Annexure 1

Key definitions

Smart proteins: According to the Center for Strategic & International Studies 2023,[41] 'alternative proteins' (known as 'smart proteins' in India) is a *'term of art that describes foods that are produced to provide the sensory experience of animal meat—but using plants, fermentation, or cellular agriculture.'* These products are derived from sustainable sources with a low environmental footprint to reliably and predictably substitute the consumption of conventional meat, eggs, dairy and seafood.[42] Smart proteins are designed to taste the same as or better than and cost the same or less than animal-derived products.[43] India is uniquely positioned to harness the potential of smart proteins to drive sustainable growth for the economy, environment, and employment.

Plant-based smart protein: The term *'plant-based'* refers to products that are solely made of ingredients derived from protein-rich crops such as pulses (pea, chickpea, mung bean), oilseeds (soy), cereals (wheat, rice), nuts (almond, cashew), and others (millets, jackfruit, potato). This category includes plant-based meat, seafood, eggs, and dairy that serve as sustainable alternatives to their corresponding animal-derived products. Like animal products, they are composed of protein, fat, vitamins, minerals, and water. Next-generation plant-based alternatives look, taste, and cook like conventional meat and offer a comparable or higher amount of protein and dietary fibre.

Plant-based value chain refers to the following developmental stages of plant-based smart protein production from farm to factory gate (Fig. 3):

- **Stage 1: Crop development** includes the development of crop varieties suitable for the smart protein industry, using tools such as crop breeding, gene editing, and biofortification.
- **Stage 2: Cultivation** includes crop breeding, biofortification, and farming the crop in a suitable environment with the highest yield potential.
- **Stage 3: Primary ingredient fractionation and modification** deals with the primary (dehulling, milling) and secondary (extraction of oil, protein, fibre or starch-rich fractions; physical and chemical modifications) processing of crop inputs.
- **Stage 4: Composite and secondary ingredient processing** involves processes that fall between ingredient processing and final product formulation (e.g., extrusion, alternative fat production, and flavour development), which bring ingredients together to form the 'building blocks' of plant-based alternatives.

- **Stage 5: End-product formulation and manufacturing** includes final product development, scale-up, commercialisation, and production.

