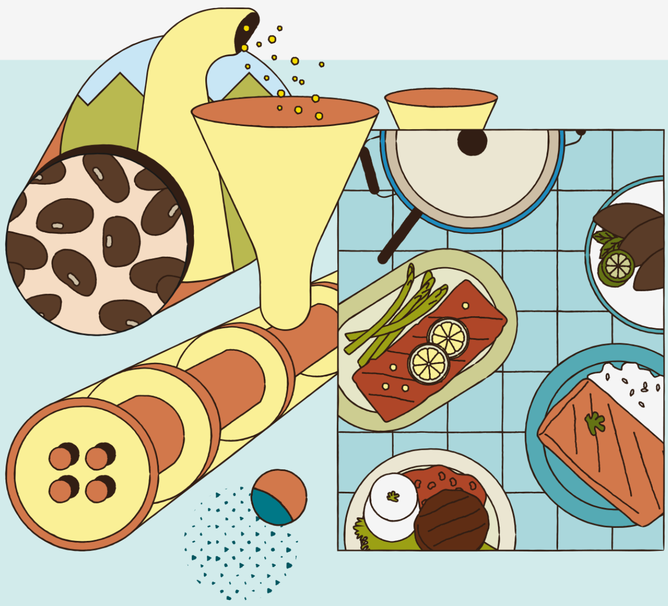
Beans Technical Forum Report

Boosting the potential of beans in plant-based products: strategies and opportunities

Plant-based chicken - Incrível!



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The Good Food Institute is a non-profit organization working globally to accelerate innovation in the alternative protein market. We believe that the transition to a more sustainable food system is fundamental to addressing the climate crisis, decreasing the risk of zoonotic diseases, and feeding more people with fewer resources. That is why we collaborate with scientists, investors, entrepreneurs and government agents to develop plant-based, cultured, or fermentation-enabled food products.

Our work is focused on three main areas:

In **Corporate Engagement**, , we support companies of all sizes to develop, launch, and market alternative protein products, offering tools that assist startups and entrepreneurs in their business strategies. We also provide market intelligence to help companies make decisions, conducting research to identify and overcome challenges.

In **Science and Technology**, we fund cutting-edge research on alternative proteins, foster collaboration between scientists, companies, and governments, publish data and findings to drive scientific progress, and design educational programs to build the capacity of the next generation of leaders in alternative proteins.

In **Public Policies**, we advocate for public policies that support the development and marketing of alternative proteins, work with governments to create a favorable regulatory environment, educate the public about the benefits of alternative proteins, monitor the political landscape, and defend the interests of the sector.

With this work, we seek solutions to:

- Safely, equitably and sustainably feed nearly ten billion people by 2050;
- Contain climate change caused by the current food production system;
- Create a food production chain that does not depend on animals;
- Reduce the contribution of the food sector to the development of new infectious diseases, some of which with pandemic potential.

In almost 10 years of operation in Brazil, GFI has already helped the country to become one of the main players in the global plant-based protein market. The goal is to continue conducting this work to transform the future of food, promoting new protein sources and offering alternative proteins analogous to animal-based proteins.

Disclaimer

The strategic guidelines and research opportunities presented in this report were established by The Good Food Institute Brasil by systematizing the technical contributions collected during all stages of the Beans Technical Forum held between February 2024 and August 2025. This process included a structured technical form, an online meeting with experts from academia and industry, and one-on-one interviews with strategic stakeholders. Although this report systematizes challenges and opportunities based on technical insights from experts, there was no systematic consideration of the feasibility of implementing the solutions discussed.

In this report, the GFI had the role of surveying, consolidating, and systematically distributing insights from reliable sources, and the topics listed here are not investment recommendations, but rather a means of sharing technical information. Possible projects that derive from this knowledge shared by GFI must undergo further technical assessment, with rigorous analysis of commercial, regulatory and logistical feasibility of each alternative before investment decision-making.

Contents

1. Introduction

The Good Food Institute (GFI), a global organization dedicated to the advancement of alternative proteins, has promoted and fostered the development of plant-based ingredients for application in plant-based products through scientific research, coordination with industry, and funding programs in Brazil and abroad. Among the various possibilities of plant-based raw materials with potential to meet the growing demand for plant-based products, beans are notable as a promising ingredient, alongside more established alternatives such as soybeans and peas.

Beans have several positive attributes when compared to soybeans and peas, such as a consolidated national production, lower dependence on imports, competitive cost, good agronomic adaptation, and higher acceptance among allergen-sensitive consumers. In addition, the diversity of species and functional profiles enables a wide adaptation to different productive settings, favoring its inclusion in public policies for food and family farming. From a nutritional perspective, beans are noted for providing good quality proteins, fibers, micronutrients and bioactive compounds that are relevant to health and a moderate energy value. Additionally, beans are noted for sustainability attributes, such as low carbon footprint, improved soil quality and reduced dependence on inputs. Their diversity of colors, textures and flavors expands possibilities of formulation in innovative products, including plant-based products. Finally, the cultivation of beans reinforces the role of family farming and contributes toward the development of the regional bioeconomy, being aligned with food and nutritional security policies and strengthening its strategic relevance for both the market and society.

In recent years, GFI has supported strategic studies focused on the sensory, technological and functional evaluation of beans, such as the **Carioca Bean Project with** EMBRAPA, the Cowpea Dry Fractionation Project with Neuman & Esser (NEA) and the Federal University of Santa Catarina (UFSC), the **Sensory Improvement Project** with UFSC and the **Mung Bean Study** conducted by GFI APAC. In these initiatives, beans have been repeatedly pointed out by experts as a legume with high potential for application in plant-based products, due to their wide availability, high protein content and nutritional balance. However, their large-scale application still faces relevant technological challenges, such as the presence of off-flavors (e.g. beany flavor, bitterness and/or astringency), the presence of antinutritional factors, full use of the bean (hull, protein fraction and starch) and functional limitations, which require advances in processing and formulation to increase their competitiveness in plant-based products.

