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RESEARCH ARTICLE

Evaluation of Soybean for Nutritional and Physical Traits

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ABSTRACT

The legume crop soybean (*Glycine max*) functions as an essential plant throughout worldwide markets because it produces abundant protein at 36–40% protein content and oil at 18–20% oil content, which serves human diets and animal feed alongside industrial needs. Soybeans deliver nutritional value to humans, but this value is reduced because of the presence of anti-nutritional factors like trypsin inhibitors, lectins, and phytic acid. The bioactive components of soybeans, named isoflavones, contribute health advantages to human systems through the prevention of cancer, along with protection against heart disease. Soybean displays various growth forms and responds strongly to light duration and environmental heat, thus determining where it can effectively grow within different geographic areas. According to estimates for 2023–2024, the world produced 399.5 million metric tons of soybeans, where Brazil led as the top producer and sharing the lead with the United States, followed by Argentina and China. Brazil's soybean crop will experience a predicted 30% production reduction by 2050 due to climate change. Soybean Mosaic Virus, together with whitefly, along with environmental hazards, lead to significant productivity issues in regions such as Pakistan, which faces difficulties in soybean cultivation even though it has high demand for poultry feed. Soybean's nutritional value and production statistics undergo evaluation while solving anti-nutritional factors, and worldwide cultivation patterns and essential limitations need new stress resistant variety development along with sustainable farming practices for future food security.

Key words: Soybean, Anti-nutritional factors, Global production, Soybean challenges, Nutritional and physical traits.

INTRODUCTION

Soybean is an important crop worldwide, providing protein for human consumption directly and indirectly through processed foods or livestock products (Mishra et al., 2022). Morphologically, the soybean plant is characterized by trifoliate leaves, small white or purple flowers, and pods containing three to four seeds shown in Fig 1. These seeds or beans are renowned for their high protein content, typically around 36-40% and substantial oil content of about 18-20% (Duan et al., 2023). This crop is responsible for providing 25% of the world's consumable oil and two-thirds of the total protein required for livestock feed, highlighting its critical importance in agricultural practices and food supply chains (Amrate et al., 2023). Soybeans are particularly noted for their high protein content, which ranges between 35% to 40% on a dry weight basis in fully developed seeds (Mandić et al., 2020a). In addition to protein, soybeans contain about 20% lipids, which are beneficial fats contributing to energy and nutrient absorption. They also have approximately 9% dietary fiber, promoting digestive health, and around 8.5% moisture, which affects the seed's storage and processing qualities.

Soybeans dominate the legume crop sector, covering 80% of the area dedicated to legume cultivation and contributing to 68% of the global legume production. This prominence underscores the vital role of the soybean crop in both food and industrial applications (Naamala et al., 2016). The wide

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Fig. 1: Soybean Plant.

spread adoption and cultivation of soybeans are attributed to their versatility and substantial contributions to agricultural economies. By 2017, Europe had become the second largest market for soybeans, accounting for approximately 12% of global soybean production. This significant market share highlights the growing demand for soybeans in various regions beyond their historical origins in Asia (Voora et al., 2020). The soybean is a major source of protein for humans and is used as premium animal feed. It originated in China. With around 80% of global production, the primary suppliers to the soybean market are the United States of America, Brazil, and EU; imports from Argentina rely on these nations (Stoicea et al., 2024). Soybean is an annual legume crop under the pea family, also known as Fabaceae. Here is a brief kingdom of soybeans that are described in Table 1.

Table 1: Soybean Nomenclature (Boerma et al., 2004)

Kingdom	Plantae
Clade	Tricheophytes
Clade	Angiosperms
Clade	Eudicots
Clade	Rosids
Order	Fabales
Family	Fabaceae
Subfamily	Faboideae
Genus	Glycine
Species	G. max

The nutritional profile of soybeans is further enriched by the presence of Iso-flavonoids and folic acid, making them a preferred component in health-conscious diets. Iso-flavonoids, a class of phytoestrogens of soybean, can lower the risk of cancer (Ferreira et al., 2015). Folic acid, a vital nutrient for cell growth and metabolism, adds to the health benefits of soybean consumption. Soybeans are also a rich source of essential vitamins, including E and K, which play roles in antioxidant protection and blood clotting, respectively. Additionally, they provide riboflavin, thiamine, niacin, and choline, which are important for energy production, neurological health, and metabolic processes. The antioxidant properties of soybeans are bolstered by compounds such as iso-flavones, which help in protecting the body against oxidative stress. Thus, soybeans not only contribute significantly to dietary needs but also support overall health through their rich and diverse nutrient contents (Singh et al., 2018). Their impact on both human and animal nutrition, coupled with their industrial applications, underscores their global significance as a staple crop in agriculture and food industries. The ongoing research and development in soybean cultivation and processing continue to enhance their value and utilization, ensuring that soybeans remain a pivotal crop for addressing future food and nutritional security challenges.

