from ~8–25%, while amaranth (~14.6%), quinoa (~16.3%), buckwheat (~13.1%), and millets (~6–12%) also present valuable alternatives.[14] Beyond proteins, crop-derived ingredients can contribute functional oils (e.g., high-oleic groundnut[15]), natural colourants, flavour compounds, and stabilisers for plant-based foods. For example, the Himalayan plant Rhododendron arboreum is rich in anthocyanins that could serve as natural food colourants (Fig. 2).

Neglected and underutilised crops[16] that were traditionally used species but declined in prominence over the years are regaining global interest due to their climate resilience[17] and lower input requirements compared to major commodity crops. However, relatively lower yields remain a barrier to their large-scale adoption in commercial food processing. Therefore, the right crops must be identified, processed minimally to extract proteins and other valuable ingredients, and made available at an optimal price to the manufacturing sector. If all these opportunities are efficiently leveraged, India can emerge as a global hub for plant-based smart protein ingredients and end products.

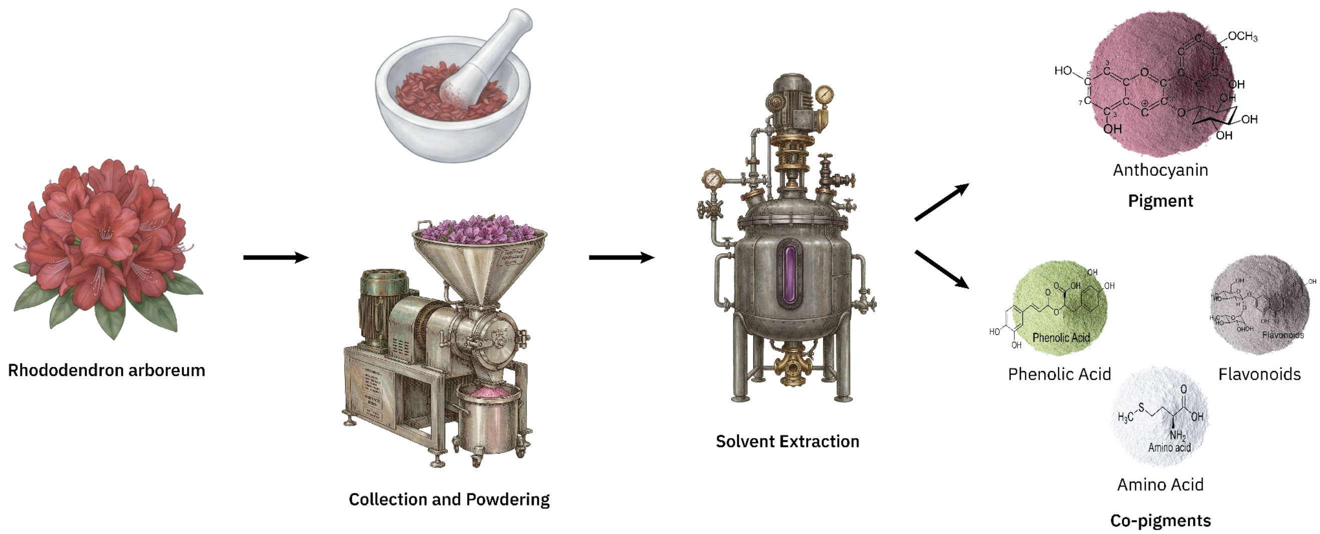

Figure 2. Rhododendron arboreum: A potential indigenous source to derive colourants for smart protein applications

R&D opportunities in this area include:

- **Understanding the mechanism of grain protein filling in indigenous and underutilised crops.** Grain protein filling is the mechanism by which plants convert available nitrogen into storage proteins that ultimately become protein-rich ingredients in food products. Beyond protein content, grain protein filling also determines the quality, composition, and functional performance of crop-based proteins in food applications. The limited understanding around biological and agronomic mechanisms that govern protein accumulation across different crops constrains optimisation for ingredient applications in plant-based meat, egg, and dairy products. Yield-protein trade-offs, inefficient nitrogen use, and increasing climate stress further reduce the consistency and suitability of grain proteins for processing and formulation. While crop scientists investigate the genetic, physiological, and agronomic drivers of grain protein filling in indigenous and underutilised crops, food scientists can simultaneously evaluate the influence of variations in protein accumulation on ingredient functionality and performance in plant-based food formulations.