In this context, beans are positioned as a strategic alternative to expand and diversify the industry's portfolio of plant-based ingredients, especially considering the growing search for productive autonomy, improved sensory solutions and cost reduction. However, full leverage of this potential still requires coordinated research and development (R&D) to address the current technological challenges. This document contains priority R&D strategies and opportunities focused on the technological exploitation of beans, considering dry, wet and hybrid processing routes and emerging technologies, consistently with the demands of the alternative protein production chain. In addition, it offers a comprehensive overview of the ingredient, systematizing technical, functional, nutritional and sustainability data and potential applications in plant-based formulations.

2. Brazilian Beans: An Ingredient with Disruptive Potential

Beans are undoubtedly one of the most traditional staple foods of the Brazilian diet. Far beyond their cultural and nutritional relevance, they have functional and ecological properties that qualify them as a potential candidate for transformation into a high-value ingredient for plant-based products in Brazil.

2.1. Nutritional Composition

From a nutritional perspective, beans are notable for providing good quality proteins, fibers, micronutrients and bioactive compounds that are relevant to health and a moderate energy value, mainly from complex carbohydrates (formed by long chains of sugars that are digested more slowly, providing energy gradually and favoring higher satiety). Their varied composition enables them to complement other food sources and meet the demands of a balanced diet. Below, we present their main nutritional characteristics.

- **Proteins:** On a dry basis, beans have around 20–25% protein. Among the main *Phaseolus vulgaris* cultivars (carioca, black, pinto/red), contents are usually in the range of 21–24%. While cowpea (*Vigna unguiculata*) and some other varieties tend to have higher content values, 24–27%, with variations by environment, soil and post-harvest (Domene *et al*., 2021).
- **Amino acids:** Beans have a high content of lysine and arginine; on the other hand, they have a low concentration of sulfurized amino acids, especially methionine, requiring supplementation with cereals in the meal.
- **Dietary fibers**: In dry beans, the total dietary fiber content ranges from 18–30% of the mass, being composed of insoluble fractions (cellulose and lignin) and soluble fractions (pectins and gums). Insoluble fibers promote bowel movement, while soluble fibers contribute to the modulation of blood glucose and serum cholesterol levels. As they are rich in complex carbohydrates and also a good source of protein, beans have a low glycemic index, favoring the maintenance of satiety and metabolic balance (Domene *et al*., 2021).
- **Resistant starch:** Resistant starch is the starch fraction that is not absorbed in the small intestine, reaches the colon and is fermented by the microbiota, acting as a component of dietary fiber with a prebiotic effect and generating short-chain fatty acids. In beans, its content varies according to the cultivar and processing, and cooking tends to reduce it, while cooking-cooling cycles (storage under refrigeration) favor retrogradation (Bozkir *et al*., 2023; Fabbri; Schacht; Crosby, 2016).
- **Oligosaccharides:** In beans and other legumes, the most common oligosaccharides are raffinose and stachyose. These non-digestible carbohydrates area intact when they reach the colon, where they are fermented by the intestinal microbiota, a process associated with the production of gases (flatulence). Despite that, their fermentation also contributes to beneficial effects, such as the formation of short-chain fatty acids (Leterme, 2002; Messina, 2014).
- **Energy value**: Beans have an average energy value of around 329 kcal per 100 g of dry beans. In traditional Brazilian diets, the average daily consumption of beans reaches 21 g per person, providing about 3% of the energy supply in the diet (Domene *et al*., 2021). Energy comes mostly from complex carbohydrates, starch and resistant starch, as well as small amounts of non-starch polysaccharides.
- **Micronutrients**: The main minerals noted are potassium, phosphorus and magnesium, in addition to calcium, iron, zinc and manganese. In smaller amounts, copper and selenium, and sodium at very low levels. As for vitamins, B complex vitamins predominate, especially thiamine and folate, in addition to niacin and vitamin B6, with riboflavin present in smaller amounts; traces of vitamin C may occur according to variety and processing (TBCA, 2023).

- **Bioactive compounds**: They include polyphenols, phytates, saponins and tannins that, in general, act as anti-nutritional factors, hindering the digestibility of proteins and the bioavailability of minerals, in addition to influencing sensory quality (e.g., astringency perception). However, they also have beneficial functional effects, such as antioxidant, anti-inflammatory, and lipid metabolism regulatory action.

2.2. Production, Consumption and Sociocultural Importance of Beans in Brazil

Beans play a central role in the Brazilian diet, both due to the wide availability and diversity of cultivars and their daily presence in the population's diet. In addition to their nutritional value, beans have strong cultural symbolism, being one of the pillars of Brazil's national food security. The following are data on the most consumed types, production and their sociocultural importance.

- **Types of beans:** About 80% of the beans consumed in the country are common beans (*Phaseolus vulgaris*) and 20% correspond to cowpea (*Vigna unguiculata*). Within the common bean category, 56% are of the carioca type, 21% of the black type and 3% are classified as special types (Wander; Silva, 2025).
- **Per capita consumption:** In 2023, the average national consumption was approximately 12.8 kg per inhabitant (Wander; Silva, 2025), evidencing their relevance as a regular component of the Brazilian diet.
- **Diversified and wide production:** National production is distributed in three harvests and grown in several biomes (Coêlho; Ximenes, 2020), which ensures continuous supply and resilience of the production system. In 2023, Brazil consolidated as the second largest bean producer in the world, behind only India, reaching 2.9 million tons, which represents 10.2% of global production (Embrapa, n.d.).
- **Available genetic diversity:** At least 20 cultivars of carioca beans (Melo *et al.*, 2025), 14 of black beans (Pereira *et al.*, 2025) and 34 of cowpeas (Rocha, 2021) have already been officially registered in Brazil, reinforcing the potential for selection for different climatic conditions, management and consumption profiles.
- **Culturally rooted:** Beans are a food with high cultural acceptance, incorporated into the popular taste, constituting a comparative advantage for formulations aimed at the national market.
- **Role in food and nutritional security:** Beans play a central role in Brazilian food and nutritional security, both for their nutritional and cultural qualities and for their inclusion in public food programs, contributing toward reducing hunger, supporting family farming and reinforcing food sovereignty (Chaves *et al.*, 2024).
- **Economic and commercial aspects:** Brazil reached record bean exports, with 400,000 tons exported in 2024, resulting in a revenue above R$ 2 billion in the period (Agro Estadão, 2025). Despite this result, the country still is not among the main global exporters, since much of the production is allocated for the domestic market (Embrapa, 2021).

