

Beyond Protein: Phytochemical-Driven Engineering of Herbal-Enriched Plant Protein Powders for Functional Nutrition and Human Health

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ABSTRACT

Nutraceuticals combine nutritional benefits with biologically active components that may support health and help reduce the risk of certain health disorders, with plant proteins from legumes, cereals, pulses, soybean, and oilseeds providing an accessible and nutritious alternative to animal-derived proteins. This review aims to highlight the nutritional importance of plant proteins and their associated bioactive compounds, with an emphasis on their potential application in developing functional nutraceutical products. A narrative review approach was used to examine various plant-based protein sources-including legumes, cereals, pulses, soybean, sattu, and seeds-and evaluate their associated nutritional and phytochemical components. Sattu, soybean, seeds, and related plant ingredients provide essential proteins alongside dietary fibre, minerals, and diverse phytochemicals, including polyphenols, flavonoids, tannins, carotenoids, and saponins. Plant-based proteins and their accompanying bioactive compounds offer significant potential for the development of nutritious, convenient, and functional nutraceutical formulations.

Keywords: Bioactive compounds, Bioavailability, Digestion, Nutraceuticals, Plant-based proteins.

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INTRODUCTION

The concept of nutraceuticals was introduced in 1989 by Dr. Stephen De Felice, derived from the word's nutrition and pharmaceutical. Nutraceuticals refer to specially formulated products which contain one or more nutrients or biologically active components that help in maintaining health and reducing the risk or severity of certain diseases. The primary goal of nutrition in the past was to avoid nutrient deficiencies, such as a lack of vitamins or minerals. Nutritional science has grown in the modern era, and scientists are investigating how foods and nutrients might support overall health and chronic illnesses (Figure 1).^[1]

Protein is an important for the normal body functioning, required for the growth, maintenance and repair of body tissues and muscle. Plant-based foods such as legumes, pulses, cereals, grains and oilseeds are important sources of protein. Common

plant protein sources include lentils, chickpeas, soybean, peas, pumpkin seeds, flax seeds, sesame seeds, almonds, hazelnuts, cashew nuts, peanuts and walnuts.^[2] Combining different plant protein sources provide a wider range of essential amino acids and improve the nutritional profile of a formulation. The plant-based protein is affordable and accessible and also provides micronutrients such as iron, calcium, magnesium, zinc, vitamins like Vitamin E, Vitamin B1, B6 and B.^[3]

Nutraceutical are present in different dosage forms like cereals, tablets, capsules, nanoparticles, cookies, protein bar and granules, with granules offering better flowability, handling and dispensability than powders (Figure 2).

Classification of Nutraceuticals

Traditional nutraceuticals- are bioactive compounds taken from food or other natural sources with little to no alteration. Lycopene, which is present in watermelon, tomatoes, pink grapefruit, papaya, and guava, is one of the elements that give them their red colour.^[4]

Non-traditional Nutraceutical- Products that are developed or improved using modern biotechnological, technical and food processing methods as opposed to being consumed in its natural state are referred to as non-traditional nutraceuticals.



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These methods are mostly used to improve bioactive substances' bioavailability, stability, efficacy, and targeted administration. example calcium-fortified milk, vitamin D-fortified cereals.^[4]

Demand of Nutraceutical

The market for nutraceuticals in the United States has grown significantly in recent years, mostly due to rising consumer interest in preventative healthcare and health awareness. The market includes a broad variety of functional meals, nutraceutical beverages, and dietary supplements. Products enhanced with vitamins, minerals, and herbal extracts are becoming more and more popular but "Nutraceuticals" is not a recognised legal category according to the Food and Drug Administration (FDA). Instead, nutraceuticals might be classified as dietary supplements but The FDA keeps a close eye on the dietary supplement industry in order to spot and resolve any safety issues. For example, it has issued warnings regarding products like supplements containing kava, which have been linked to serious liver damage. Nutraceutical is specifically recognised in India by the Food Safety and Standards Authority of India (FSSAI) under the Food Safety and Standards Act, 2006. The FSSAI defines nutraceuticals as foods or portions of foods that include ingredients like extracts, isolates, purified substances. These compounds are expected to have evidence-based beneficial physiological effects and could promote health or aid in the prevention of specific illnesses. FSSAI sets safety and quality standards for nutraceutical. Based on a number of official books, formularies, and pharmacopoeias, FSSAI also acknowledges traditional knowledge from the Ayurveda, Siddha, and Unani systems. These recommendations aid in ensuring that conventional ingredients and preparation methods are applied in accordance with accepted norms.^[5] The Indian market estimated value was USD 6.11 billion in 2024 and is projected to expand significantly, reaching around USD 11.55 billion by 2033, Japn's market was valued at approximately USD 28.31 billion in 2024 and is projected to expand significantly, reaching around USD 66.4 billion by 2033.^[6,7]

People looked for natural ways to stay healthy, herbal compounds, probiotics, and plant-based products became more popular. During the COVID-19 pandemic, as people were more concerned about improving their health and immunity interest in nutraceuticals increased significantly. Consuming specific nutraceuticals on a regular basis, such as vitamins, minerals, probiotics, and bioactive substances derived from plants, may help maintain healthy immune function. However, nutraceuticals' primary function is to enhance general nutritional and immunological health; they should not be characterised as proven agents for avoiding viral infections or COVID-19.^[4]

In recent years, the people are focusing on the development of innovation food technologies and its solutions. These food innovations are being developed to improve nutrition, support

health, and provide more sustainable choices for consumers and fulfill the demand of proteins.

Plant based protein

Protein rich are formulated to provide a convenient source of essential nutrients when obtaining adequate nutrition from regular foods is difficult or impractical. Protein is commonly consumed by athletes, young adults, and teenagers to promote muscle development, support recovery, and maintain a balanced protein intake.^[8] Natural and plant-based supplements are replacing synthetic ones as health and wellness become more widely recognised. Plant-based protein substitutes are in high demand due to the growing popularity of vegetarian and vegan diets. The usage of animal-derived proteins, such as whey and casein, which may not be appropriate for some populations and may trigger allergic reactions or gastrointestinal distress in sensitive people, is one of the drawbacks of traditional protein powders. Concerns about the long-term health implications of commercially accessible protein powders are further raised by the fact that many of them contain artificial flavours, preservatives, and other ingredients, hence herbal or plant-based protein demand significantly increased.^[9]

Soy protein

The soybean a class of legume family, cultivated in Asia and have been used traditionally for many years as an important food crop.^[10] It is highly nutritious and have valuable source of plant-based protein, healthy fats, and dietary carbohydrates. It contains 36% protein, 15% soluble carbohydrates, 15% insoluble carbohydrates, and 18% oil.^[11] The major proteins in soybean are globulins and Soy contains all nine essential amino acids and has a PDCAAS of 0.92-1.00 with high digestibility.^[11]

Oilseed protein

One of the biggest and most important crops consumed worldwide is oilseed crops. Because they are high in dietary fibre, vital minerals, healthy fats, and bioactive substances, oilseeds provide a variety of health advantages.^[12] Common oilseeds with distinct nutritional and functional components are soy, peanut, rapeseed, sunflower, sesame, and chia, stand out as important sources of proteins (Table 1).^[12]

Legumes

Legumes belong to the family Leguminosae. Most of the primary legumes grown and consumed^[15] worldwide are peanuts, lentils, chickpeas, soybeans, and common beans.^[16]

Beans

Common beans (*Phaseolus vulgaris* L.), sometimes referred to as French beans, kidney beans, snap beans, runner beans, or string beans, thrive in regions with moderate rainfall.^[16] Most common beans are sold as dry beans; only few are marketed as fresh pods.