Soybean is an erect plant with a hairy stem of 30cm to 130cm in height, depending on environmental conditions. It is an annually grown plant with three distinct leaf types: true (trifoliate) leaves, primary (unifoliate) leaves, and the initial pair of cotyledon (seed) leaves. Attached to the embryonic stem, the cotyledons are components of the embryo that germinate and rise to the soil's surface (Miladinović and Đorđević, 2011). Their leaves can be either green or yellow in color, round in shape, and covered in stomata and epidermis. Soybean is made up of numerous secondary roots that support multiple orders of smaller roots as well as a taproot that is typically indistinguishable from other roots of comparable dimensions (Kaspar et al., 2022). Plants cultivated singly in an open field, the side roots can grow up to 250cm in length, and the taproot can go as deep as 200cm. Some lateral roots run between 40cm and 75cm obliquely, then curve sharply downward, occasionally reaching 180cm. The majority of lateral roots develop from the taproot's top 10 to 15cm and stay roughly horizontal (Lersten and Carlson, 2004). Three primary classifications of soybean stem structure, known as determinate, semi-determinate, and indeterminate, can be distinguished (Zhou et al., 2022). This review highlights soybean's nutritional significance, anti-nutritional constraints, phenotypic traits, global production trends, and key challenges, emphasizing the need for improved breeding, stress-resistant varieties, and sustainable farming practices to ensure future food and feed security.

Life cycle of soybean

The development of the plant from seed germination to producing seeds is necessary for the soybean's growth, development, and reproductive capabilities. Here are the most important parts of the soybean life cycle. To begin life, soybean seeds are germinated by having favorable conditions such as the correct soil moisture, the right temperature, and sufficient oxygen available. After water is absorbed, the seed coat becomes softer, and metabolism starts which breaking the dormant state and beginning the growth of the seedling. The seedling first starts to grow with the stem and cotyledons appearing under the soil, and then the stem breaks through the surface with the seedling fully showing (Anwar et al., 2016). When the seeds have sprouted, the plant starts to develop its leaves, stems, and roots during vegetative growth. The plant is anchored in the ground and supplied with water and nutrients because of the primary root system. While this is happening, new leaves and extra branches grow out of the plant's center through cell divisions and expansions. Now, the plant puts energy into building up its roots and growing a large biomass for reproduction.

The soybean plant goes into reproductive growth when flowering begins. Flowering depends on the light cycle and temperature. Soybean flowers are generally able to pollinate themselves, and pollen moves from one part of the same flower or one flower to another on the soybean plant. As a result of pollination, the plant assigns male and female cells to developing seeds, which form its pods. After fertilization, the ovaries of pollinated flowers transform into pods that hold many seeds inside them. Pods are formed through cell division and growth, and they also change in color, size, and texture. The number of pods and seeds a plant gets depends on its genes, the environment, and the actions taken by farmers.

During their maturity, seeds inside pods change and collect needed nutrients, as well as grow the outer layer, called the seed coat. When seeds mature, their color, how damp they are, and their texture usually change shown in Fig 2. Seeds need to be harvested after they have become physiologically mature. When to harvest is very important for best seed quality and balancing factors like seed moisture, damaged pods, and weather (de Barros et al., 2014).

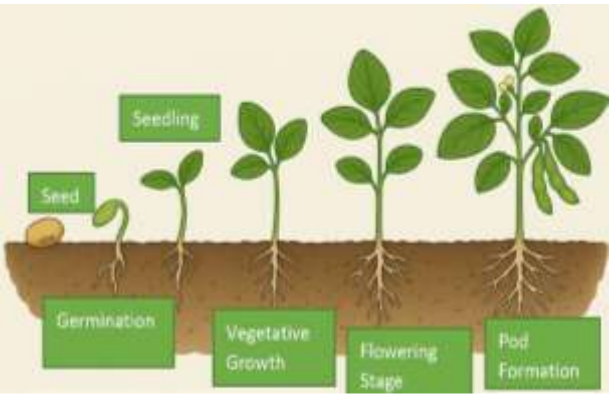

Fig. 2: Life cycle of soybean.