2.3. Crop Sustainability

Bean cultivation has important environmental advantages compared to other crops, such as low carbon footprint, improved soil quality and reduced dependence on inputs. These characteristics make beans a strategic legume for low-impact agricultural systems and regenerative management practices. The points below detail their key sustainability attributes.

- **Low carbon footprint:** Legumes in general have lower greenhouse gas emissions due to biological nitrogen fixation (BNF) and low use of synthetic fertilizers, favoring agroecological and organic systems and reducing production costs.

- **Potential for regenerative management:** Recent studies show that legume-intercropping cultivation systems increase soil organic matter and nitrogen content, can reduce CO_2 and N_2O emissions by 28% and 71%, respectively, and contribute toward increased productivity (Liu *et al.*, 2024, Mirzaei *et al.*, 2025).
- **Adaptation to different systems and regions:** Beans are grown in all Brazilian biomes, from technified agriculture to family systems, and can integrate rotations and intercrops that contribute to the diversification of agricultural landscapes.
- **Contribution of family farming:** Family farming is responsible for at least 42% of Brazil's national bean production (Conafer, 2022), a segment that historically adopts practices with low environmental impact and contributes to local food security.
- **Compatibility with low-input agriculture:** BNF enables reducing or eliminating nitrogen fertilization, reducing Brazil's dependence on imported inputs and favoring the reduction of production costs. In 2017, Brazil saw BNF providing savings estimated at US$ 119 million for common beans, US$ 59 million for cowpeas, and US$ 6 million for mung beans (Telles *et al.*, 2025). As for productivity, the adoption of BNF in bean crops enables achieving yields of up to 3,000 kg/ha (Embrapa, 2014).

2.4. Beans as a Strategic Candidate for Application in Plant-based Products

The above discussed nutritional, cultural and environmental qualities of beans reinforce their position as a key ingredient for formulations of plant-based products. Their competitive protein content, combined with high cultural acceptance in Brazil and wide agricultural availability, provide unique advantages over other legumes. In addition, their contribution to low-impact production systems increases attractiveness in a global market that is increasingly aware of sustainability. Therefore, beans constitute one of the most promising crops for the development of high value-added ingredients for plant-based products. At the same time, considering the broader role of plant-based products in the transformation of food systems, notable benefits include:

- **More efficient food:** Plant-based products, produced from legumes, can reduce water consumption by 93%, land use by 91% and mitigate 94% of greenhouse gas emissions compared to their animal-based counterparts (Earthshift Global; Good Food Institute, 2024).
- **A climate solution:** Of the 26 most promising interventions to mitigate emissions in the agri-food sector, alternative proteins were ranked second by the World Bank, behind only reforestation (World Bank, 2024).
- **Alternative that drives the economy:** The transition to alternative proteins is estimated to have the potential to create 83 million new jobs and generate US$ 686 billion in Gross Value Added (GVA) for the sector by 2050 (ClimateWorks Foundation, 2023).

3. Beans Processing for Application in Plant-based Products

The use of beans as a base for plant-based products goes beyond simple application as a bean or flour. To transform it into a functional ingredient, it is essential to master different technologies to isolate, modify and structure their proteins, providing appropriate properties for the development of new foods. These processes influence not only the final composition, but also the sensory, nutritional and technological quality of the ingredients.

In this section, we present the main methods for obtaining and modifying bean proteins, noting how each technology impacts their industrial potential and features. Next, we describe the different types of resulting ingredients, flours, concentrated, isolated, hydrolyzed and textured proteins, with their features, applications and limitations. We also discuss challenges such as digestibility, antinutritional compounds, off-flavors and scaling-up, in addition to providing examples of technological routes under development by universities, research centers, startups and companies in Brazil. By integrating ongoing processes, ingredients and solutions, we seek to support the construction of a national chain of bean-based ingredients with high functional, sensory and sustainable value, boosting the technical and economic viability of their application in plant-based meat and other plant-based food products.

3.1. Obtainment, Modification and Structuring Processes

In the case of beans, different industrial processes enable obtaining protein ingredients through various technological routes, which can concentrate, isolate or modify their proteins. Each of these routes has its own characteristics in terms of complexity, yield, cost and impact on nutritional, sensory and functional quality. In addition to enabling extraction, many of these processes also enable modifying or structuring proteins, adjusting their nutritional, technological and sensory properties to the most diverse applications and expanding their industrial relevance. In practice, the chosen process depends on the type of ingredient desired, from simple flours to high purity isolates, the available infrastructure conditions and the industrial application profile. Among the main ones, the following are noted:

- **Grinding:** Process that reduces particle size by friction or impact and can be performed directly to obtain the final ingredient (whole flour) or as a preparatory step for subsequent processes, such as fractionation or texturing.
- **Dry fractionation:** Set of physical processes that are based on separation by density, size, shape and/or electrical charge, using air flow, mechanical friction or electrostatic fields. It does not use solvents or water, promoting sustainability and nutritional preservation.
- **Wet fractionation:** Set of processes that are mainly based on alkaline extraction and isoelectric precipitation steps under strict pH and temperature control. It may include additional operations (membrane filtration, salting in/out, drying) to adjust purity, stability, and functionality.
- **Hybrid fractionation:** Set of processes that combine the advantages of dry and wet fractionation, reducing anti-nutritional factors and improving the performance of proteins in formulations.
- **Enzymatic hydrolysis:** Set of biotechnological processes that use specific enzymes to produce smaller peptides, modulating solubility, emulsifying capacity, flavor and digestibility.
- **Low-moisture extrusion:** Thermo-mechanical process with low water content (10–30%), which provides extruded products (expanded, porous, with crunchy texture) from flours, concentrates and isolates.
- **High-moisture extrusion:** Thermo-mechanical process with high water content (50–80%), which results in dense and fibrous products, with long and juicy fibers, with a texture similar to meat muscle fiber.