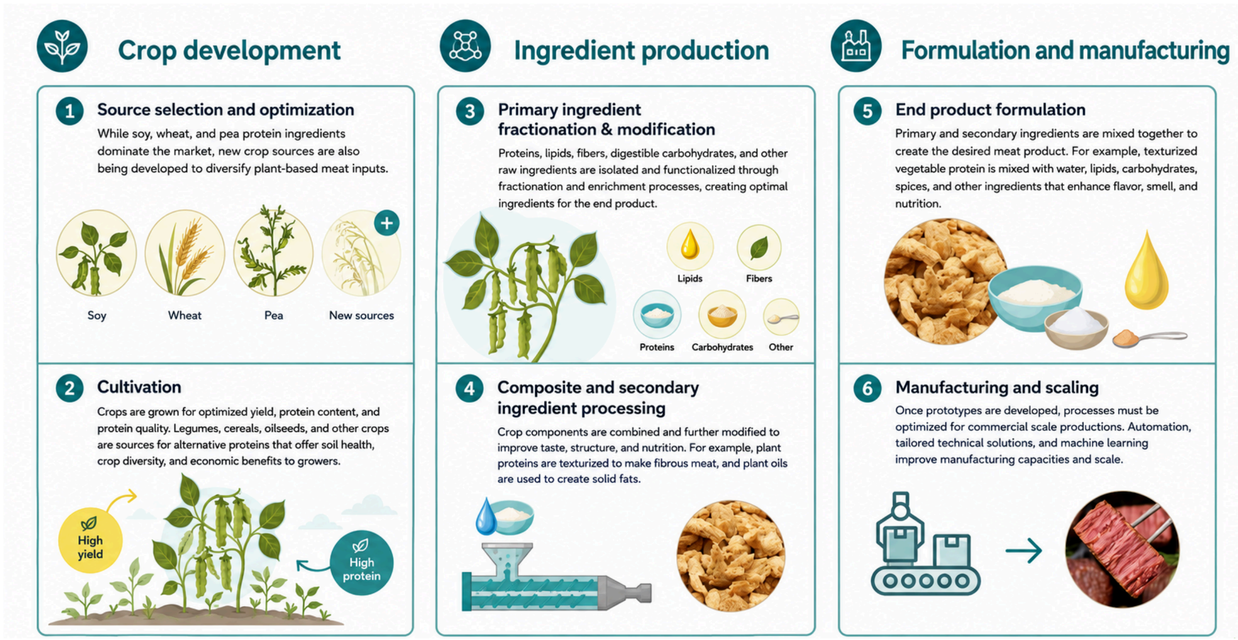

Figure 3. Value chain of plant-based meat production

Protein quality: Protein quality is the ability of dietary protein to supply essential amino acids and nitrogen to maintain bodily functions and composition.[44] Several factors determine protein quality, including amino acid content, nitrogen balance, and protein digestibility, which are assessed by the below parameters:

- Digestible Indispensable Amino Acid Score (DIAAS): DIAAS is defined as: DIAAS % = 100 x [(mg of digestible dietary indispensable amino acid in 1 g of the dietary protein) / (mg of the same dietary indispensable amino acid in 1 g of the reference protein)].[45]
- Protein Digestibility Corrected Amino Acid Score (PDCAAS): PDCAAS is defined as: PDCAAS % = 100 x [(mg of limiting amino acid in 1 g of test protein) / (mg of same amino acid in 1 g of reference protein)] x [fecal true digestibility, in %].[46]

Higher scores indicate a better match to human amino acid requirements and digestibility.

Anti-Nutritional Factors (ANFs): ANFs comprise naturally occurring compounds in plants such as phytates, lectins, and tannins, which inhibit protein absorption or digestion. Breeding and processing are the major routes for mitigating ANFs.

Functional properties of proteins: The functionality or functional property of any food substance refers to its physical, chemical, and organoleptic properties and their intricate relationship with the structure and molecular components (Kumari & Raghuvanshi, 2015). The performance of plant-based proteins in end-product applications (meat, egg and dairy alternatives) is governed by their functional ability to biomimic the texture, mouthfeel, and structure of animal proteins. Key functional properties of proteins are illustrated in Fig. 4.