Nutritional Composition of Soybean

According to the dry weight of mature raw seeds, soybeans typically contain 40% protein content, 20% oil content, 17% dietary fiber, and about 8% moisture (Świątkiewicz et al., 2021). The location, planting conditions, and soybean variety all affect its composition (Dukariya et al., 2020). In addition, it is an important source of oil and protein for humans, animals, and poultry, and it provides the raw material for the bioenergy, pharmaceutical, and technical industries. All of the essential amino acids, including lysine, which is especially deficient in other staple crops, are present in soybean protein (Agyenim-Boateng et al., 2023). It is considered a good alternative to animal protein and one of the most affordable dietary protein sources. A great source of protein, fiber, vitamins, and minerals, soybeans also contain essential unsaturated fatty acids in their fat. First and foremost, the soybean proteins are globulins, which make up around 70% of all proteins and serve auxiliary purposes. Approximately 6% of soluble soybean proteins are protease inhibitors (Kudełka et al., 2021). As for proteins, the nutritional makeup of soybean amino acids is as follows: tryptophan, tyrosine, valine, arginine, alanine, aspartic acid, cysteine, glutamic acid, glycine, histidine, phenylalanine, isoleucine, lysine, leucine, methionine, proline, serine, and threonine that are shown in Fig 3. An excellent source of antioxidants and omega-3 fatty acids, soybeans are low in lactose, free cholesterol, and saturated fats and abundant in fiber, protein, and phytoestrogens. Additionally, adding 12–14% moisture to soybeans can increase their stable storage (Kim et al., 2021).

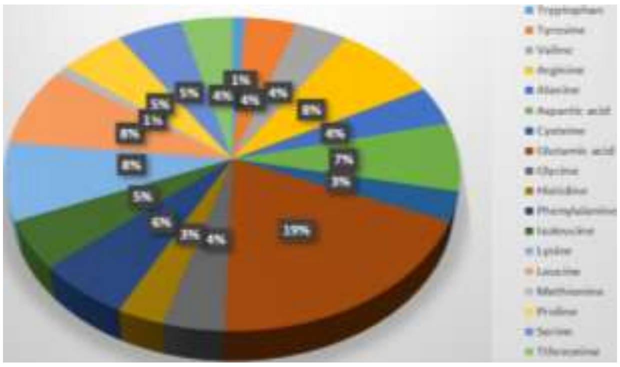

Fig. 3: Nutritional Composition of Soybean.

Phenotypic characteristics of soybean

Soybean growth habit can be erect, semi-erect, prostrate, or semi-prostrate, while growth type can be either determinate or indeterminate (Pathak et al., 2021). It produces around eighty pods, each of which contains triplet beans. It contains a higher seed size. It contains 60-70 grams per 100 seeds. It can fix nitrogen (N) with Rhizobia (Chander et al., 2021). It is vital in various aspects of human and animal food consumption. The plant shape can be bushy or non-bushy. Its pods are consumed in the human diet while the remaining plant is used as fodder. Beans have different color variants, viz., yellow, green, brown, and black (Uebersax et al., 2022). The growth of soybeans in diverse climates is dependent upon temperature and photoperiod. The ideal temperature for soybean seed development is 25°C to 35°C (Poudel et al., 2023). The soybean plant has numerous phenotypic characters that are essential to study for its breeding. These characters need to be observed at different stages of the plant for studying its morphology and behavior in that specific environment. Based on these phenotypic characters, we can divide soybean plant into different groups shown in Fig 4 (Oliveira et al., 2017). These characters are listed below.

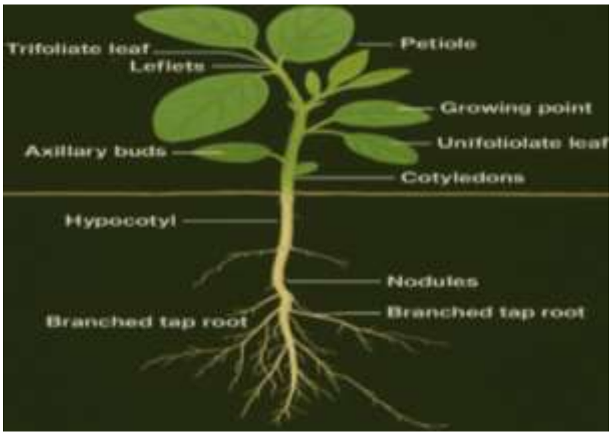

Fig. 4: Morphological Appearance of soybean.