- **Fermentation**: Used to improve the sensory profile (reduction of off-flavors) and enrich the nutritional value.
- **Enzymatic crosslinking**: Promotes crosslinking between proteins, increasing the stability of emulsions, gels, and structured textures.
- **Assistive technologies (ultrasound, microwave and cold plasma)**: Processes to optimize yield, modify secondary structures and improve technological performance of isolates and concentrates.
- **Supercritical fluid extraction (SFE)**: It uses solvents such as CO_2 in a supercritical state to remove lipids and compounds responsible for off-flavors, in addition to modifying proteins in a clean and sustainable way.
- **Emerging structuring technologies: Electrospinning**, structured freezing, shearing and 3D printing provide new possibilities for textures, but are still in the validation phase.

📌 NOTE: Processes such as supercritical fluid extraction, enzymatic hydrolysis and extrusion exemplify how protein obtainment and modification operations can directly produce final ingredients or serve as tools to adjust functional and sensory properties depending on the intensity and time of application. This integrated approach enables the industry to plan flexible routes, combining extraction, purification and modification steps in chains optimized for cost, yield and functionality, fostering the creation of higher value-added ingredients.

TECHNOLOGICAL POTENTIAL AND SCALE-UP BARRIERS

Emerging technologies provide new possibilities; however, their industrial-scale adoption still faces challenges. In Brazil, the main bottlenecks are:

- Shortage of pilot plants and centers with infrastructure for scaling-up;
- High cost of acquisition and operation of equipment;
- Need for specialized technical training;
- Retrofitting and adaptation of production lines to integrate technologies.

Commercial viability will depend on the development of testing and prototyping infrastructure, in addition to incentive policies and partnerships between industry, academia and government, capable of transforming innovations into scalable and competitive solutions.

3.2. Types of Protein-Based Ingredients

The processes described above can provide different types of protein ingredients, each with specific properties and potential applications. This subsection presents the main categories, flours, concentrated, isolated, hydrolysed and textured proteins, highlighting their processes, average protein contents, technological features and uses in food formulations (Table 1).

Table 1 – Bean-Based Protein Ingredients: Processes, Features and Applications

Ingredient type	Protein content (%)*	Process(es)	Technological features	Potential applications
Whole flour	20–25%	Grinding (with or without prior peeling) of dried beans.	Fiber and protein source, water absorption capacity, increased viscosity and body in formulations.	Bakery, whole snacks and extruded products with fiber content.
Starchy flour	8–15%	Grinding (with or without prior peeling) of dried beans followed by dry fractionation or by-product generated during wet fractionation.	Thickening, low sensory interference (neutral color and flavor).	Bakery, pasta, soups, sauces and gluten-free cookies, giving viscosity and structure to the formulations. It can be used as a source of carbon and nitrogen in fermentations for the production of alternative proteins.
Protein concentrate	50-70%	Grinding (with or without prior peeling) of dried beans followed by dry or wet fractionation.	Emulsifying capacity, gel formation and water retention.	Enrichment of breads, pasta and cereal bars, use in textured protein formulations, alone or combined with soy isolate or concentrate. Partial replacement of soy protein isolate or concentrate in plant-based meat and application in snacks and other plant-based food products.
Protein isolate	> 70%	Grinding (with or without prior peeling) of dried beans followed by wet or hybrid fractionation.	High solubility, emulsifying capacity, foaming.	Plant-based protein beverages, yogurts and desserts,plant-based meat, egg substitutes in bakery and confectionery. Often applied in salty products or in formulations in which sodium content can be adjusted to optimize taste and sensory acceptance.
Protein hydrolysate	70–85% (varies according to degree of hydrolysis)	Protein isolate or concentrate submitted to controlled enzymatic hydrolysis.	Rapid solubility, release of free amino acids, low viscosity.	Protein beverages, enteral formulas, flavor enhancers, broths, sauces. It can also be used as a source of amino acids in culture media for the production of cultured meat.
Textured protein	50–70% (varies according to formulation and addition of other proteins such as soy isolate or concentrate)	Extrusion (low- or high-moisture extrusion) through isolates, concentrates, flours, or combinations thereof.	Fibrous structure, chewability, water and fat retention capacity, meat-like appearance.	Plant-based meat (burger, ground beef, strips, chicken substitutes), fillings.

* Technical note: The protein contents presented in this table are average estimates obtained based on data from the scientific literature and information made available by ingredient manufacturers, research centers and technical-scientific institutions. To date, there is no universal or national regulatory standardization for exact classification between the different types of protein ingredients.

3.3. Production of Plant-based Meat

The production of plant-based meat involves processes that give the protein ingredients structural, sensory and functional properties comparable to those of animal meat. This step is essential to provide fibrous texture, juiciness and chewiness characteristics, which are determinant for consumer acceptance. The most consolidated routes include the production of TVP (Textured Vegetable Protein) and fillet-type plant-based meat.

3.3.1. Production of TVP (Textured Vegetable Protein)

The production of TVP is mainly intended for the formulation of reconstituted products, but it can also be consumed directly as plant-based “ground beef” or in ready-made preparations. Traditionally, soybeans are the main raw material used in this process, but, recently, peas have also started to gain momentum. Similarly, beans arise as a relevant alternative, fostering the diversification of raw materials.

The process begins with the protein base, which can be composed of flours, concentrates or isolates of beans, used alone or combined with other plant sources to optimize functional and nutritional properties. The adjustment of moisture and additives occurs before extrusion, when the protein mass is hydrated until it reaches water contents between 10 and 30%. In this step, functional additives may be incorporated for the purpose of improving the stability, texture or processability of the mixture.

The central step of the process is low-moisture extrusion texturing, performed in single or twin screw extruders. During this procedure, food matrix proteins undergo denaturation and structural reorganization. In the final phase of the process, rapid pressure decrease and instantaneous evaporation of water causes the product to expand and solidify, forming a porous and expanded structure. During cutting, the mass is molded into pellets or blocks, adjusted in size and shape according to the final application.

To ensure stability and extended shelf-life, the product undergoes a drying step, responsible for removing residual moisture. The result is dehydrated TVP, a versatile ingredient that can be rehydrated and applied in different formulations, such as burgers, meatballs, fillings, pasta and ready-made dishes. In addition, TVP can serve as a basis for the development of ready-to-eat products, such as sauces (e.g. vegetable bolognese), frozen prepared dishes and ready meals, expanding its market potential.