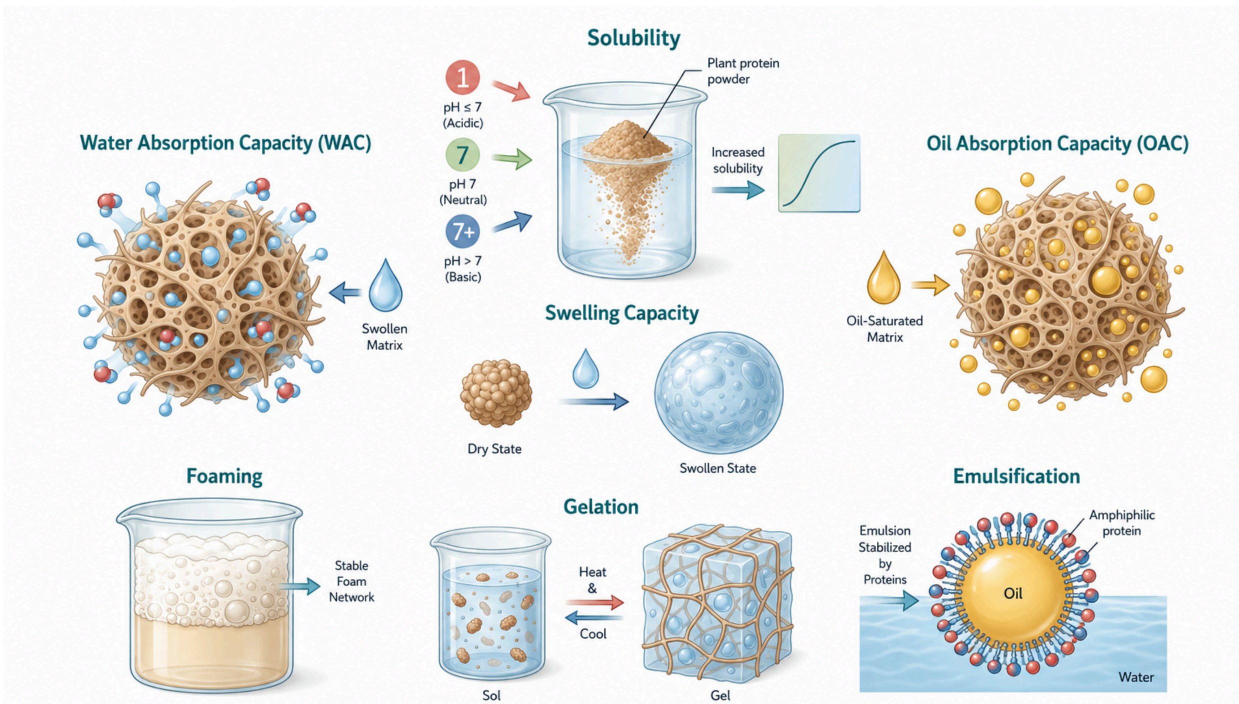

Figure 4. Functional properties of plant proteins

Underutilised crops: Region-specific crops that are scant in their availability or rarely used are referred to as underutilised plants. Underutilised crops include minor millets such as foxtail millet; legumes such as horse gram, field beans, moth bean, winged bean, and lablab bean; and other crops such as quinoa, amaranth, buckwheat, moringa, and jackfruit.

Crop optimisation for smart protein applications: Crop optimisation for smart protein application comprises phenotypic characterisation of crops and targeted breeding to introduce desired target traits into a crop that enhance its suitability as an ingredient in plant-based meat, egg, dairy and seafood. These targeted efforts are intended to produce plant-based sources with:

- High-protein content;
- Improved nutritional quality of proteins and fats (availability of essential amino acids and a desirable fatty acid profile, including a balanced composition of monounsaturated and polyunsaturated fatty acids);
- Enhanced technofunctional properties through biofortification approaches such as traditional breeding or genetic engineering.

Crop breeding: Breeding involves generating, identifying, and stabilising enhanced lines or varieties of crops with desirable characteristics such as higher yields, better nutritional content, and greater resilience to environmental shifts. This method offers a sustainable approach to increasing production and yield consistency without further reliance on fertilisers and pesticides.

Genetic modification: Genetic modification of crops for smart protein applications refers to the use of molecular biology tools, such as gene editing and transgenic approaches, to enhance their suitability as protein sources for developing plant-based meat, egg, and dairy products. The end results include, but are not limited to, improving the quantity, quality, digestibility, functionality, and nutritional profile of plant-based proteins and reducing anti-nutritional factors and allergens. Gene editing techniques such as CRISPR/Cas9 facilitate targeted trait development by allowing precise modifications without the need for introducing foreign DNA.[47] In addition, transgenic approaches such as agrobacterium-mediated transformation and biolistics (particle bombardment) have been used to introduce novel genes encoding desirable traits such as higher essential amino acid content (e.g., methionine, lysine), increased protein accumulation, or improved processing characteristics.[48-52]

Crop diversification: Crop diversification refers to expanding the range of crops (e.g., millets, pulses, sorghum, and hemp) used for alternative protein production to increase resilience, reduce monoculture dependency, and unlock new functional and nutritional benefits.

Trait optimisation: Trait optimisation entails the modification or selection of specific crop traits such as protein and micronutrient content, amino acid/fatty acid profile, protein digestibility and functionality (solubility, gelation, and emulsification), flavour, anti- and non-nutrient factors, toxicity, and allergenicity to improve their performance in plant-based meat, egg, and dairy products.[53]

Phenotyping: Phenotyping is the process of measuring and analysing observable traits of crops—morphological (height, length, shape, and colour), physiological (yield, growth patterns, and stress tolerance), and biochemical (protein content and amino acid composition)—that are influenced by genetic and environmental factors.

Artificial intelligence (AI): AI refers to the science of automating human intelligence using computer programs or machines. It facilitates data-based decisions to carry out tasks without human intervention.[54]

Machine learning (ML): Machine learning is a branch of artificial intelligence, which involves a set of methods that allows computers to automate data-driven model-building and programming. This is achieved through a structured discovery of statistically significant patterns within available data.