- **Mapping of Quantitative Trait Loci (QTL) and genotype-to-phenotype (G2P) relationships** pertaining to grain protein content, amylose content, and oleic acid, using omics and high-throughput phenotyping tools. Complementing these efforts, food scientists can assess how these traits translate into nutritional value and functional properties in ingredient and product development.

- **Establishing a correlation between crop traits (upstream) and ingredient functionality indicators (downstream)** such as solubility and amino acid score. Agronomists and food scientists can collaborate during the initial phases of crop development and breeding to explore specific traits or agricultural techniques that could boost nutritional value and facilitate processing.[18]

2. Increasing the yield of high-protein crops

While India is a global leader in the production of cereals and pulses,[19] many staple crops are inherently low in protein or exhibit strong trade-offs between yield and protein content. Demand for affordable, high-quality plant proteins is rising, both as functional fortificants in food formulations and as ingredients for plant-based meat, egg, and dairy products. Enhancing the productivity of high-protein crops, focusing not merely on higher grain yields but maximising protein output per hectare, is critical for strengthening India's nutrition security and supporting the growth of a thriving smart protein ecosystem. Crops such as pulses, millets, oilseeds, and high-protein cereal varieties developed through biofortification approaches are particularly important in the Indian context due to their nutritional value, climate resilience, and cultural acceptance. However, current breeding and agronomic strategies largely prioritise yield and have a limited emphasis on protein concentration, quality, and stability across diverse growing conditions. Addressing this gap requires targeted R&D that integrates crop physiology, genetics, and agronomy with end-use and ingredient functionality considerations.

The R&D opportunities in this discipline include:	
Decoupling yield–protein trade-offs:	• Elucidating the physiological and genetic basis of yield dilution effects, where higher grain yield leads to lower protein concentration and identifying the traits that allow simultaneous improvement of yield and protein accumulation.
Crop- and trait-focused breeding strategies	• Prioritising breeding programmes for high-protein pulses (e.g., chickpea, pigeon pea, and lentils) and nutri-cereals (e.g., sorghum, pearl millet, and finger millet).
Improving nitrogen use efficiency for protein yield:	• Studying nitrogen uptake, assimilation, and remobilisation pathways that directly influence protein accumulation rather than biomass alone. • Developing crop varieties that maximise protein yield per unit of nitrogen applied, while simultaneously reducing reliance on synthetic fertilisers. • Exploring biological nitrogen fixation efficiency in pulses and root–microbiome interactions in non-legume crops.
Climate-resilient protein productivity:	• Assessing the effects of heat stress, drought, and elevated CO_2 on protein accumulation and protein composition in Indian cropping systems. • Identifying traits that stabilise protein yield under climate stress, such as extended grain filling duration or stress-tolerant nitrogen metabolism. • Integrating climate resilience into high-protein crop ideotypes.

3. Crop optimisation approaches to improve the nutritional and functional quality of proteins

As plant-based meat, egg, and dairy alternatives scale in India, the nutritional quality, digestibility, bioavailability, and functional consistency of crop-derived proteins will play a critical role in determining commercial viability, consumer acceptance, and potential health benefits. Optimising protein quality at the crop level can reduce reliance on downstream fortification and processing, while improving sustainability and returns for farmers.