3.3.2. Production of Fillet-type Plant-based Meat

The main objective of fillet-type plant-based meat is to reproduce cuts of meat with a fibrous texture, high succulence retention and differentiated chewability.

The process begins with the protein base, which can be composed of a single ingredient or by combining different plant sources. Currently, soybeans are the most used raw material, followed, more recently, by peas, which have been gaining momentum in the market. Beans, in turn, arise as a strong candidate, providing potential for ingredient diversification, nutritional improvements and valorization of crops that are widely available in Brazil. The adjustment of moisture and additives occurs before extrusion, when the mixture is hydrated to reach high water contents, ranging from 50 to 80%, and enriched with oils, fibers and aromas. These components contribute to improving the juiciness, texture and sensory acceptance of the final product.

The central step of the process is high-moisture extrusion texturing, performed in twin-screw extruders. This process uses controlled heating and cooling zones that promote protein alignment and fibrillation, forming a fibrous network that is close to the structural organization of animal meat.

After this step, there is forming and cutting, in which the extruded mass is continuously molded into the desired shapes, such as fillets, strips or cubes, preserving the integrity of the internal fibrous network. The final product is a wet extrudate, which has texture and juiciness that are similar to those of meat. These can be sold as they are, usually in chilled or frozen form, or in marinated form, ready for immediate preparation, serving both industrial applications and final consumers.

3.4. Technological Challenges

Although promising, the use of beans in plant-based meat still faces relevant limitations:

- **Antinutritional compounds:** Beans contain several antinutritional compounds, such as protease inhibitors (e.g. trypsin), lectins, tannins, saponins and phytates. These compounds can reduce the digestibility and bioavailability of minerals such as iron, zinc, and calcium. However, these compounds can be significantly reduced by:
    - Heat treatments (such as cooking and extrusion);
    - Controlled fermentation;
    - Germination.

  📌 These techniques not only reduce antinutritional compounds, but can also improve the sensory and functional profile of proteins. In addition, the use of peeled beans can be prioritized, as the peel concentrates both phenolic compounds related to bitterness and astringency and antinutritional compounds that affect mineral absorption.

- **Off-flavors**: One of the main sensory challenges is the presence of volatile compounds responsible for undesirable flavors and aromas, often described as earthy, bitter, astringent, metallic or "green." Hexanal (green, *beany* aroma) is noted as one of the most characteristic markers of common beans (*Phaseolus vulgaris*), in addition to other volatiles such as (E)-2-hexenal and 1-octen-3-ol. These off-flavors mainly result from the oxidation of unsaturated fatty acids catalyzed by the action of lipoxygenase, producing aldehydes, alcohols and ketones. Phenolic compounds and tannins also contribute to bitter and astringent notes. Mitigation techniques include:
    - Enzyme inactivation;
    - Fermentation with crops that degrade undesirable compounds;
    - Encapsulation or masking with natural aromas;
    - Selective extraction of oxidized lipids (e.g. washing with ethanol).

  📌 Controlled fermentation with specific microorganisms emerges as one of the most promising strategies to reduce off-flavors and improve sensory acceptance. Prioritizing peeled beans is also an effective measure to reduce both the volatile aroma compounds responsible for the "beany flavor" and the antinutritional compounds present in the peel, thus contributing to more sensorily and nutritionally balanced formulations.

- **Digestibility and protein quality:** In relation to proteins, beans have good lysine content, but values are limited in methionine and cysteine, which reduces protein quality compared to animal proteins and soybeans. In addition, compounds such as phytates, tannins, and digestive enzyme inhibitors can hinder digestion and decrease nutrient absorption. The digestibility of bean proteins is considered moderate, with PDCAAS (Protein Digestibility Corrected Amino Acid Score) values between 0.6 and 0.7. These values are lower than sources like soy and wheat, but they can be optimized by:
    - Enzymatic hydrolysis, which can release bioactive peptides and increase bioavailability;
    - Fermentation with fungi and bacteria, which can degrade complex proteins and antinutritional compounds of beans, and also add microbial protein, which can complement the amino acid profile;
    - Combination with other protein sources (e.g. rice, quinoa or soybeans), as it enables complementing profiles of limiting amino acids, such as methionine.

- **Technological features:** Compared to widely studied sources such as soybeans and wheat, bean proteins remain relatively unexplored in terms of functional characterization. Technological modification and exploitation strategies, although promising, still lack specific and systematic studies focused on beans, especially considering their particular composition and the high variability between cultivars. A deeper understanding of these features is essential to broaden their use in applications with more complex functional requirements.

- **Intermediate-level scale-up:** The lack of accessible pilot plants in Brazil limits the practical validation of wet and hybrid processes before industrial scale-up. Currently, the chain operates between bench results and industrial structures designed for soybeans, which are not suitable for beans in terms of the minimum volume required. Operating in these facilities would require much higher quantities of raw material than what is normally available for research and development, which makes testing more expensive and unfeasible. This infrastructure gap is one of the main bottlenecks to transform scientific advances into competitive solutions, hindering the evolution of the ingredient in commercial applications.

3.5. Solutions under Development in Brazil

Brazil has relevant initiatives in the development of bean-based protein ingredients with high functional and sensory performance, which can contribute to reduce dependence on imports, foster local innovation and expand the supply of plant-based products produced in the country. The following are some examples of projects and solutions already in progress:

- **EMBRAPA Food Technology**, in a project led by Dr. Caroline Mellinger, with funding from GFI US, developed a set of strategic studies on carioca bean proteins. The studies address the functional and technological characterization of the concentrates, the nutritional comparison with commercial ingredients from other legumes, and the processes for obtaining new protein ingredients. The results reinforce the potential of beans as a strategic source of plant protein. The expectation is that, with the availability of equipment on a pilot scale, it will be possible to advance to intermediate tests that enable expanding their commercial application in the food industry.
- The **ProVerde** startup, with support from FAPESP, developed a fermented bean concentrate without use of water, with gains in flavor and digestibility.
- The ***BeanPossible*** startup**,** with support from FAPERP, using sustainable raw material and national, integrated and science-based technology, produced three bean-based ingredients for the food industry: concentrated protein, insoluble fiber and starch.
- **SL Alimentos** markets several bean-based ingredients. They include: black or carioca bean flour, obtained by grinding the grains of black or carioca beans (*Phaseolus vulgaris* L.); cowpea flour, produced by peeling and grinding cowpea beans (*Vigna unguiculata* L.); textured protein, prepared with the combination of concentrated proteins from peas, beans, oats, soybeans or the mixture between them; and concentrated cowpea protein, obtained by peeling and grinding cowpea beans (*Vigna unguiculata* L.), followed by an aeroclassification process.
- Within the scope of the **Cowpea Dry Fractionation Project with NEA and UFSC**, an initiative of the GFI aimed at integrating farmers into the alternative protein sector, a pilot test was conducted to evaluate the potential of cowpea beans (*Vigna unguiculata*) in plant-based meats and explore viable processing methods for rural properties and cooperatives. The beans, donated by LC Sementes, were processed by the Neuman & Esser (NEA) company using dry fractionation and then sent to the Federal University of Santa Catarina (UFSC), under the coordination of Prof. Acácio Antonio Ferreira Zielinski, for functional and nutritional analyses of the ingredients obtained.
- GFI Brasil released a call for proposals entitled "Study to identify technological routes to obtain bean proteins with improved sensory and nutritional aspects." The selected proposal is coordinated by the **Federal University of Santa Catarina (UFSC)** and focuses on improving the sensory and nutritional quality of bean protein.

- A **UFSC** doctoral thesis researched conventional methods and emerging technologies, such as ultrasound, microwaves and pressurized liquid extraction (PLE), to recover high nutritional and functional value proteins from the co-product of black beans. Among the approaches evaluated, PLE was notable for its efficiency and favorable environmental profile, with lower CO_2 emissions, lower energy consumption and reduced waste generation.
- **Embrapa Rice and Beans** researchers used the gene editing technique to eliminate two bean genes responsible for the production of oligosaccharides from the raffinose family, compounds that cause digestive discomfort and flatulence. The project, funded by CNPq, is in the phase of advancing generations to stabilize the characteristic and, in up to eight years, could result in the commercial launch of a new variety of beans with better digestibility and nutritional quality.
- A group of researchers from the **Federal University of Goiás (UFG)**, in partnership with **Embrapa Rice and Beans**, developed a **study to evaluate the functional and nutritional quality of flours from different common bean cultivars**. The results showed significant variation in nutritional composition, bioactive compounds and technological properties, indicating that the flours of aged beans have potential for application in various food products with functional and nutritional appeal.
- Researchers from the **Food Technology Department of the Federal University of Viçosa (UFV)** conducted a **literature review to evaluate the techno-functional and structural properties of bean proteins**. The study collects several current articles addressing desirable techno-functional properties and potential modifications for a wide range of applications in the food industry.
- An **article published** by researchers from the **State University of Campinas (Unicamp)**, in collaboration with the **University of Copenhagen**, noted bean protein as a promising alternative for the food industry. The study investigated the effects of dynamic high pressure (DHP) on carioca bean protein concentrate (CBPC), evaluating its structural, techno-functional and color properties. The results showed that DHP improves the solubility, foaming and emulsifying properties of CBPC, in addition to maintaining an attractive white appearance. These findings suggest that the technique can expand the use of CBPC as an ingredient in different food applications.
- Researchers from the **Federal Rural University of Pernambuco (UFRPE)** characterized for the first time the creole variety of **Fogo na Serra beans** (*Phaseolus vulgaris L.*), grown in the Southern Agreste of Pernambuco. The study evaluated the nutritional composition, color profile and phenolic and flavonoid contents. The group maintains active contact with the **Agronomic Institute of Pernambuco (IPA)**, which has a germplasm bank with a wide diversity of cataloged beans, reinforcing the importance of conservation and valorization of regional varieties for food diversification, nutritional security and biodiversity preservation.

These efforts converge to consolidate beans as a strategic ingredient in the alternative protein sector. Beyond providing technological solutions, they indicate ways for sustainable innovation, diversification of raw materials and valorization of an agricultural crop that is widely available in Brazil.

LEARN MORE: COWPEA BEANS

- **Evaluation of the technological potential of cowpea beans in the development of food products: an integrative review.**
- **Strategic Potential of Cowpea Beans as an Ingredient for *Plant-Based* Foods.**
- **Cowpea beans in Brazil: Production, genetic improvement, advances and challenges.**

4. Research and Innovation Opportunities for the Use of Beans in Plant-Based Products

The following opportunities were structured in a procedural format, reflecting the stages of the chain, from the pre-harvest stage to the application in the final product. This approach shows how science, technology and the market can be strategically integrated to enable the use of beans as a protein source in plant-based products.

4.1. Pre-harvest stage

At this stage, attention is focused on the development of cultivars that are more suited to industrial and nutritional needs, in addition to the adoption of sustainable agricultural practices. The pre-harvest phase is decisive to ensure that the beans reach the processing step with characteristics that maximize their use in ingredients and final products.

- **Genetic improvement**: Developing cultivars with improved industrial characteristics, such as higher protein content, less antinutritional factors and reduced off-flavors.
- **Diversity of cultivars**: Identifying cultivars with different attributes (flavor, technological features, peel color, digestibility).
- **Sustainable practices**: Fostering regenerative and integrated cultivation systems, connecting agricultural production to the demands of food chains with lower environmental impact.
- **Climate impact metrics:** Including climate impact metrics (carbon footprint, water efficiency) in the cultivar selection process.

Points to consider regarding viability and implementation:

Advances in pre-harvest not only increase agronomic efficiency, but also directly influence the cost and access to raw materials. More productive and adapted cultivars reduce the cost per ton, while the diversity of cultivars can be leveraged to differentiate products in the market, reinforcing the positioning of beans as “Brazil’s protein.” However, it is important to consider that gains in protein content can imply losses in agricultural productivity; therefore, it is essential to assess economic viability and structure incentive models or differentiated remuneration to foster the adoption of cultivars with specific industrial characteristics. It is also important to understand whether the new cultivars will require segregated processing, storage and transport to avoid mixing with other grains since this can imply relevant cost increases for the ingredient. In addition, including family farmers in this process expands the supply base and strengthens social impact and food sovereignty. Finally, sensory characteristics, such as peel color and flavor, should be considered at this stage, as they determine not only technological performance, but also consumer acceptance of final products.