In contrast to lentils and peas, beans have more protein.^[16] Beans are a great source of dietary fibre, vitamins, and minerals and only contain 4% fat when compared to animal protein sources. Beans also possess carbohydrates, primarily oligosaccharides. Additionally, it contains a wide range of bioactive substances with various biological functions, including polyphenols, flavonoids, anthocyanins, and carotenoids. Compared to grains like rice, wheat, and maize, common bean seeds contain four to ten times more iron (Fe).^[17] The first limiting amino acid may differ based on the variety of bean, and the protein content may vary between 21.4 and 23.6%.^[18]

Pea

Peas are the second most popular legume crop. In addition to varying in particle size and skin thickness, common peas can be classified as yellow, brown, or green based on their colour.^[16] The Glycaemic Index (GI) of pea is normally less than 60.^[19] Common peas are an excellent source of energy and are high in starch (45%) and protein (18.3-31%).^[16] Globulin, albumin, protamine, and gluten are the four main groups into which pea protein is typically divided. Addition to it there is a significant amount of amylose in the pea starches. Pea seeds have a relatively low lipid content, making them a low-fat diet. Polyunsaturated fatty acids contain a large percentage of pea lipids, while unsaturated fatty acids are present in smaller amounts.^[19]

Lentils

The lentil (*Lens culinaris*) has been cultivated around for more than 8000 years and is estimated to have originated in the Near East. Eating lentils leads to a lower incidence of type 2 diabetes, colon cancer, and have lipid-lowering effects in humans.^[20] High-quality protein (23-32%) that contains all of the essential amino acids, particularly lysine, can be found in lentils.

Approximately 16% albumins, 70% globulins, 11% glutelins, and 3% prolamins are found in lentil proteins. Furthermore, lentils are rich in condensed tannin, flavonoids, and phenolic compounds.^[20] Example of Lentil is as *Lens culinaris* (Lentil/Masoor), *Cicer arietinum* (Chickpea/Chana), *Cajanus Cajan* (Pigeon pea/Toor dal), *Vigna mungo* (Black gram/Urad dal), and *Vigna radiata* (Green gram/Moong dal).

Chickpea/Chana/Bangal Gram

The chickpea, or *Cicer arietinum*, belongs to the Fabaceae family of legumes and is widely grown for its nutritious and flavourful edible seeds. The plant usually reaches a height of 20 to 50 centimetres, though this might vary based on the type and growing environment. Depending on the type of plant, the seeds might be beige, green, black, or red and have typically spherical and have a smooth feel. Protein, carbs, vitamins, minerals, and dietary fibre are all found in chickpeas, making them a nutrient-dense food. They are a good source of plant-based protein because they contain between 19 and 25 percent protein. They also contain a lot of complex carbohydrates, primarily starch, which gives them energy. Additionally, the Vitamins C, E, and K found in chickpeas boost the immune system and general wellness of the body.^[21]

Sattu/Roasted Bengal Gram

Sattu is flour made from a combination of cereals and ground pulses. The traditional Indian diet frequently includes sattu as it has high protein that is readily available India.

People make a variety of sattu using local raw materials and their own preferences. Bengal gram sattu is typically made in eastern Uttar Pradesh and Bihar and in Punjab is typically produced with maize and barley.^[22] Sattu flour can be consumed uncooked.^[23] Sattu has a naturally cooling impact on the body, making it especially good in the summer. It is a nutrient-dense option for

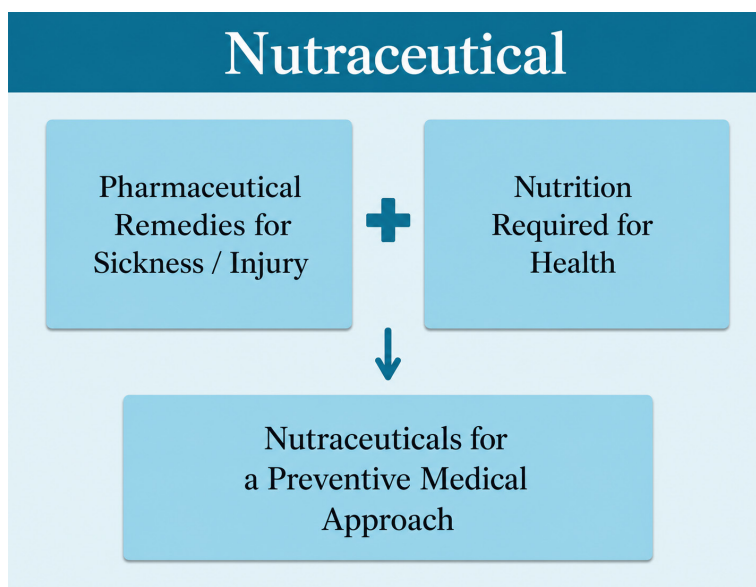


Figure 1: Concept of Nutraceuticals.

a balanced diet because of its low glycaemic index,^[24] and high dietary fibre content. In addition to supplying key minerals like calcium, magnesium, and iron,^[25] sattu is a good source of plant-based protein. It also contains high iron hence used in anemia prevention.^[26] Sattu is one of the richest plant-based sources of protein flours on the market, with an impressive 20-26 g of protein per 100 g. This range varies depends on the main ingredient; chana-based sattu typically contains 22-26 g of protein per 100 g. All nine essential amino acids, which the body is unable to create on its own, are found in sattu, a healthy source of plant-based protein. Additionally, it offers a significant amount of leucine (around 1.8 g per 100 g), which supports its nutritional significance as a food high in protein. Sattu's protein quality ranks highly on the Digestible Indispensable Amino Acid Score (DIAAS) and Protein Digestibility Corrected Amino Acid Score (PDCAAS) measures (Table 2).^[22]

Soluble fibre of roasted bangle gram helps regulate or maintain the cholesterol and blood sugar level, while insoluble fibre promotes regular bowel movements and gut barrier integrity (Figure 3).^[28]