R&D opportunities in this area include but are not limited to:	
Protein quality traits as breeding targets	• Defining breeding targets relevant to nutritional quality traits such as amino acid composition, protein digestibility, reduction of antinutritional factors, protein fraction composition (albumins, globulins, legumins, vicilins), protein structural properties affecting digestibility, micronutrient interactions, and protein stability during processing. • Establishing early-stage screening tools that connect breeding decisions to ingredient performance and characterise the influence of different varieties and environments on protein composition and its relevance to ingredient performance in plant-based food applications. • Breeding and gene editing for a balanced essential amino acid (EAA) composition (e.g., methionine and cysteine in pulses; lysine and tryptophan in cereals) and low-anti-nutrient ideotypes (low-phytate, low–trypsin inhibitor) that raise true digestibility without costly downstream processing.
Germplasm collection and trait screening	• Identifying and characterising seed traits, including protein content, EAA composition, anti-nutritional factors and those traits influencing the ease of processing, such as seed coat thickness, in the existing germplasm of indigenous legumes (horse gram, moth bean, winged bean, and jack bean) and millets/pseudocereals (kodo millet, barnyard millet, buckwheat, and amaranth).
Breeding for protein molecular traits relevant to food structuring	• Protein functionality in plant-based meat applications depends on molecular properties, including subunit composition, hydrophobicity, and disulfide bonding potential. There is a significant opportunity to integrate these molecular traits into crop breeding targets for improved texturisation and gel formation.
Reducing off-flavour-causing enzyme activity and precursor compounds	• Targeted crop improvement to address these presents an important whitespace for ingredient development.

4. Hydroponics for producing protein-rich crops

Hydroponics is a soilless agricultural technique where plants are cultivated in a nutrient-rich solution.[20] It is capable of enhancing both protein content and functionality by precisely controlling nutrients, light, and hygiene in closed systems. This makes hydroponics well-suited for cultivating plant-based smart protein sources that require consistency, safety, and year-round availability. Beyond terrestrial leafy greens such as amaranth and spinach, protein-rich aquatic micro-crops (ex. duckweed, azolla; >30–45%, dry weight) are fast-growing candidates that are amenable to shallow-water or recirculating culture. Recent research efforts highlight their amino-acid profiles and pathways to scale. India's interest in the field is evident through various urban hydroponic case studies to school meal pilots,[21,22] which point to a growing feasibility for decentralised nutrition and climate-resilient supply.

Research whitespaces include:

- Identifying factors that affect protein quantity and quality and designing hydroponic ideotypes of protein-rich leafy crops and microgreens (amaranth, chickpea, pea shoots, mung bean).
- Evaluating pulses and legumes for soilless culture to improve total protein and EAA ratios tailored to plant-based meat/egg functionality.
- Developing India-specific tailored nutrient solutions (including amino-acid and micronutrient supplements) to maximise protein content in crops, fine-tuning nitrogen and micronutrient delivery, and understanding nutrient interactions, while suppressing antinutrients (phytate, trypsin inhibitors) and nitrate.
- Understanding the direct impact of protein hydrolysate-based biostimulants on protein yield and quality in edible tissues.
- Creating 'LED light recipes'[23] for smart protein-relevant crops to achieve enhanced protein yield-per-kWh and downstream techno-functional traits of extracted proteins
- Domestic strain discovery and breeding of aquatic micro-crops for higher protein, lower off-notes, and reduced heavy-metal uptake, coupled with HACCP-grade, pathogen-controlled cultivation.
- Coupling hydroponics with safe organic nutrient streams (e.g., treated aquaculture effluents/compost extracts) and validating food-safety and residue limits for human-grade biomass.
- Life cycle assessment (LCA) and techno-economic analysis (TEA) benchmarks of grams of digestible protein per litre of water and per kWh against rainfed pulses and protected cultivation, to guide policy incentives.
- Post-harvest bioprocessing pipelines comprising gentle dewatering of aquatic crops and green extraction/fractionation that are optimised for clean-label protein ingredients.

5. Improving the nutritional quality of fatty acids

Indian plant-based meat products predominantly use vegetable oils such as sunflower oil, palm oil, soybean oil, and coconut oil. While many studies have established the health benefits of plant-based meat products, scope for improvement exists with respect to achieving a PUFA-rich fatty acid profile and reducing saturated fats. Based on the findings from GFI India's nutritional analysis,[24] sunflower, soybean, rice bran, and canola oils can boost monounsaturated fatty acid (MUFA) and polyunsaturated fatty acid (PUFA) content in plant-based meats. In this context, optimisation of crops for desirable fatty-acid profiles results in healthier, more stable lipids (e.g., high-oleic, low-linolenic, or ω-3–enriched oils) that improve nutrition, oxidative stability, shelf life, and mouthfeel of smart protein end products. Indian oilseed[25] development is progressing, as seen in the breeding and selection of low-erucic and canola-grade Brassica juncea (mustard)[26] to substitute high-erucic edible oils. This demonstrates the viability of targeted fatty-acid improvement on a large scale. Globally, gene editing of desaturase/elongase loci[27] (e.g., FAD2/FAE1) is known to raise oleic acid and reduce polyunsaturates in soybean,[28] rapeseed, and cotton. Metabolic engineering in Camelina has produced field-grown seed oils with EPA/DHA at levels similar to those present in fish oils. Established global technical precedents provide a foundation that India can tailor to its diverse crops and regulatory framework.