Technology Readiness Level (TRL): Technology Readiness Levels (TRL) measure a technology's maturity. They provide a structured assessment system where each project is evaluated against specific parameters and assigned a TRL rating based on its advancement.[55] The scale ranges from TRL 1, the most basic level, to TRL 9, representing the highest level of maturity, with a total of nine levels (Fig. 5).

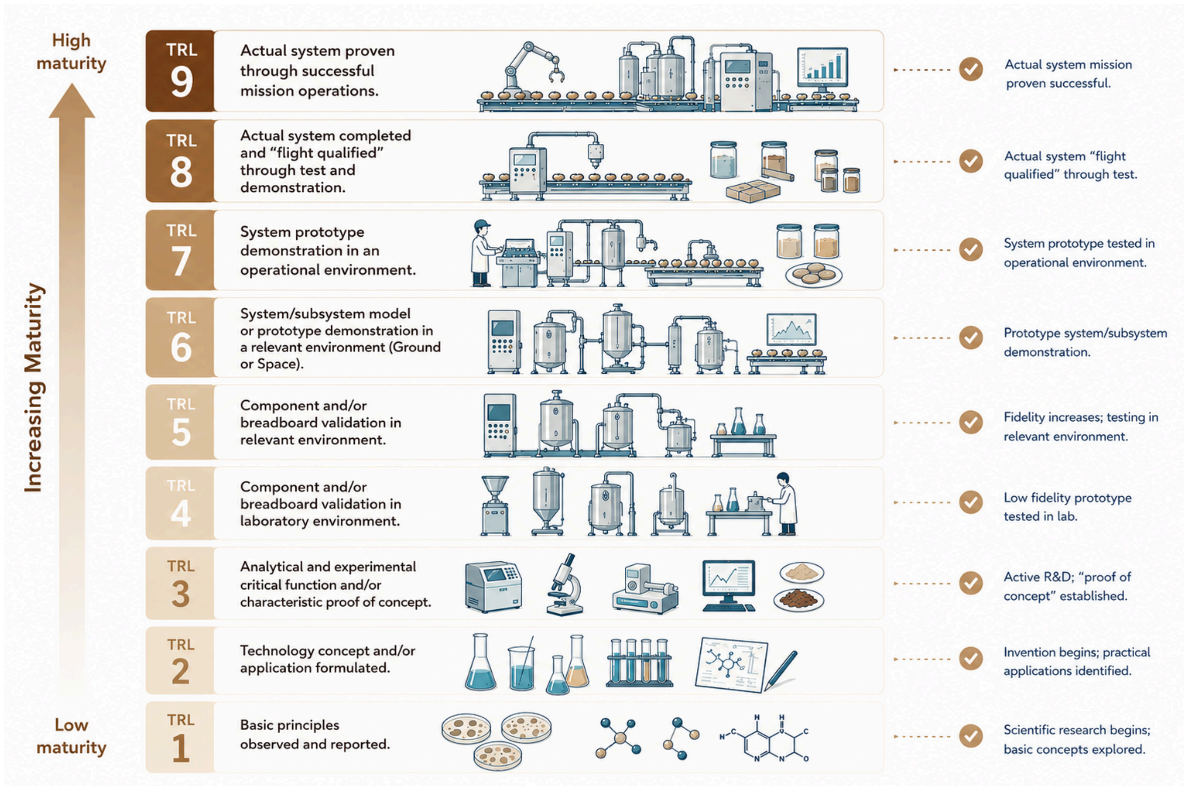

Figure 5. Technology Readiness Levels (TRL) of relevance to plant-based smart protein production

Annexure 2

List of prominent Indian institutions working on crop development and optimisation for nutritional enhancement

Name of the institution	Location	Type of institution	Focus area
Indian Council of Agricultural Research (ICAR)	New Delhi	India's apex agricultural research body under the Department of Agricultural Research and Education (DARE), Ministry of Agriculture and Farmers Welfare, Government of India	Apex body for coordinating, guiding, and managing research and education in agriculture, including horticulture, fisheries, and animal sciences
ICAR–Indian Agricultural Research Institute (IARI)	New Delhi	Central Government	Genomic selection for protein quality in wheat and maize; nutritional genomics to map traits like grain iron and zinc, which often correlate with protein bioavailability
ICAR–National Bureau of Plant Genetic Resources (NBPGR)	New Delhi	Central Government	Mandated to manage and evaluate the nation's germplasm, specifically identifying 'nutri-dense' wild relatives and landraces for use in quality-improvement breeding programmes, trait discovery and validation for nutrition and quality, pre-breeding support and utilisation pathways
ICAR–Indian Institute of Rice Research (IIRR)	Hyderabad, Telangana	Central Government	Focuses on enhancing the nutritional value of rice, targeting traits like high