Polyphenols

Polyphenols are secondary metabolites, generally involve in defence mechanism against UV radiation. Natural sources of plant polyphenols include fruits, vegetables, cereals, plants. Polyphenols are characterized by one or more phenolic rings and have a wide variety of complex chemical structures. According to certain research, polyphenols can help prevent cancer, diabetes,

liver disease, and cardiovascular disease. Stronger human clinical data is needed before polyphenols may be regularly advised as therapeutic supplement; however, they may help manage type 2 diabetes by enhancing glucose and lipid metabolism, insulin sensitivity, oxidative stress, inflammation, and vascular function.^[3] Dietary polyphenols also influence peripheral glucose uptake in both insulin sensitive and non-insulin sensitive tissues.^[29] Polyphenols widely classified as Phenolic acid, Flavonoid, tannin, and anthocyanins.^[3]

Phenolic acids

They are present in a wide range of fruits and vegetables. They are generally classified into two major groups: hydroxybenzoic acids and hydroxycinnamic acids. Phenolic acids are a diverse class of plant polyphenols^[3] It is produce through shikimic acid by phenylpropanoid pathway. According to reports, phenolic acids function as antioxidants through a number of processes that stop metal catalysis and the production of free radicals.^[3]

Flavonoids

The most abundant polyphenols in the human diet are flavonoids.^[29] Plants contain more than 4000 flavonoids, which give vegetables, fruits, grains, seeds, leaves, flowers, and bark their colour.^[30] They are primarily found in plant cell vesicles as glycosides. The three cyclic structures of C6-C3-C6 make up the fundamental skeleton of flavonoids. Flavonoids, which are found in the majority of plants, are crucial for plant growth,

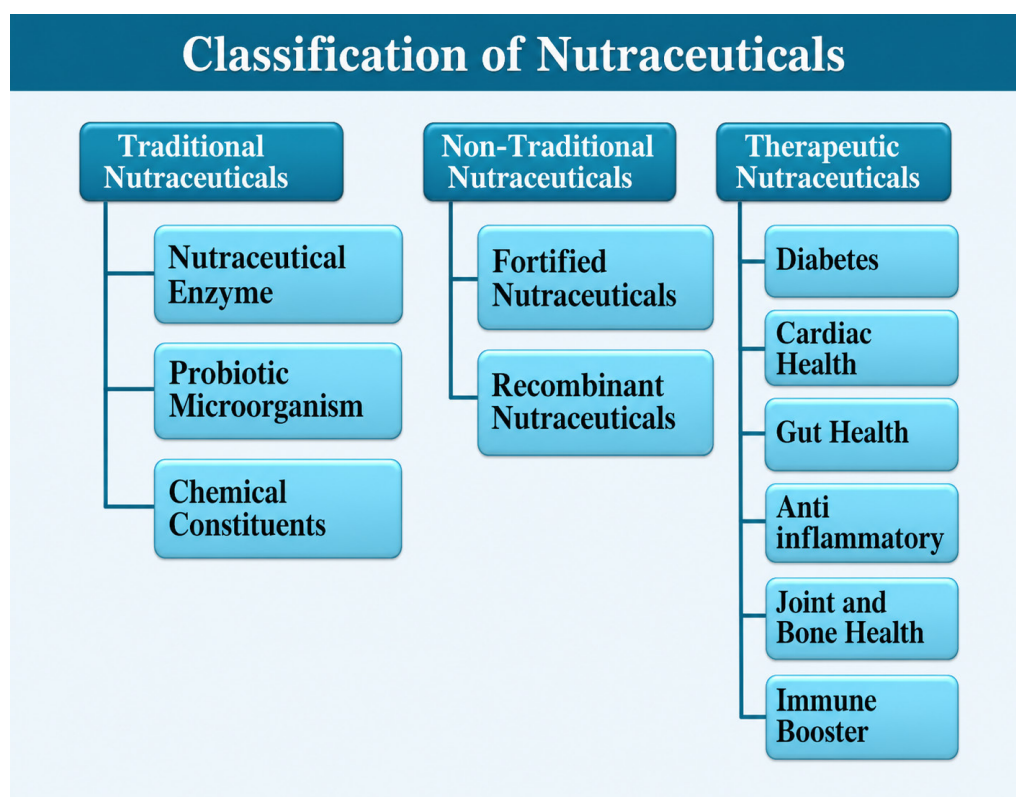


Figure 2: Classification of Nutraceuticals.

Table 1: Protein Profile of Selected Seeds.^[1,2,12-14]

Protein Source	Protein content	Importance of Protein	Main Protein
Peanut	~25%	Protein-rich and has most essential amino acids; also have good digestible Protein.	Arachnin and conarachin
Sunflower	20-21%	Excellent digestibility and have a broad spectrum of essential amino acids.	Sunflower albumins and helianthinin
Rapeseeds	~38%	Have significant levels of unsaturated fatty acids and are rich in oil (about 42%) and proteins (approximately 38%).	Cruciferin and napin
Flaxseed	28-30%	Have good amount of arginine, aspartic acid, and glutamic acid, making it valuable for nutritional and functional food applications.	Linin and colinin
Sesame seed	19-35%	The ratio between essential and nonessential amino acids is well Balanced.	Edestin
Hemp seed	20-25%	A good source of protein that is highly digestible and contains sufficient amounts of key amino acids.	11S Globulin
Pumpkin seed	24-30%	Protein supports muscle repair, supplies essential amino acids.	Cucurbitin

development, flowering, fruiting, antibacterial activity, and disease prevention. Flavonoids are further classified into flavones, flavones, isoflavones, anthocyanins, flavanones, flavanols, and chalcones based on variations in their chemical structures (Table 3).^[3]

Tannin

Tannins are important secondary metabolites in plants and belong to a class of polyphenolic chemicals. Condensed tannins, complex tannins, hydrolysable tannins, and pseudo-tannins are the different class of tannins. Dietary tannins may support gut microbiota and cognitive function while preventing diabetes, cancer, and cardiovascular disease. Tannins are powerful antioxidants because of their high polyphenol content, which effectively scavenges free radicals, lowers oxidative stress, and inhibits lipid peroxidation.^[38]

Anthocyanins

Anthocyanins are largely present in coloured fruits, vegetables, and flowers, providing them blue, purple, red, and black colours. The pH and metal ion complexes can affect the pigments of the colour. Thus, fruits and vegetables in the human diet are significant sources of anthocyanins.^[39] There are several known anthocyanins, including cyaniding, peonidin, delphinine, malvidin, pelargonidin, and petunidin.^[39]

Other phytochemicals

Carotenoids

Over 700 natural carotenoids have antioxidant properties., protecting tissues and cells from the harmful effects of free

radicals. Carotenoids are rich in foods including amaranth, chenopods, mustard, fenugreek, spinach, cabbage, radish, and turnip. Based on their structure, they have been divided into two main groups: carotenes (lycopene, beta carotene). The most active is beta-carotene. Vitamin A is derived from natural beta-carotene, which also protects against cancer and eye disorders. Carotenes improve the immune system and protect skin cells from UV exposure. They minimise risk of asthma, age-related visual problems, cardiovascular illnesses, and inflammation.^[30]