In the above context, whitespace opportunities for Indian researchers span crop science, metabolic engineering, processing, and nutrition, with strong potential to bridge agriculture and food technology:

- Precision breeding and CRISPR editing in climate-resilient Indian oilseed crops such as mustard, groundnut, soybean, and sesame can deliver high-oleic, low-PUFA, and low-erucic ideotypes that serve as healthier and more functional edible oils for smart protein fats.
- Metabolic engineering and stacking of ω-3 pathways (α-linolenic acid [ALA]→ stearidonic acid [SDA]/Eicosapentaenoic acid [EPA]) in oilseed crops, supported by regulatory science and confined field trials, can help position India at the frontier of functional lipid innovations.
- Parallel ingredient-translation research, developing oleogels and structured lipids from high-oleic mustard, rice-bran, or groundnut oils and validating their performance in smart protein prototypes can enable clean-label structuring solutions for industry.

Nutrition-centric research linking improved crop oil profiles with Indian dietary patterns and guidance from the Indian Council of Medical Research–National Institute of Nutrition (ICMR–NIN) can ensure public health relevance. Together, these research directions can integrate varietal improvements with downstream food technology applications, ultimately driving both consumer health benefits and innovation in India's smart protein sector.

6. Development of hypoallergenic plant protein sources

Many of India's staple and high-protein crops, such as chickpeas, peanuts, and legumes, contain allergens (ex. globulins that are primarily storage proteins) that can trigger IgE-mediated reactions. Due to health concerns, plant-based foods and ingredients tend to have limited consumer acceptance, which affects their market access and export potential. While developing hypoallergenic plant proteins is technically feasible, current work is fragmented across species, focused on a few allergens, and rarely linked to agronomy, processing, or clinical outcomes. A combination of genetic (allele selection, gene editing), biochemical (targeted protease/enzymatic hydrolysis), and bioprocessing (controlled fermentation, pressure/thermal treatments) approaches is known to reduce IgE reactivity or remove dominant epitopes, which are protein- and matrix-dependent. This literature,[29] together, points to a feasible pathway, from the discovery of allergenic epitopes[30] to breeding/editing, which India can leverage to develop safe, affordable, and regionally relevant hypoallergenic protein ingredients.

From an Indian R&D perspective, the whitespace opportunities fall into three connected streams:
• Characterising and prioritising to build a national catalogue of dominant food-allergen epitopes across major pulses, oilseeds, and pseudocereals (chickpea, pigeon pea, lentil, peanut, soy, sesame, and millets) using population-representative serum panels and modern proteomics/immunomics.
• Genetic and pre-harvest solutions that deploy conventional mapping, precision-breeding or targeted genome editing (CRISPR/Cas) to knock down or alter major allergenic proteins, in conjunction with assessment of nutritional impacts and pleiotropy (a condition in which a single gene or genetic variant influences multiple phenotypic traits).
• Multi-trait optimisation, as only a few studies jointly optimise low allergenicity with yield, protein quality, antinutritional factors and stress tolerance.
• Allergenicity and toxicology of many novel plant proteins that are derived from crops like quinoa, duckweed, hemp, and leafy greens remain scarcely quantified, especially under realistic processing and diets.
• Mapping allergen variability across Indian agro-ecologies, as natural genetic variation and agro-ecological factors (soil, climate, cultivation conditions) can influence allergen expression in crops such as groundnut and soybean. These genotype–environment effects remain poorly characterised in India. Systematic mapping across agro-climatic zones could enable breeding of low-allergen varieties and support more robust risk assessment and regulatory thresholds.