			zinc/iron content, low glycemic index (GI), and superior milling quality for irrigated ecosystems; host of the Consortia Research Platform on Biofortification
ICAR–NRRI (formerly CRRI)	Cuttack, Odisha	Central Government	Conducts strategic research to improve rice grain quality and health-promoting functional properties (like antioxidants), specifically for diverse and fragile ecosystems.
ICAR–Indian Institute of Wheat & Barley Research (IIWBR)	Karnal, Haryana	Central Government	Develops end-product specific varieties with enhanced nutritional quality traits; characterisation of genes associated with different quality traits and their deployment in high-yielding backgrounds; biofortification and enhancing the bioavailability of micronutrients (Fe and Zn)
ICAR–Indian Institute of Millets Research (IIMR)	Hyderabad, Telangana	Central Government	Global hub for 'nutri-cereals,' focusing on maximising the natural mineral and fibre content of millets through value-added processing and breeding
ICAR–Indian Institute of Pulses Research (IIPR)	Kanpur, Uttar Pradesh	Central Government	Targets pulse crop improvement for the reduction of anti-nutritional factors (like phytates) and enhancement of protein bioavailability and micronutrients in pulses

ICAR–Indian Institute of Vegetable Research (IIVR)	Varanasi, Uttar Pradesh	Central Government	Mandated to develop ‘Nutri-garden’ modules and vegetable varieties rich in vitamins, minerals, and bioactive compounds to combat ‘hidden hunger’
ICAR–Indian Institute of Horticultural Research (IIHR)	Bengaluru, Karnataka	Central Government	Focuses on ‘breeding for quality,’ enhancing the shelf-life, antioxidant capacity, and phytochemical content of fruits, vegetables, and medicinal plants.
ICAR–National Institute of Plant Biotechnology (NIPB)	New Delhi	Central Government	Uses advanced molecular tools and metabolic engineering to manipulate plant pathways for enhanced nutritional profiles and stress-resilient functional traits
ICAR–Indian Institute of Groundnut Research (IIGR)	Junagadh, Gujarat	Central Government	Targets the improvement of oil quality (high oleic acid) and the reduction of aflatoxin contamination to enhance the safety and health benefits of groundnuts
BRIC–National Agri-Food and Biomanufacturing Institute (NABI)	Mohali, Punjab	Central Government	Specifically mandated to bridge the gap between agriculture and nutrition through designer crops and evidence-based functional foods
BRIC–National Institute of Plant Genome Research (NIPGR)	New Delhi	Central Government	Conducts frontier genomic research to decode the genetic basis of nutritional traits and manipulate plant genomes for superior nutrient density
International Crops Research Institute for	Hyderabad, Telangana	International, CGIAR (Consultative Group on International Agricultural Research)	Focuses on biofortifying dryland crops (pearl millet, sorghum, legumes) to

the Semi-Arid Tropics (ICRISAT)			improve the health of vulnerable populations in the semi-arid tropics
Tata Institute for Genetics and Society (TIGS)	Bengaluru, Karnataka	Private, scientific research institute	Employs cutting-edge genetic technologies like CRISPR to address nutritional deficiencies and enhance the functional resilience of staple Indian crops
Punjab Agricultural University (PAU)	Ludhiana, Punjab	State Government	Leading state university mandated to develop high-yielding, nutrient-efficient varieties (like high-amylose wheat) tailored for the food processing industry
ICARDA Food Legume Research Platform (ICARDA–FLRP)	Amlaha, Madhya Pradesh	International agricultural research platform under the International Center for Agricultural Research in the Dry Areas (ICARDA)	Focuses on enhancing the micronutrient profile (particularly iron and zinc) and climate resilience of food legumes like lentils and chickpeas
IRRI South Asia Regional Centre (IRRI–ISARC)	Varanasi, Uttar Pradesh	International research centre of International Rice Research Institute (IRRI)	Targets the development of health-healthier rice varieties for South Asia, focusing on biofortification and grain quality standards
International Centre for Genetic Engineering and Biotechnology (ICGEB)	New Delhi	Intergovernmental research organisation	Utilises molecular biology tools to improve crop nutritional value and metabolic efficiency through international collaborative research