Saponins

Plants contain glycosides called saponins. They are mainly made up of sugar and sapogenin moieties. Legumes such as black gram (*Vigna mungo* L.), garden pea (*Pisum sativum* L.), pigeon pea (*Cajanus cajan* L.), and common bean (*Phaseolus vulgaris* L.) are rich in saponins. Saponins also helps in prevention of erectile dysfunction.^[40]

Polysaccharides and Dietary Fibre

A group of monomer sugar molecules joined by glycoside bonds is called a polysaccharide. They can also be non-digestible substances like cellulose, pectin, beta-glucan, hemicelluloses, resistant starch, lignin, etc. that are collectively referred to as dietary fibre, or they could be stores of energy like starch and glycogen. These elements are digested in the gut microbiota in the large intestine rather than by human digestive enzymes. Dietary fibre may be found in many plant-based food products, since it is particularly abundant in carob beans, rice, corn, oats and green beans.^[41]

Alkaloids

Alkaloids are a large and diverse group of naturally occurring organic compounds, mainly produced by plants. Alkaloids are essential for controlling the human body's neurochemical balance, autonomic activities, and metabolism. They also help in prevention of sedation and helping with anxiety and insomnia. Alkaloids like atropine used in ophthalmology to dilate pupils of eyes. Addition to that some alkaloids like scopolamine are help in the prevention of motion sickness and nausea while caffeine helps to reduce fatigue.^[42]

Terpenes

Terpenes are a wide class of chemical molecules that are found naturally in a variety of plants, especially in their essential oils. Chemically, terpenes are made up of isoprene units the human body. Terpenes like pinene have bronco-dilatory effects, which help in treatment of conditions like asthma. Some terpenes have

anti-inflammatory, analgesic effects. It also helps in improve the memory.^[42]

Chlorophyll

Chlorophyll is the natural green pigment in plants, algae, and cyanobacteria and are essential for photosynthesis. They mainly found in two forms chlorophyll a and chlorophyll b. They are mainly lipophilic phytochemicals and widely obtain from the leafy vegetables. Chlorophyll is rich in antioxidant property. It shows anti-inflammatory effect on wound when apply topically. It also help to maintain the alkaline pH.^[42]

Polyphenols and protein

When polyphenols and proteins coexist in food or the digestive system, they interact with one another. The interaction may alter compounds stability, structure, solubility, digestion, and biological activity. The interaction can be either weak and reversible or strong and covalent. A stable polyphenol-protein

Table 2: Nutritional Composition of Sattu.^[27,8]

Nutrient	Per 100 g Sattu	Significance
Protein	20-22 g	An abundant source of plant protein that promotes muscle growth and repair.
Dietary Fibre	7.6 g	Maintains fullness, aids with digestion, and avoids constipation.
Iron	8-9 mg	Maintains optimum blood levels and helps in the production of RBCs.
Magnesium	166 mg	Provides support for energy production and muscle function.
Potassium	800 mg	Helps maintain normal blood pressure
Zinc	3.8 mg	Supports healthy skin
Calories	406 kcal	Provides energy and important nutrients

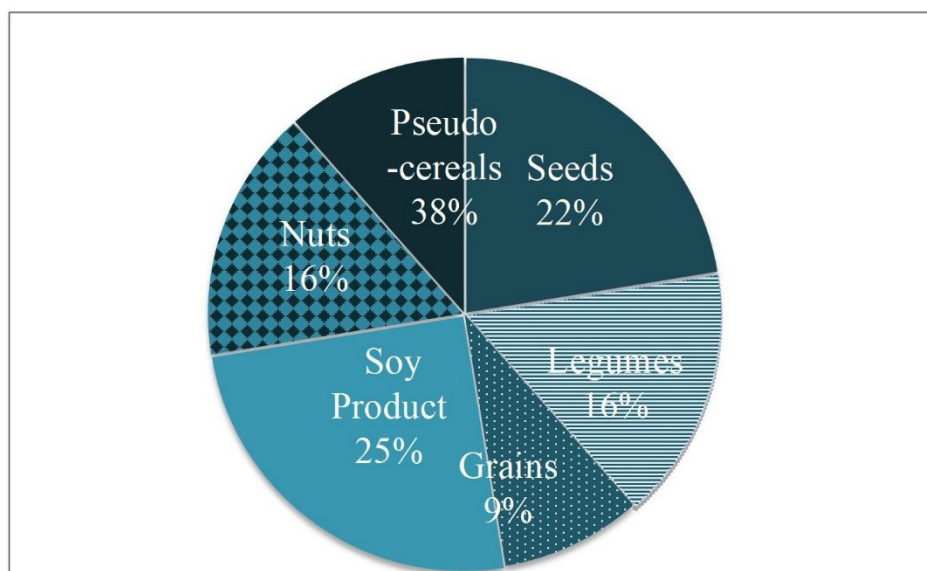


Figure 3: Distribution of Plant Protein Sources.

Table 3: Pharmacological Activity and Food Source of Flavonoids.^[31-37]

Flavonoids	Food Source	Pharmacological Activity
Quercetin	Onion, Apple, Tea, Broccoli	Antioxidant, Anti-allergic
Rutin	Figs, Buckwheat	Antioxidant, Anti-inflammatory
Luteolin	Celery, Chamomile	Antioxidant, Anti-inflammatory, Anti-cancer
Morin	Mulberry, Figs, Almonds, Guava	Anti-diabetic, Antioxidant, Anti-inflammatory
Daidzein	Soybeans, Legumes	Phytoestrogenic, Antioxidant, Cardio-protective, Bone-protective
Tangeretin	Citrus peels	Anti-inflammatory, Anti-cancer
Catechin	Green tea, Cocoa, Apple, Red wine	Antioxidant, Anti-cancer, Cardio-protective
Genistein	Soybeans, Soy milk, Coffee, Lupin	Antioxidant, Anti-osteoporotic, Anti-cancer

conjugate is created when Amino groups (-NH₂) and sulfhydryl or thiol groups (-SH) interacts. Polyphenols can become extremely reactive upon oxidation.^[43]

Covalent Interaction

One of the most significant ways that polyphenols interact with proteins is by covalent contact. Polyphenol oxidation is one of the primary covalent interaction processes between proteins and polyphenols. When polyphenols are exposed to oxygen, heat, alkaline pH, or certain enzymes, polyphenols can lose electrons and get oxidized and it will form semi-Quinone radicals and Quinones. Quinones are highly reactive molecules and can easily react with certain amino acids in proteins. Some amino acid like cysteine, lysine, methionine, and tryptophan contain groups that can react with Quinones. Therefore, the formation of Quinones is an important first step in the formation of strong covalent bonds between polyphenols and proteins.^[43] Different polyphenols vary in their chemical structures, particularly in the number and position of Hydroxyl (-OH) groups present in their molecule. Like EGCG, Gallic acid, Catechin, and Chlorogenic acid have different structure. The binding ability followed.