7. Improving the micronutrient content of crop-based protein sources

Indian plant-based meat products often lack key micronutrients such as iron, zinc, vitamin B12, and calcium, which are naturally found in animal-sourced foods. This highlights the need to enhance nutrient density at the crop level to reduce the dependency on later fortification steps. While biofortified cereals show promise, key gaps remain in integrating protein quality with micronutrient enrichment, targeting pulses and other crop-based proteins, and embedding such approaches in policy and large-scale delivery models beyond cereals.

Specific R&D opportunities:
• Most Indian biofortification work targets rice and wheat Zn/Fe with little focus on pulses (e.g., chickpea) and oilseeds as dual targets for high protein + high micronutrients. Early work in blackgram shows large Fe/Zn variation and scope for breeding.[31]
• Current varieties often raise single micronutrients. Combining high-quality protein (amino acid profile) with iron, zinc, calcium, selenium (Fe/Zn/Ca/Se), and low antinutrients needs to be explored.
• Research efforts are required on the genetics and physiology of micronutrient uptake, transport, and bioavailability in protein-rich crops, including interactions with antinutrients and heavy metal co-accumulation risks. Increasing mineral concentrations alone may not translate to improved nutrition due to antinutrients such as phytates and polyphenols that limit absorption. R&D opportunities exist in developing crop varieties and processing-compatible traits that combine higher Fe/Zn/Ca levels with reduced antinutrients or improved mineral bioavailability, particularly in pulses, millets, and oilseeds.
• Methods such as micronutrient-enriched fertilisers, foliar sprays, seed priming, and residue recycling show promise for improving nutrient profiles in protein crops, but require greater optimisation and context-specific validation under Indian agro-ecological conditions.
• Limited research exists on how micronutrients present in biofortified crops are retained through protein isolation, extrusion, fermentation, and other processing steps used in plant-based meat and egg production. Understanding and improving micronutrient retention during downstream processing could help ensure that crop-level gains translate into nutritionally meaningful end products.

8. Enhancing crop suitability for enhanced extraction yields of plant-based proteins and fats

The size and shape of seeds are important crop traits that govern the extraction yield of protein and oil from plant-based sources. Large seeds contain greater food reserves. Similarly, the globular shape of seeds (e.g., chickpeas)[32] correlates with higher protein content.[33] Seed size is directly influenced by the composition and amount of seed storage reserves.[34] For instance, soybean seeds typically consist of nearly 60% oil and protein, making seed size, oil, and protein content highly correlated agronomic traits. There are several strategies for improving seed traits, including traditional breeding, crossbreeding, selection, mutational breeding, and gene editing (e.g., CRISPR-Cas9). Scientists are combining traditional breeding with genetic engineering and new protein extraction methods to optimise crop seed traits for improved nutritional value.

Future research areas in traditional breeding:
• Diverse germplasm, multi-environment phenotyping for stable seed traits, and physiological factors like seed fill rate and coat thickness that impact nutrient deposition.
• Cross-breeding can combine high-protein and oil lines, introduce wild alleles, map heterosis, and pyramid traits like reduced anti-nutritional factors.
• Further, artificial intelligence (AI) tools can accelerate phenotypic and genomic selection by leveraging high-throughput seed phenotyping, marker-assisted recurrent selection, and genomic prediction models.
• Integrating metabolomics will also help identify genotypes with desirable nutrient allocation. Mutational breeding, aided by advanced phenotyping and omics tools, can potentially create new gene variations to improve seed coat, embryo size, and storage tissue, helping identify beneficial mutants for precise trait expression.
• CRISPR-Cas gene editing offers precise ways to improve seed development, simultaneously enhancing size, protein, and oil.[35] It also allows for fine-tuning gene expression and optimising seed shape for better packing and processing, ultimately boosting both yield and nutritional quality.
• Critical gaps include uncovering spatial and temporal dynamics of protein accumulation at single-cell resolution, elucidating how nitrogen assimilation pathways connect with storage protein synthesis, and disentangling the regulation of albumins, globulins, gliadins, and glutenins under varying nutrient conditions.
• Environmental stresses such as heat strongly affect hormone signalling, transcription factors, and stress-responsive proteins, yet their downstream impacts on protein quality and overall yield remain inadequately understood.
• Modifying crop chemical composition, such as starch, sugar, oil, protein, fibre, and moisture levels, to enhance suitability and efficiency for industrial processing.