The shape of a soybean plant is influenced by its growth habit and can vary significantly. Typically, soybean plants can be described as having an erect, bushy, or semi-bushy shape. Erect soybean plants have a more vertical and upright growth form characterized by a single main stem that supports the branches (Xing et al., 2022). This shape is often associated with indeterminate varieties where the plant continues to grow taller throughout the season, producing leaves, flowers, and pods along the stem and branches. Bushy soybean plants, often found in determinate varieties, have a more compact and rounded shape (Nchogu et al., 2022). These plants tend to stop growing taller once they begin flowering, leading to a denser arrangement of branches and leaves. This shape facilitates easier access to sunlight and can enhance the plant's ability to support a higher number of pods per unit area (Kumar et al., 2015). The classification of soybean as a short-day plant highlights the critical role of photoperiod in its flowering and maturity (Hou et al., 2022). This photoperiodic response is essential for determining the best growing conditions and regions for soybean cultivation. It influences agricultural planning and the adaptation of soybean varieties to different latitudes and climates (Lin et al., 2021). By understanding this trait, farmers and breeders can optimize soybean production, enhance crop resilience, and ensure successful cultivation across a wide range of environments (Cooper and Messina, 2023).

Anti-nutritional contents in soybean

Soybean has good nutritional value whether it is food, feed or fodder, but there are some anti-nutritional contents also present in soybean which reduce its nutrition (Prvulovic et al., 2017). Some of the anti-nutritional contents are given below. The nutritional value of soybeans is primarily limited by the presence of trypsin and chymotrypsin inhibitors and pectins, and proteins with immunological activity (Di et al., 2024). The most significant inhibitors are the Kunitz and Bowman-Birk inhibitors. In animals, these inhibitors reduce nitrogen retention, decrease performance, and increase metabolic nitrogen excretion. Heat processing or toasting can significantly reduce the activity of these inhibitors in soybean products, eliminating over 90% of antitrypsin activity (Nair et al., 2023). Different animal species react variably to trypsin inhibitors in feed; for instance, goslings and chickens are more sensitive compared to piglets and calves. Lectins, also known as hemagglutinins, are proteins that specifically bind to carbohydrates. In their raw form, soybeans contain lectins that can inhibit growth and increase mortality rates in animals (Shea et al., 2024). The concentration of lectins in soybeans can range from 37 to 323HU/mg of protein. In soybean meal, the content of lectins binding to carbohydrates ranges from 0.2 to 3.1 g/kg, with agglutinating lectins being the most. The detrimental effects of lectins are significantly reduced when soybeans are subjected to autoclaving, which practically eliminates their negative impact (Gao et al., 2024).

Soybeans contain isoflavones, which are compounds with various biochemical activities, including estrogenic, anti-estrogenic, and hypocholesterolemia effects (Jeske et al., 2017). The total iso-flavone content in soybeans ranges from 160.8 to 284.2mg per 100g. Iso-flavones in soybeans and soy products exist in three main types: daidzein, genistein, and glycitein, each occurring in three different isomers and forms, resulting in a total of 12isomers (Kuligowski et al., 2022). The isoflavone content in soybeans is influenced by various factors and is an important component in preventing certain cancers and reducing the risk of cardiovascular diseases (Zaheer and Akhtar, 2019). The role and utilization of isoflavones in animal production are gaining interest due to their positive effects on the immune system and improvement in performance and trait quality. The total iso-flavone content in Korean soybean cultivars ranges from 110 to 330 mg per 100 grams of feed (Lee et al., 2021). Stachyose and raffinose are low molecular weight carbohydrates found in both raw soybean seeds and toasted soybean meal. The concentration of raffinose in soybean seeds ranges from 0.1 to 0.9g per 100 grams on a fresh weight basis (Leamy et al., 2017). While stachyose content ranges from 1.4 to 4.1g per 100grams. Phytic acid acts by chelating essential minerals like calcium, magnesium, potassium, iron, and zinc, making them unavailable to non-ruminant animals (Reddy et al., 1978). High levels of phytates in diets reduce the availability of these minerals, particularly calcium, phosphorus, and zinc. Anti-nutritional substances found in soybeans are described in Table 2, as highlighted by Pusztai (1991), are crucial to consider.