EGCG > Gallic acid > Protocatechuic acid > Para-hydroxybenzoic acid.^[44]

The protein unfolding

Proteins often have a folded, tight structure with some reactive groups are hidden inside the protein.^[43] On treatment with heat or change in the pH can partly unfold the protein structure and expose these groups on its surface. For example, soy, pea, and chickpea proteins when treated with high temperature and alkaline pH showed structural changes in the protein. This allowed more EGCG to attach to the proteins.^[44]

Enzymatic method

Polyphenols are commonly oxidize and transformed into reactive Quinones by enzymes such laccase, tyrosinase, and polyphenol oxidase and this Quinones help in the formation of covalent bond. enzymatic treatment has an advantage as it requires relatively mild conditions for reaction.^[44] enzymatic reaction also has certain limitations as like Poor stability, high cost and Substrate limitations.^[43]

Free radical grafting

This method involves a chemical reaction to produce extremely reactive particles known as free radicals, which help in the binding of the polyphenol and protein. First, an oxidizing agent is added to the mixture like H₂O₂, Fenton's reagent and some enzyme-based oxidants also added. Ascorbic acid also helps to initiate the reaction. This reaction will generate the free radicals which are highly reactive and it will further forms intermediate and at the end there will be formation of the covalent bond.^[43] Alkaline method: The Common way of formation of protein-polyphenol conjugates without using enzymes is alkaline method. At alkaline pH and presence of oxidising agent will help in formation of Quinones which will further form covalent bond.^[44]

Non covalent Interaction

Non covalent Interaction is rapid and reversible. It mainly involves Ionic or electrostatic interactions and Hydrogen bonding.^[44]

Hydrogen bonding

This interaction occurs when the protein group contains oxygen or nitrogen and it will react with the -OH group of polyphenols.^[43] These interactions can alter the structure, external features, and functional activity of the protein and stabilize the polyphenol-protein complex. Hydrogen bonding and hydrophobic interactions together can increase the stability of

protein-polyphenols complexes and its emulsion. The hydrophobic areas of proteins and the aromatic rings of polyphenols are the primary sites of these interactions like Hydrophobic amino acids, including leucine, valine, alanine, methionine, and glycine, can interact with the non-polar aromatic regions of phytochemicals such as theaflavin, EGCG, curcumin, and genistein. These interactions can help stabilize the protein-phytochemical complex and influence its structure and properties. These interactions also change the solubility, emulsifying properties, stability, binding affinity and hydrophobicity of protein. The structure and functional characteristics of non-covalent polyphenol-protein complexes are maintained in a significant way by hydrophobic interactions.^[44]

Ionic or electrostatic interactions

These interactions occur between oppositely charged protein and polyphenol groups, and change in pH has a significant impact on them. The charge of a protein depends mainly on its amino-acid composition. Ionic interactions affect the conformation, charge, stability, and functional characteristics of polyphenol-protein complexes.^[44]

Effects of protein-polyphenols complex

When a protein-polyphenol combination is consumed, it passes through these multiple processes. Mouth has salivary glands and saliva contain different proteins such as Proline-Rich Proteins (PRP) which involve in polyphenols binding, can interact with polyphenols through hydrogen bonding and hydrophobic interactions. This can cause the formation of protein-polyphenols complex which may produce the astringent or dry sensation mainly in substance which is rich in tannin like tea. The stomach has digestive enzymes such as pepsin and low pH environment. When polyphenols are bound to proteins, the protein matrix helps to protect some of the polyphenols from rapid degradation. In small intestine the pH becomes higher than the stomach and in pancreas the pancreatic enzymes continue the protein digestion. The protein carrier may eventually breakdown, making the polyphenol accessible for absorption (Table 4).

Protein Digestibility and Bioavailability

Protein digestibility means the body ability to digest the protein which is present in the human diet and convert them into smaller peptides and amino acids that can be absorbed and used by the body. Protein digestibility is a key measure of protein quality addition to that type, quantity, and accessibility of essential amino acids to the body is also important for digestibility.^[48]

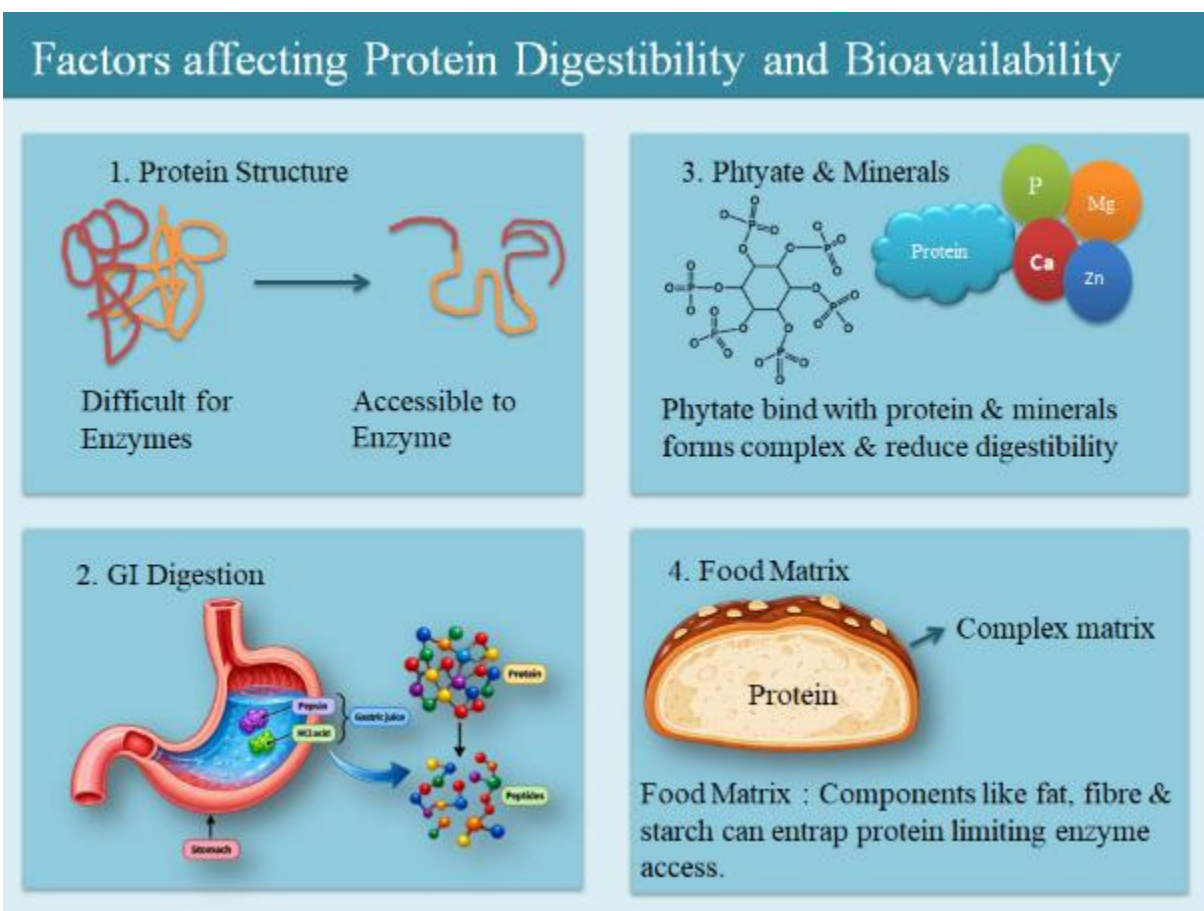


Figure 4: Factors affecting Protein Digestibility and Bioavailability.