9. Development of fermentation-compatible crops

Optimising crops to act as feedstocks that provide sugars, nitrogen, and other nutrients for microorganisms is a scalable and commercially viable approach for alternative protein production. Using crop residues as substrates for fermentation processes is gaining momentum as an effective approach to improve the affordability and sustainability of alternative protein ingredients and end products. Agricultural crop residues are considered as 'second-generation' feedstocks, but they also contain recalcitrant polysaccharides such as cellulose, hemicellulose, pectin, lignin, and lignin-carbohydrate complexes. Consequently, the cell walls of crop residues are highly resistant to saccharification, fermentation, and valorisation.[36] The presence of complex polysaccharides reduces the cell-wall digestibility and thereby limits the bioconversion efficiency and release of fermentable sugars for microbial growth.

Research priorities
• Several complementary approaches can be pursued to develop fermentation-compatible crop varieties with low lignin content, a high starch-to-lignin ratio, and improved levels of readily fermentable carbohydrates such as soluble sugars, starch, and pectin. One strategy involves the regulation of genes encoding enzymes in the lignin biosynthetic pathway to reduce lignin deposition. Parallel efforts could focus on breeding inherently low-lignin mutant lines and engineering cell-wall composition for improved substrate accessibility.
• 'Improved cell-wall traits' mean low cellulose crystallinity, reduced wall thickness, increased soluble pectin content, a loosely arranged polysaccharide network, reduced phenolic cross-linking, and enhanced porosity and surface area.
• Advanced *in silico* and omics-based tools can be employed to identify lignocellulose-metabolising microbial communities and discover novel enzymes that facilitate the efficient bioconversion of agricultural crop residues.
• At the processing interface, opportunities include designing crops that require minimal pretreatment, co-optimising crop-microbe systems to maximise yield and functional outputs, and developing resilient crops that maintain feedstock quality under stress conditions.
• At the systems level, circular feedstock design, climate-adaptive varieties, and integrated life cycle and techno-economic modelling can ensure that crop innovations reduce costs, improve sustainability, and enhance the scalability of fermentation-derived proteins.

10. Sensory-centric breeding: Eliminating off-notes of plant-based protein sources at the crop level

Plant proteins often carry bitter, beany, or grassy off-flavours that hinder achieving sensory parity with animal-derived products. Mitigation strategies include flavour masking, encapsulation with spices or carrier materials, fractionation, fermentation, and enzymatic treatments. However, the most sustainable upstream solution is to reduce off-flavour precursors at the crop level through plant breeding and genetics. Developing crop varieties with reduced off-notes and improved sensory traits can significantly enhance consumer acceptance of plant-based meat and dairy alternatives. Breeding can also introduce positive flavour attributes, reducing dependence on added flavouring agents. A major bottleneck[37] remains the lack of high-throughput phenotyping tools that can screen flavour and aroma traits within breeding pipelines.[38] In addition, research must extend beyond widely studied crops such as pea, fava bean, and soybean to include regionally important and underutilised protein sources.

- In India, pulses such as chickpea, lentil, pigeonpea, and mungbean form the backbone of traditional diets and hold strong potential in smart protein applications. Yet breeding efforts for these crops have largely prioritised yield, stress tolerance, and protein quantity, with limited focus on systematic off-note reduction or flavour optimisation. Similarly, underutilised desert legumes such as Prosopis cineraria, Acacia senegal, and Cyamopsis tetragonoloba possess promising nutritional profiles but face challenges, including off-flavours, low productivity, and poorly understood metabolic pathways influencing flavour.

- Emerging gene editing technologies such as CRISPR/Cas9 enable precise modification of genes associated with undesirable flavour compounds.[39] However, molecular markers linked to off-note reduction remain scarce, and flavour-related metabolic pathways are poorly characterised across many legumes and indigenous crops. Future breeding efforts should therefore target biochemical pathways producing undesirable compounds such as methoxypyrazines, grassy aldehydes (e.g., 2,4-heptadienal, heptanal), and classes including saponins, tannins, phenolics, and alkaloids. Integrating genomics, analytical flavour profiling, and consumer sensory data can enable the development of crops with neutral flavour profiles, minimal bitterness, and improved ingredient functionality.