4.2. Harvest and post-harvest stages

After cultivation, the harvest and post-harvest stages are crucial to preserve nutritional and functional quality, in addition to ensuring the standardization required by the industry. Investing in this phase means reducing losses, ensuring food safety and making consistent raw material available for different applications.

- **Drying and storage technologies**: Reducing post-harvest losses, preserving nutritional value and avoiding mycotoxin contamination.
- **Connection with cooperatives**: Structuring chains that integrate small producers, ensuring consistent supply to the industry. In addition to the development of decentralized post-harvest solutions (low-cost equipment adapted to cooperatives).
- **Reuse of post-harvest** waste: Reuse of bark in functional inputs (fibers, antioxidants, bioproducts).

Points to consider regarding viability and implementation:

Investments in drying and storage technologies are decisive not only to reduce losses, but also to create supply predictability and consistency, which are critical factors for economic viability and to overcome scale-up barriers. In addition, integrating cooperatives strengthens productive inclusion and contributes to more organized chains, which increases competitiveness both in the domestic market and in export potential.

4.3. Processing to Obtain the Ingredient or Final Product

The processing stage transforms beans into higher value-added ingredients through different technological routes. Processes such as dry, wet, hybrid fractionation, in addition to extrusion and fermentation, provide the creation of diversified ingredient portfolios, capable of meeting multiple market demands and applications.

Dry fractionation

- Ensure efficient bean peeling with equipment that preserves the endosperm.
- Optimize grinding and grading processes for greater process efficiency.
- Reduce anti-nutritional factors and improve digestibility through physical, enzymatic or chemical treatments.
- Value starchy flour as a co-product, leveraging applications in baking, snacks, functional products, fermentations for the production of alternative proteins and as a substrate for bioplastics or biodegradable packaging.

Wet fractionation

- Investigate targeted functional modifications (e.g., solubility, emulsifying and gelling capacity).
- Optimize the recovery of water and solvents, ensuring greater sustainability of the process.
- Develop isolates with differentiated sensory profiles, suitable for multiple applications.

Hybrid processes (dry + wet)

- Integrate advantages of the two routes to increase efficiency and diversify the ingredient portfolio.
- Exploit multiple value-adding flows: protein, starch, fibers and bioactive fractions.
- Compare costs and evaluate retrofitting scenarios in existing lines.
- Develop adaptive protocols for small and medium-sized plants (universities, cooperatives, startups).

Extrusion

- Produce textured proteins with fibrous properties similar to meat, adjusting process parameters such as pressure, humidity and temperature.
- Expand applications beyond analog meat, including snacks, expanded cereals and ready-to-eat dishes.

LEARN MORE: EXTRUSION

For more details on the extrusion process – one of the main techniques for texturing plant proteins –, watch the **video** produced by The Good Food Institute Brasil. In addition, for a more in-depth understanding of texturing, we recommend the specific class on the topic available in **the MOOC of The Good Food Institute Brasil**.

Fermentation

- Apply fermentation to modulate flavor, reduce off-flavors and improve digestibility.
- Produce fermented flavors, enzymes, bioactive compounds and blends to increase functional, nutritional and sensory value.

LEARN MORE: FERMENTATION

For more details on how fermentation can deliver solutions to the alternative protein sector and the potential of Brazil in the use of this technology, access the publication of The Good Food Institute Brazil entitled "**Fermentation in Brazil: the potential for the production of alternative proteins**," and the **Traditional**, **Biomass** and **Precision** Fermentation datasheets to know data and details of each approach of this technology. In addition, we recommend the specific class on the topic available in the **MOOC of The Good Food Institute Brasil**.

Exploring emerging technologies

- Identify research opportunities in emerging or already established technologies, but which are still little explored in the context of beans.
- Optimize the quality and functionality of plant proteins.
- Speed up the development of differentiated ingredients to increase competitiveness in the market.
- Apply 3D printing to create new custom shapes and textures.

Points to consider regarding viability and implementation:

The different processing routes are at the core of the differentiation strategy as they determine the range of ingredients that can be offered to the industry. This relates directly to scale-up and export potential, as bean isolates, concentrates, and textured proteins can meet the growing demand in markets looking for alternatives to soybeans. In addition, overcoming infrastructural limitations for extrusion, fermentation and emerging technologies in Brazil is an essential condition to make competitiveness viable. For these routes to become viable, it is urgent to develop open prototyping structures and pilot plants on an intermediate scale, capable of simultaneously serving academia, startups and industry. In this regard, we note the creation of shared pilot plant infrastructure in a consortium between academia and the private sector, reducing costs and expanding access, and the implementation of open innovation programs to reduce costs and risks of testing by the industry. These measures are considered indispensable to overcome the current infrastructure gap and transform scientific advances into competitive solutions for the market. To fully play this role, the tests and services offered need to have affordable costs, suited to the different profiles of universities and startups, ensuring that access is not restricted only to large players in the sector.

4.4. Application in Final Product and Market

In the final stage, the opportunities are concentrated on transforming the bean-based ingredients into products that reach the consumer. This involves technical and sensory validation on an industrial scale, market introduction strategies and communication initiatives that value beans as a cultural and nutritional asset.

- **Industrial validation**: Conduct pilot tests to prove technical and sensory performance of the ingredients in actual formulations.
- **Diversification of portfolios**: Develop bean-based plant-based meats and dairy, protein drinks and snacks.
- **Life cycle assessment:** Identify and measure the environmental impacts of new bean-based products compared to their animal-based conterparts.
- **Technical-economic analysis (TEA):** Evaluate the financial and productive viability of bean ingredients at different scales, identifying production costs, technological bottlenecks and minimum competitive selling price compared to animal-based conterparts.
- **Public procurement and school meals**: Incorporate bean ingredients into institutional food policies, generating nutritional and economic impact.
- **Storytelling and cultural identity**: Value beans as a Brazilian asset, creating authentic narratives that connect sustainability, health and food tradition.
- **Strategic investments**: Direct seed capital to startups and impact businesses, prioritizing solutions that generate social, nutritional and climate value.