Table 4: Effects of Phytochemical Binding on Plant Proteins.^[45-47]

Effects	Main Observation	Example
Protein conformation	Phytochemical binding can modify the protein's α -helix; β -sheet and also change they can change the folding of the protein.	EGCG + β -lacto-globulin
Solubility	In protein-phytochemical complex, phytochemicals may help proteins interact better with water which helps to improve solubility but when too much phytochemical is present, stronger binding form aggregate and reduce the solubility.	EGCG + soy protein isolate
Protein aggregation	Polyphenol have multiple sites for the binding with protein and acts as bridges between different protein molecules which leads to bring the proteins together and forms protein aggregate.	Tannins+ proteins:
Foaming	Can alter foam formation and its stability.	Lentil protein + onion-skin phenolic
Zeta potential	When charged phytochemicals bind to proteins, it alters the electrical charge on the protein and also affects the aggregation and stability.	Plant protein-phenolic systems
Change in astringency	Proteins such as Proline-Rich Proteins (PRP) can interact with polyphenols through hydrogen bonding and hydrophobic interactions. This can cause the formation of protein-polyphenols complex which may produce the astringent or dry sensation.	Tannins + salivary proteins
Change in thermal stability	Binding can modify the forces maintaining protein structure and therefore alter the temperature at which the protein unfolds.	Gallic acid + WPI

Bioavailability define to how much of the protein and its amino acid and bioactive peptides are digested, absorbed, reach the circulation, and become available for use by the body,^[49] hence the digestion and bioavailability are interconnected. Digestibility is important factor in protein rich nutraceuticals. As these are rich in protein percentage is still provide less nutritional benefit if the protein present in nutraceutical is difficult to digest. This is particularly relevant to plant-based nutraceuticals because plant proteins can be affected by protein structure, fibre, phytate, tannins, protease inhibitors and other components of the food matrix.^[50] There are various factors which will affect the digestibility, absorption and bioavailability of protein which are as follows.

Protein Structure

The ease with which digestive enzymes will breakdown the protein into smaller peptide and amino acid is widely affects the protein structure and it will also affect the digestibility of the protein in body. If protein is highly bounded or folded it's difficult for enzyme to react with them and it will directly lead to decreased in the digestibility and bioavailability of protein. On other hand when there is suitable processing is done with protein,

moderate folding occurs in protein structure which will increase the digestibility of protein. However, excessive heating can lead to protein aggregation making the protein less accessible to enzymes and reducing digestibility.^[51]

Gastrointestinal Digestion of Protein

The stomach has an acid pH because of hydrochloric acid. The low pH can change the structure of many proteins and make them more accessible to pepsin and it will break the larger protein into smaller peptide and amino acid. In small intestine pH becomes less acidic and pancreatic enzymes become more active. These enzymes further break proteins into small peptides and amino acids for absorption.^[19]

Effect of Maillard Reaction on Digestibility

When reducing sugars and protein amino groups interact during heating, the Maillard reaction takes place. Lysine is an essential amino acid some plant proteins contain relatively well amounts of lysine like soybean, peas, and beans. Lysine is important as it take part in Maillard reaction. This reaction is mainly responsible for aroma, colour, but excessive reaction can reduce nutritional quality.^[52]

Phytate and Protein Digestibility

Natural plant-based foods like seeds, cereals and legumes, contains Phytate (phytic acid). Phytic acid interacts with protein and minerals and forms complex that are less easily digested and absorbed. Soaking, germination and fermentation can help reduce phytate levels.^[53] Tannins and other polyphenols bind to proteins through hydrogen bonding, hydrophobic, electrostatic and sometimes covalent interactions. These interactions may change protein structure and depending upon the changes it may increase or decrease the digestion and bioavailability (Table 5).

Effect of Processing on Protein Digestibility and Bioavailability

Food Matrix

In nutraceutical along with protein there is fat, carbohydrate, fibre, phytochemicals, and minerals are also present. These components can interact with each other and affect the digestion and bioavailability as fibre may physically restrict enzyme access, while polyphenols can bind proteins. Therefore, protein source and other ingredients together determine the final digestibility (Figure 4).^[54]

Strategies for Improving the Digestibility and Bioavailability of Protein-Rich Nutraceuticals

Enzymatic hydrolysis -when proteins are treated with certain enzyme like pepsin, papain and trypsin the large proteins are convert into smaller peptides and amino acids. This will ultimately leads to increase the digestibility and bioavailability.^[55]

Reduction of anti-nutritional factors

Soaking, germination, fermentation, and suitable heat treatment are the processing methods which are help to reduce the anti-nutritional factors like phytate, tannins, trypsin inhibitors, and lectins. This reduction makes plant proteins more accessible to digestive enzymes which will further help in increase the absorption and bioavailability of nutraceuticals.^[49]

Germination/sprouting

Germination activates endogenous enzymes in seeds and legumes, which can break down storage proteins and reduce some anti-nutritional compounds. This may improve protein digestibility and amino-acid availability.^[55]

Encapsulation systems- Proteins can be used to develop nanoparticles, emulsions, liposomes and other delivery systems. These systems protect bioactive compounds from being damaged during processing and digestion while also supporting their gradual and controlled release (Figure 5).^[49]

Health Benefits of Plant-Protein-Rich Nutraceuticals

Weight Management

Plant-protein-rich nutraceuticals help in controlling hunger and supporting healthy body weight. While digestion, plant proteins may release amino acids relatively slowly and steadily, which may prolong satiety.^[2] Some reason like presence of dietary fibre in many plant-based nutraceutical formulations can further support fullness by slowing gastric emptying time.^[56]

Cardiovascular Health

Plant proteins also help to prevent the cardiovascular disease by maintaining the blood lipid levels, blood pressure, and inflammation. The plant proteins and soluble fibre such as β -glucan help in the reductions of LDL cholesterol and also influence cholesterol metabolism by enhancing cholesterol clearance and reducing its synthesis also reduces the cardiovascular risk markers. Along with protein other phytochemicals also present in nutraceutical which will further work together and help to maintain the CVD.^[56]

Antioxidant Protection

Most of the plant-based nutraceuticals are rich in polyphenols, flavonoids, phenolic acids, carotenoids and other antioxidant compounds by neutralize reactive molecule. These substances may decrease oxidative stress. Antioxidant-rich plant ingredients may also contribute to cardiovascular and metabolic health through their effects on oxidative and inflammatory processes.^[2]

Gut Health

The legumes, pulses, soy, seeds and grains contain protein and amino acid which are helpful for growth and repair of body tissues. The human gut microbiota is crucial for host digestion, immunological control, and metabolic balance as human gut microbiota is a highly diverse and dynamic ecosystem. To lower structural barriers and improve upper gastrointestinal digestibility a variety of processing strategies have been developed. Plant-based diets contain fewer sulphur-containing amino acids than the animal based protein. The lower sulphur

Table 5: Effect of Processing on Protein Digestibility and Bioavailability.