Crop-level improvements that reduce flavour masking and enhance formulation efficiency can significantly improve ingredient performance in plant-based meat and dairy applications. Aligning breeding targets with downstream processing needs will be key to unlocking the full potential of Indian crops for smart protein production.

Recommendations for food and agricultural scientists

Align crop development with end-product performance

Based on the priorities discussed in this whitepaper and from a sectoral standpoint, crop optimisation is a strategic fulcrum to produce affordable and nutrition-forward ingredients for India's smart protein ecosystem. Food scientists must work with agronomists to identify traits or agronomic practices that can improve nutritional value and facilitate processing early in the crop development and breeding stages to meaningfully improve the taste, texture, and nutrition of plant-based meat, egg, and dairy products.[40] Although breeding programmes have traditionally prioritised yield and pest resistance, it is equally important to address processor and consumer preferences to drive improved product formulations and wider adoption. Therefore, food scientists should define and measure the functionality endpoints that breeding should address, create validated processing flowsheets (say, for extrusion-ready pulse/rice/millet fractions) and communicate those specifications as trait targets for breeders and map interactions between cultivar and process that affect flavour and structure. If food scientists could standardise tailored sensory evaluation protocols for plant-based protein crops, cross-study comparisons and breeding progress would become seamless.

Build a shared trait-to-function evidence base

Agricultural scientists can also think beyond yield, disease, and pest resistance and consider traits for functionality, nutrition, and climate resilience. While the primary focus should be on pulses, oilseeds, and millets, underutilised regional sources should not be neglected. Together, food and agriculture scientists can co-design an *'ingredient functionality ↔ crop trait'* map and build a shared *'trait→function'* dataset, such that upstream phenotypes predict downstream performance.

De-risk allergenicity through cross-disciplinary validation

Moreover, interdisciplinary efforts and collaboration between scientists from agriculture, food science, and life science backgrounds are required to establish standardised *in vitro* and *in vivo* allergenicity assays; regulatory engagement to define acceptable thresholds for hypoallergenic claims; and industry-academia pilots to translate lab-scale de-allergenic processes into scalable, cost-effective ingredient streams for India's smart protein sector.

Recommendations for the private sector

The private sector's involvement in addressing the identified R&D opportunities should be explicitly encouraged, owing to the commercial nature and potential of the crop traits discussed in this whitepaper. Industry-led or industry-co-designed research can ensure that breeding targets, agronomic practices, and post-harvest characteristics align with real market requirements, reducing the gap between lab-scale innovation and market-level adoption. The plausible mechanisms could include:

- **Industry-funded research programmes at public agricultural universities, ICAR institutes, and other international and private organisations conducting agri-focused research**
- **Public-private research consortia focused on yield, quality, and cost-efficiency traits**
- **Joint field trials and demonstration plots involving farmers, researchers, and industry partners**

These models can accelerate innovation while maintaining public oversight and broad dissemination of results

Recommendations for the Government of India's scientific agencies and funding bodies

Build a national 'smart crops for smart proteins' initiative

To unlock the full potential of smart protein applications in India, a coordinated yet mandate-aligned national approach is essential, one that clearly distinguishes while strategically integrating upstream crop development and downstream product innovation. India's premier scientific agencies and funding bodies can collaborate on a strategically designed 'Smart crops for smart proteins' initiative. At the upstream level, the Department of Agricultural Research and Education (DARE)/ICAR ecosystem is best positioned to drive producer-centric innovation. Its core role would be to develop and disseminate crop varieties with traits aligned to defined end-use requirements such as protein content and quality, starch composition, fibre profile, and functional properties. Embedding use case-linked trait targets (for example, pulses optimised for extrusion or millets suited for wet fractionation) into breeding pipelines can ensure that crop development is not decoupled from downstream demand. ICAR institutions, along with State Agricultural Universities (SAUs), can further support seed systems, varietal release, and farmer adoption, ensuring these improved crops reach scale within India's agri-food systems.