Points to consider regarding viability and implementation:

The opportunities for application in the final product demonstrate how technical advances can translate into market value. Portfolio diversification and storytelling strategies strengthen the positioning of beans as a national protein, while partnerships with startups create means to overcome scale-up challenges and expand social impact, in line with the conditions of economic viability. One of the main points of attention raised by sector players is the high cost of new bean ingredients, which often limits the companies' willingness to test them against already consolidated alternatives, such as soybeans and peas. Thus, diversifying applications beyond plant-based meat arises as an essential strategy to generate volume traction, dilute costs and speed up the introduction of beans as a competitive ingredient in the market.

The analysis of opportunities along the bean chain – from the pre-harvest stage to the final product – shows that each stage has distinct but interdependent types of strategic potential. To consolidate the opportunities and challenges presented throughout this section, Table 2 summarizes in an integrated manner the main points identified at each stage of the bean chain. This synthesis aims to provide a clear and comparative view of the strategic paths to transform beans into a competitive ingredient for plant-based products.

Table 2 – Summary of the opportunities and challenges of beans in plant-based products along the chain.

Chain step	Main opportunities	Bottlenecks/challenges	Expected impact
Pre-harvest stage	- Genetic Improvement - Diversity of cultivars - Regenerative agricultural practices - Inclusion of climate impact metrics	-Time of development of new cultivars - Low connection between research and industry - Trade-off between protein content and agricultural productivity - Need for logistical segregation (storage, transportation)	Soil maintenance, cost reduction, greater functionality and strengthened identity of beans as "Brazilian protein."
Harvest and post-harvest stages	- Drying and storage technologies - Integration with cooperatives - Reuse of waste (bark as functional fiber, antioxidants)	- Post-harvest losses - Lack of supply predictability - Limited decentralized infrastructure	Supply consistency, less waste, food safety and productive inclusion.
Ingredient processing or obtainment	- Dry, wet and hybrid fractionation - Valorization of starchy flour as a co-product (food, fermentation, bioplastics) - Extrusion (TVP, whole fillets, snacks, cereals) - Fermentation to modulate flavor, reduce off-flavors and produce bioactives - Emerging technologies (3D printing, supercritical fluid extraction) - Adaptive protocols and retrofitting of plants for cooperatives/startups	- Shortage of pilot plants at intermediate scale - High cost of equipment - Skilled labor shortage - Limited access to open innovation and shared infrastructure	Diversified ingredients, increased functionality and international competitiveness.
Application and market	- Use of starchy and concentrated bean fractions in categories such as bars, cookies, pasta, snacks and protein drinks - Inclusion in public procurement and school meals - Cultural, nutritional and sustainability narratives - Life cycle assessment (LCA) and technical-economic analysis (TEA)	- Limited pilot tests - Low investment in applied R&D - Need for consumer education - High cost of new ingredients compared to soybeans and peas, limiting adoption by the industry	Market expansion, environmental, social and nutritional impact, and higher consumer acceptance.

5. Behind the Scenes: How This Document Was Built

This report is the result of a collaborative process conducted by GFI Brasil between 2024 and 2025, with the objective of consolidating the available technical and strategic knowledge on the use of beans in alternative proteins. Its development combined different work fronts, structured in complementary stages:

1. **Literature review and initial survey:** Survey of national and international studies on the composition, functional and technological properties of beans, as well as benchmarks on other legumes already used in the sector.

2. **Bean technical forum (2024):** Meeting with 11 experts from academia, startups and industry, which included the application of a structured technical form and a brainstorming session on sensory aspects of new ingredients. This step enabled us to collaboratively systematize the main bottlenecks and opportunities for the use of beans in plant-based products and support the formulation of specific calls for research proposals.

3. **Pilot initiatives:** Practical experiments in partnership with companies and universities, such as the cowpea bean test in the Cowpea Dry Fractionation Project with NEA and UFSC, which resulted in a functional and nutritional **technical sheet** of the ingredients obtained.

4. **Individual interviews (2025):** In-depth conversations with 4 strategic experts from academia, startups and industry, which enabled us to capture complementary insights about bottlenecks, opportunities and priorities for R&D and the market.

5. **Integration of sources:** The preparation of the report sought to consolidate all these stages, gathering technical data (nutrition, sustainability, processing), sectoral insights and strategic recommendations, among others.

6. Final Considerations

Beans have unique cultural, agronomic and nutritional attributes, which make them a promising ingredient to expand the portfolio of alternative proteins in Brazil and in the world. Despite their major potential, large-scale application is still limited by technical and structural barriers, such as the presence of antinutritional compounds and off-flavors and the shortage of infrastructure for processing and pilot tests. The survey presented in this report shows that the solutions are not concentrated in an isolated step, but depend on an integrated approach that connects:

- **Agriculture and pre-harvest** stages: Improved cultivars and regenerative practices;
- **Harvest and post-harvest** stages: Loss reduction and quality standardization;
- **Industrial processing**: Technologies that increase functionality and scale;
- **Market and consumption**: Strategies for inclusion in public policies and cultural narratives.

Thus, the viability of transforming beans into a key ingredient for plant-based products requires:

1. **Continuous investment in research and development (R&D)**;
2. **Partnerships between industry, academia and government** to overcome scale-up barriers;
3. **Regulatory support and public policies** that enable innovation and competitiveness;
4. **Strategic communication** that values beans as “Brazil’s protein,” reinforcing its cultural identity and sustainability.

With these advances, beans can be consolidated as a pillar of the Brazilian bioeconomy, with growing potential to also become an **industrial** pillar, as their uses in protein and functional ingredients are expanded. This movement can generate positive impacts on public health, food security, climate and the transition to a fairer and more sustainable food system. To this end, it will be essential to face three priority challenges: **reducing off-flavors, enabling industrial scale-up, and making processes more cost-competitive**. At the same time, strategic opportunities arise, such as the **hybrid processing route, the valorization of co-products (starch and fibers), and the diversification of market applications**. In this context, intersectoral organizations have the role of promoting applied R&D, supporting testing infrastructure and coordinating producers, academia and industry to boost the potential of beans as a national reference ingredient.

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