Annexure 3

Funding opportunities for crop optimisation

Funding body / Scheme	Eligibility for Indian researchers	Thematic thrust (relevant to crop optimisation and/or smart proteins)	Budget limit	Typical call window
ICAR–NASF	Open to researchers from Indian institutions within the National Agricultural Research System (NARS): ICAR institutes, State Agricultural Universities (SAUs), Central universities / other academic institutions, eligible R&D organisations (including some private/NGO partners in collaborative mode)	Biotechnology and genomics, abiotic/biotic stress and quality traits, precision agriculture and digital farming, post-harvest and value-addition technologies	Flexible and proposal-driven, varies by scope and network size	Pre-proposal calls released periodically (every ~1–2 years)
ANRF–Core Research Grant (CRG)	Indian academic/R&D institutions	Fundamental and applied research in plant science, crop improvement, food science	₹50–80 lakh for 3 years	Usually August–October
ANRF–Prime Minister's Early Career Fellowship (PM-ECRG)	Early-career researchers in India	Plant and food biotechnology, crop improvement, nutrition	₹1.5–2 Crore for 3–5 years	August–October

DBT–Thematic calls (biotech/crop science/food tech)	Indian researchers in DBT-recognised institutions	Protein-rich crops, trait enhancement, biotechnological interventions, functional foods	₹50 lakh–2 Crore	Rolling (March–September are most active)
BIRAC–Grand Challenges India & thematic calls	Academia, startups, industry in India	Agri-biotech, smart proteins, crop optimisation for biomanufacturing	₹50 lakh–₹2 Crore	2–3 cycles per year
Bilateral: DBT–UKRI (India–UK Partnerships)	Joint proposals with UK institutions	Crop genomics, biofortification, protein-rich crops, resilience	Typically £1M (shared)	Variable call window
Bilateral: DBT–NSF (India–US)	Joint proposal with U.S. PI	Plant biotechnology, nutrition, agri-food resilience	$300K–500K per side	Once in 2 years
Bilateral: DBT–DFG (India–Germany)	Collaborative projects with German labs	Plant sciences, functional crop traits	~€150K–200K per side	Annual (April–June)
USAID – Development Innovation Ventures (DIV)	Open globally (India eligible)	Scalable agri/food innovations (protein crops, farmer adoption)	$200K (Stage 1), $1.5M (Stage 2), $15M (Stage 3)	Rolling, year-round
Grow Further (Nonprofit)	India-specific eligibility (ICAR, universities, CGIAR, NGOs with FCRA)	Farmer-focused protein crop R&D, legumes, millets, biofortification	$10K–$100K/ year (2–5 yrs)	Annual (EOI early in year)

SreePVF–Translational Agriculture Grants	Indian researchers/consortia	Field validation of protein-rich crops, value-chain pilots	Up to ₹50 lakh + farmland access	Annual (prelims open January–March; awards later in year)
Novo Nordisk Foundation–Plant science, agri & food biotech grants	International, Indian PIs eligible through host institutions	Functional protein traits, sustainable agri-biotechnology	DKK 2–10M (~₹2.4–12 Cr)	Annual, deadline ~August
EIT Food (EU)	Requires an EU partner; Indian labs can join via consortium	Crop optimisation for alternative protein ingredients, food innovation	€100K–500K (co-funded, depends on track)	Multiple windows (spring/summer)
Horizon Europe–Cluster 6 (Food, Bioeconomy, Agriculture)	Indian institutions eligible as international partners	Crop diversification, sustainable proteins, functional foods	€2–5M (consortium projects)	Annual work programmes (spring)
Foundation for Food and Agricultural Research's (FFAR) Crop-Animal Systems RFA	Open to international institutions	Crop-animal systems integration, resilience	$300K–$1M per project; total pool up to $4M	Pre-application stage: April–June; Full proposals due: September; Awards: Mid-next year