Connect crop breeding with ingredient and product innovation

The next phase, which involves translating these crops into commercially viable food ingredients and products, requires a distinct, application-oriented R&D ecosystem. The Ministry of Food Processing Industries (MoFPI), and agencies such as the Department of Science and Technology (DST), Department of Biotechnology (DBT), Council of Scientific & Industrial Research (CSIR), Anusandhan National Research Foundation (ANRF), and BIRAC can lead translational and industry-aligned research. This includes developing processing technologies (e.g., dry/wet fractionation, extrusion), ingredient standardisation, functionality optimisation, and pilot-scale validation for end-product applications. Bridging these two layers is critical. Without downstream processing innovation, improved crop varieties risk remaining confined to commodity markets; conversely, without fit-for-purpose crops, ingredient and product innovation faces raw material constraints. A 'Smart crops for smart proteins' initiative can formalise this linkage by aligning breeding targets with processing requirements and end-product specifications.

Foster a participatory ecosystem for inter-institutional collaboration

Downstream enablement will also require institutional support beyond R&D. The Institutions of National Importance, NIFTEM-Kundli and NIFTEM-Thanjavur, under the aegis of MoFPI, can enable pilot-scale infrastructure, support industry adoption, and strengthen value-added processing ecosystems. The Food Safety and Standards Authority of India (FSSAI) can help establish regulatory clarity and nutritional benchmarks for emerging protein ingredients. Strategic coordination by NITI Aayog can ensure alignment across ministries and integration with national priorities on nutrition, sustainability, and rural livelihoods. In terms of scope, the initiative should prioritise staple, system-relevant crops such as pulses, oilseeds, and millets, given their relevance to India's protein security, climate resilience, and farmer incomes. At the same time, it should create dedicated pathways to explore emerging and underutilised protein sources, such as seaweed, duckweed, and leafy crops, which offer opportunities for diversification and future-ready supply chains. Ultimately, the transition from crop development to mainstream smart protein products depends on making these crops functionally suitable, economically viable, and sensorially appealing through targeted processing innovations. A two-tiered, well-coordinated innovation ecosystem that links ICAR-led efforts at the crop level with application-oriented research led by other scientific agencies will be key to realising this vision.

Use AI/ML for trait discovery

In addition to the above, applications of AI and machine learning (ML) in crop optimisation, such as identifying desirable traits from genomic and phenotypic datasets, are transforming how these crops can be utilised for smart protein production. These tools enhance precision breeding by predicting superior genotypes, supporting genome editing approaches such as CRISPR, and accelerating trait selection. Looking ahead, the integration of ML and deep learning in crop science will allow increasingly accurate and real-time predictions that can adapt to changing ecosystems and climate pressures. This positions AI/ML as another cornerstone for R&D in alternative protein crops.

Fund the bridge from lab discovery to market-ready applications

To effectively drive innovation and translation, dedicated funding streams—both new and existing—will become crucial. These funding mechanisms should strategically support the establishment of multi-institutional hubs, facilitating knowledge-sharing and resource optimisation. Through translational pilots, bridging the gap between laboratory research and real-world application and startup-driven innovation, agile and market-responsive solutions can be nurtured. At the same time, greater emphasis must be placed on high Technology Readiness Level (TRL) research that bridges the gap between laboratory discovery and commercial-scale ingredient and product development. Supporting pilot-scale validation, process optimisation, and industry-academia demonstration projects will be critical to ensure that promising crop traits and protein ingredients can transition efficiently into viable food applications. Collaboration between ICAR institutions and food technology institutions at both state and central levels will be critical to ensure that crop trait innovations translate into high-TRL ingredient technologies, scalable processing methods, and commercially viable smart protein products.

The success of this initiative should be tied to measurable outputs, including breeding lines with enhanced protein content and functionality, validated and scalable processing flowsheets, and a national crop trait atlas linking nutritional and functional traits of Indian protein sources to smart protein applications. With these strategic investments, India can emerge as a global leader in climate-smart, nutritionally relevant, and commercially scalable smart protein ingredients and end products, contributing to food security and sustainable agri-food systems.

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