Processing method	Effects
Cooking	Can denature proteins and reduce some ANFs
Germination	Can denature proteins and reduce some ANFs
Roasting	Can improve digestibility at appropriate conditions but excessive heating may cause undesirable reactions
Enzymatic hydrolysis	Breaks proteins into smaller peptides

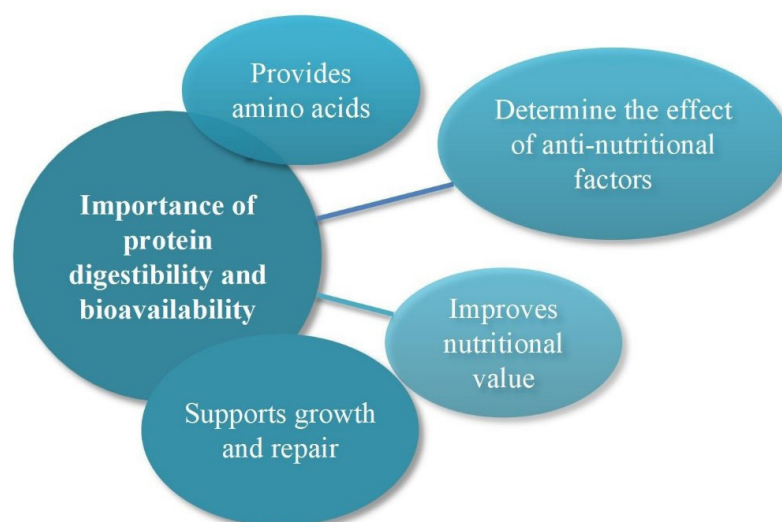


Figure 5: Importance of protein digestibility and bioavailability.

containing amino acid will reduce hydrogen sulphide production in the gut. This can help protect colon cells and the intestinal barrier. Excessive heating treatment may induce the formation of advanced maillard reaction products and insoluble protein aggregates which leads to decrease the digestibility of protein. When the plant proteins and probiotics co-administered, it will give synergistic interaction which play an important role in maintenance of the gut health.^[56]

Diabetes (Type 2)

As we already know that the Protein helps increase fullness (satiety) after eating. This may reduce unnecessary snacking and frequent hunger. This help to maintaining a healthy body weight.^[2] Maintaining healthy body weight is important for reducing the risk of type 2 diabetes. Protein-rich and fibre rich food such as Legumes when combine together digestion and absorption of carbohydrates can be slower this may help reduce a rapid increase in blood glucose after a meal. Consuming protein rich and fibre rich diet maintain the health weight can support overall metabolic health and insulin sensitivity (Figure 6).^[56]

Maintaining good memory, focus, learning capacity, attention, and normal brain function is referred to as cognitive health. By supplying proteins, vital amino acids, good fats, minerals, antioxidants, and other bioactive substances required for normal brain function. Plant-based nutraceuticals high in protein may promote cognitive health. Pumpkin seeds, sunflower seeds, flaxseeds and walnuts contain unsaturated lipids also some plant foods contain omega-3 fatty acid ALA which help in normal brain and nervous-system function. Seeds and legumes provide minerals such as magnesium, zinc and iron, which conduct normal cognitive processes. Brain also requires energy for its normal functioning so a nutritionally balanced plant-based protein and carbohydrates provide nutrients needed to support normal brain activity.^[2]

Muscle Growth and Repair

The protein-rich plant-based nutraceuticals help in the muscle growth and repair. The plant-based protein contains amino acid which are the building blocks required for the formation, maintenance, and repair of muscle proteins.^[57] Useful levels of protein and essential amino acids may be obtained from plant-based nutraceuticals that contain beans, grains, and seeds. The plant proteins can stimulate muscle protein synthesis. By combining different plant proteins, consuming adequate protein, and using appropriate processing methods help to improve protein digestion and absorption.

Types of Dosage Forms of Nutracuticticals

Powder

One of the most simple and versatile types of protein-rich nutraceuticals is powder. They can be consumed directly after being combined with water or milk, or they can be added to smoothie, cereal, bakery products, and other dishes. It is having plus point which that it can easily combine with different type of plant based powder and improve nutritional profile. It has limitation also like problem of solubility and dispensability that can be overcome by doing suitable processing of powders.

Plant-based protein powders available in the market are Oziva plant protein powder which made of pea and brown rice.^[58]

Granules

Granules offer a substitute for traditional powders and consumption more convenient. With the use of desired flowability, handling qualities, stability and suitable binders convert powder into granules. It can be consumed directly or mixed with warm milk or water. Granules can offer several practical advantages over conventional powders as granule have good flow property as compare to powder and it form less dust particle. hence granules are easy to handle as compare to powders. It also reduced

tendency to form lumps and improved dispensability. As compare to powder, granules have better appearance and acceptability. In market mostly protein rich powders and bars are presents, hence there is still scope to develop a convenient granule.^[58]

Protein Bars

Protein bars are small, portable products made to offer protein and energy in a convenient manner. Plant proteins can be incorporated into bars along with other natural substance like Plant proteins can be included into bars along with substances such as nuts, seeds, cereals, dried fruits, chocolate, dates or natural binders which also provide high nutritional profile.^[59] Rite Bite Max Protein, Muscle Blaze and Yoga Bar are some of the popular marketed protein bars. Protein is can be developed in different flavour as per the market demand. The major limitation of it is they are relatively high cost than the powder and granules nutraceuticals.^[60]

Protein-Rich Plant-Based Beverages

Protein-rich plant-based beverages are liquid which can consumed as ready-to-drink beverages or prepared from protein-rich powders. Soy beverages contain a good amount of protein while other plant protein may have less protein. Therefore, extra plant protein added to make the beverage protein-rich. It

has limitation of stability. To maintain the stability and for long shelf life the optimum pH, proper homogenization addition of stabilizer, prevent microbial growth is important factors. If the stability is not good the drink may change its colour, odour and taste. These are mostly placed at cool environment and away from the sunlight. So Good Soy Protein, Maiva Pro Vanilla Daily Shake are the popular marketed drinks.^[60]

Protein-Rich Breakfast and Cereal Products

Plant-based protein can be incorporated into breakfast. Although cereals are a naturally significant source of plant protein, protein content can be enhanced by mixing them with pseudo cereals, legumes, pulses, and seeds. Examples of high-protein breakfast items made from plants are Protein oats, protein muesli, Protein granola, Protein breakfast flakes. They are mainly made from the mixture of legumes, oats, beans and nuts.^[58]