Annexure 4

Crops with potential ingredient applications in plant-based meat, egg, and dairy products

Crop	Potential ingredient applications
Chickpea (*Cicer arietinum*)	Protein isolates/concentrates (plant-based meat), aquafaba for foaming applications (plant-based egg), and emulsification (plant-based dairy)
Pigeon pea / Toor dal (*Cajanus cajan*)	Protein source for plant-based meat, texturised proteins, savoury flavour base
Green gram / Mung bean (*Vigna radiata*)	High-functionality protein for plant-based egg (gelation, emulsification) and plant-based dairy
Black gram / Urad bean (Vigna mungo)	Protein for plant-based egg (foaming, binding) and fermented plant-based dairy
Horse gram / Kulthi (*Macrotyloma uniflorum*)	Protein concentrates for plant-based meat, fibre-protein blends
Cowpea/ Lobia (*Vigna unguiculata*)	Protein isolates for plant-based meat and plant-based dairy
Lentil / Masoor (*Lens culinaris*)	Protein isolates or concentrates for plant-based meat and fermented plant-based dairy
Rice / Chawal (*Oryza sativa*)	● Hypoallergenic protein source for plant-based dairy products ● Starch for thickening dairy alternatives, binding in plant-based meat ● Colourant in fermented plant-based dairy (black rice)
Coconut (*Cocos nucifera*)	● Saturated fat for plant-based dairy (butter, cheese), creaminess, melt behavior in plant-based meat products ● Fermented plant-based dairy (yogurt, kefir-style products) ● Dairy-Like flavour enhancers ● Fatty and creamy flavour for applications in plant-based dairy and plant-based meat products

Sesame / Til (*Sesamum indicum*)	Oil for mouthfeel, fat phase in plant-based dairy, flavour
Groundnut / Peanut (*Arachis hypogaea*)	Fat and protein for plant-based dairy (milk, yogurt), emulsified fat systems
Mustard (*Brassica juncea*)	Oil for savory fat systems in plant-based meat, flavouring
Niger seed / Ramtil (*Guizotia abyssinica*)	Specialty oil for fat structuring, nutritional lipid source
Finger millet / Ragi (*Eleusine coracana*)	• Starch and fibre for texture, nutritional fortification • Fermented bases for plant-based dairy with improved digestibility
Sorghum / Jowar (*Sorghum bicolour (L.) Moench*)	• Starch for extrusion, structure of plant-based meat • Fermented bases for plant-based dairy with improved digestibility • Colourant in plant-based meat products (raw-to-cooked colour)
Pearl millet / Bajra (*Pennisetum glaucum*)	• Starch and fibre for meat textures and dairy viscosity in plant-based alternatives • Fermented bases for plant-based dairy with improved digestibility
Little millet (*Panicum sumatrense*), Foxtail millet (*Setaria italica*), Kodo millet (*Paspalum scrobiculatum*)	• Clean-label starches, fibre-rich texture modifiers • Fermented bases for plant-based dairy with improved digestibility
Cassava / Tapioca (*Manihot esculenta*)	Starch to achieve elasticity in plant-based cheese, binding in plant-based meat
Psyllium husk (*Plantago ovata*)	Gelling, binding, moisture retention in plant-based meat and egg
Cluster bean / Guar (*Cyamopsis tetragonoloba*)	Guar gum for thickening plant-based dairy, stabilising emulsions

Fenugreek (*Trigonella foenum-graecum*)	• Soluble fibre for emulsification, mouthfeel, binding in plant-based egg • Savoury, slightly bitter flavour, umami-enhancing for applications in plant-based cheese, butter, and cultured dairy
Jackfruit (*Artocarpus heterophyllus*)	Texture and anisotropic structure in whole-muscle plant-based meat
Banana – raw (*Musa* spp.)	Starch and fibre for binding, plant-based dairy texture enhancement
Turmeric (*Curcuma longa*)	• Natural yellow colourant in plant-based eggs (yolk colour), cheese, butter, and ghee • Widely accepted, heat-stable
Annatto (*Bixa orellana*)	• Colourant in plant-based cheese, butter, • Neutral flavour • Used in plant-based dairy products globally
Rhododendron (*Rhododendron arboreum*)	Red colourant in plant-based meat