Research Gaps

Limited development of plant-based protein nutraceutical granules- As most studies focus on individual plant protein sources such as soy, pea, wheat, rice, chickpea or other legumes. Limited studies on the combined nutritional effect- Most published research evaluates individual ingredients separately. There is a research gap. Insufficient optimization of granule

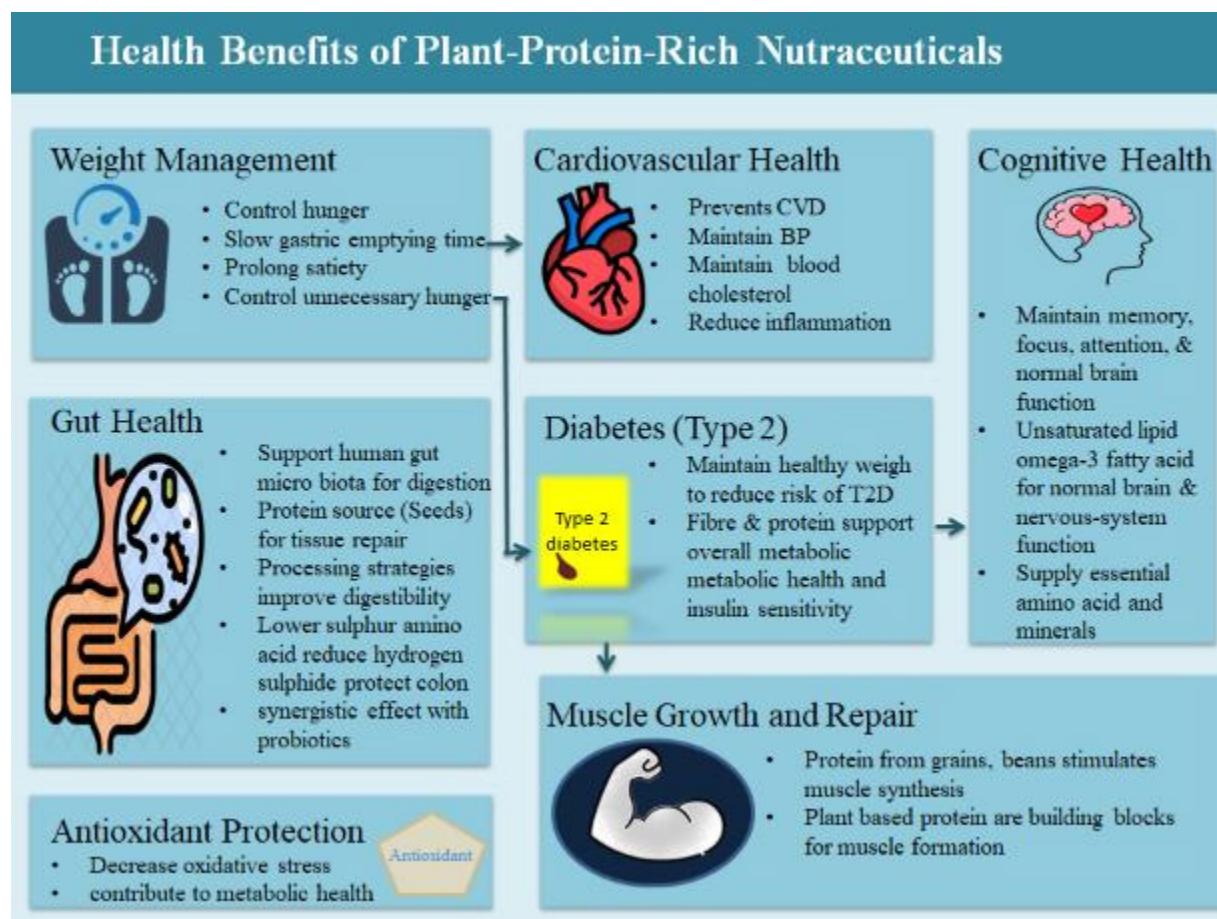


Figure 6: Health Benefits of Plant-Protein-Rich Nutraceuticals Cognitive Health.

formulation- The quantity of protein sources, binder, sweetening agent and excipients can influence granule formation, flowability, moisture, hardness. Stability during storage needs greater attention- Seed-containing formulations contain unsaturated lipids that may undergo oxidation during storage. Moisture uptake can also affect granule texture, flowability and microbial stability.

Sensory acceptability remains an important challenge- Plant protein and seed powders can produce earthy, bitter or nutty flavours and may affect mouth feel. More research is needed to optimize taste, aroma, colour, texture and overall acceptability while maintaining nutritional value. Limited information on solubility and dispensability of protein-rich granules. Limited clinical evidence. Much of the available evidence for plant-based functional ingredients comes from laboratory or animal studies. Human studies evaluating the effects of consuming such protein-rich nutraceutical formulations on nutritional status, satiety, muscle recovery or general health remain comparatively limited.

FUTURE PERSPECTIVES

Improvement of protein quality

Future formulations can focus not only on increasing total protein but also on improving the amino-acid balance and protein digestibility by combining complementary plant protein sources.

Protein digestibility and bioavailability studies

In vitro gastrointestinal digestion models can be used to determine how effectively protein is released and digested. Further studies can evaluate amino-acid availability and protein quality.

Protein digestibility and bioavailability studies

In vitro gastrointestinal digestion models can be used to determine how effectively protein is released and digested. Further studies can evaluate amino-acid availability and protein quality.

Development of ready-to-use beverages

The optimized granules could be further developed into a protein-rich instant beverage. This would provide an additional application for the formulation and could improve convenience for consumers.

Use of natural functional ingredients

Future formulations could explore natural ingredients rich in antioxidants, dietary fibre and micronutrients to enhance the functional value of the product while maintaining a plant-based profile.

Scale-up and industrial feasibility

Future research should move beyond laboratory-scale preparation and examine large-scale manufacturing, including

mixing uniformity, granulation efficiency, drying, packaging, and production cost and batch-to-batch consistency.

CONCLUSION

Plant-based nutraceuticals offer a promising approach for combining nutritional value with naturally occurring bioactive compounds. Sources such as soybean, sattu, legumes, and oilseeds can provide substantial protein along with dietary fibre, minerals, and beneficial phytochemicals. Combining different plant sources may improve the overall nutritional profile by providing complementary nutrients and amino acids. Granules can further provide a convenient and easily handled dosage form. Overall, plant-based protein-rich nutraceutical formulations have potential as practical nutritional products, although their safety, nutritional quality, stability, bioavailability, and functional properties should be appropriately evaluated before use.

ABBREVIATIONS

FDA: Food and Drug Administration; **FSSAI:** Food Safety and Standards Authority of India; **PDCAAS:** Protein Digestibility Corrected Amino Acid Score; **DIAAS:** Digestible Indispensable Amino Acid Score; **GI:** Glycaemic Index; **LDL:** Low-Density Lipoprotein; **CVD:** Cardiovascular Disease; **EGCG:** Epigallocatechin Gallate; **ANF:** Anti-Nutritional Factor; **PRP:** Proline-Rich Proteins; **ALA:** Alpha-Linolenic Acid.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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