Table 2: Anti-nutritional contents in soybean

Anti-nutritional Factor	Concentration in Soybean	Effects	Mitigation Methods	Description	References
Trypsin & Chymotrypsin Inhibitors	Varies (activity reduced by heat processing)	Reduces nitrogen retention, decreases animal performance, and increases metabolic nitrogen excretion	Heat processing eliminates of >90% of activity	Proteins that inhibit digestive enzymes	(BIRK, 1985)
Lectins	37–323 HU/mg protein (raw soybeans); 0.2–3.1 g/kg (soybean meal)	Inhibits growth, increases mortality in animals	Autoclaving eliminates negative effects	Carbohydrate binding proteins	(Di et al., 2024)
Isoflavones	160.8–284.2 mg/100g (total isoflavones); 110–330 mg/100g (Korean cultivars)	May prevent cancers, reduce cardiovascular risks; impacts animal immune system and performance	Beneficial in moderation; processing may alter bioavailability	Estrogenic, anti-estrogenic, and hypocholesterolemic compounds	(Wang et al., 2022)
Stachyose and Raffinose	Raffinose: 0.1–0.9 g/100g; Stachyose: 1.4–4.1 g/100g	Causes flatulence, reduces digestibility in monogastric animals	Fermentation or enzymatic treatment can reduce levels	Low-molecular-weight carbohydrates (oligosaccharides)	(Guo[a] et al., 2024)
Phytic Acid	0.44–13.2 mg/g	Reduces mineral availability (Ca, P, Zn) in non-ruminants	Phytase enzyme supplementation, fermentation, or processing	Chelates essential minerals (Ca, Mg, K, Fe, Zn)	(Chen et al., 2024)
Saponins	0.5–6% (dry weight)	Hemolytic activity at high doses Bitter taste Hypocholesterolemia effects	Soaking + boiling - Alcohol extraction -Fermentation	Saponins are a double-edged sword undesirable in livestock feed due to bitterness and anti-nutritional effects, but potentially health-promoting in human diets.	(Timilsena et al., 2023)
Tannins	0.1–0.5%	Reduces protein digestibility - Astringent taste - Liver/kidney damage at high levels	Heat treatment - Polyphenol oxidase enzymes - Alkaline processing	Tannins are anti-nutritional primarily for monogastric animals but offer health benefits for humans as antioxidants.	(Pechyen et al., 2024)
Oxalates	10–50 mg/100g	- Kidney stone formation (Ca oxalate) - Binds calcium	- Blanching (reduces 30–50%) -Calcium supplementation	Oxalates are anti-nutritional due to mineral binding but pose minimal risk in properly processed soy foods.	(Zhao et al., 2024)
Goitrogens	1-3 mg/g	Soybeans contain compounds that can interfere with thyroid function, particularly in individuals with iodine deficiency or pre-existing thyroid disorders.	Ensure adequate iodine intake. Prefer fermented soy. Space soy consumption away from thyroid meds Cook soybeans thoroughly	Soybeans contain several anti-nutritional factors (ANFs) that can interfere with nutrient absorption, digestion, and metabolic functions. Goitrogens are one class of ANFs, but soybeans also contain other compounds that may impact health.	(Goldsmith, 2024)
Protease Inhibitors	15-30mg/g Kunitz Trypsin Inhibitor (KTI)	Reduced Protein Digestibility Hypertrophy Growth Inhibition	Moist Heat (Boiling, Steaming) Dry Heat (Roasting, Toasting) Fermentation (Tempeh, Miso, Natto) Industrial Processing (Extrusion,	Protease inhibitors (PIs) are anti-nutritional compounds in soybeans that block digestive enzymes (trypsin and chymotrypsin), reducing protein digestion and absorption.	(Paul and Bhattacharjee, 2024)

			Autoclaving)		
Allergens	0.2–0.4% of allergic individuals worldwide.	Soybean allergens primarily impact human health rather than the plant itself, as they evolved as storage proteins (e.g., glycinin, β-conglycinin) or defense proteins (e.g., PR-10).	Boiling Autoclaving Extrusion Roasting	Soybeans contain multiple allergenic proteins that can trigger immune reactions in sensitive individuals. The major allergens are classified by the World Health Organization/International Union of Immunological Societies (WHO/IUIS) and have varying effects based on their stability and prevalence.	(Wiederstein et al., 2023)
Lipoxygenase	1-2%	Lipoxygenase (LOX) plays a significant role in soybean quality, affecting flavor, aroma, nutrition, and processing.	Blanching LOX-Null Beans Antioxidants Roasting Ultrafiltration	Lipoxygenase is an iron-containing dioxygenase enzyme that catalyzes the oxidation of polyunsaturated fatty acids (PUFAs) like linoleic acid and linolenic acid. It introduces molecular oxygen at the pentadiene position, forming hydroperoxides	(González-Gordo, 2023)
Glycosides	1–4 mg/g	Soybean glycosides contribute to plant resilience and offer health benefits (antioxidant, hormonal modulation) but require microbial conversion for full bioavailability. Their effects depend on processing, gut health, and individual physiology.	Glycosides' effect in Soybean enzymatic hydrolysis, chemical, and solvent extraction genetic & breeding approaches	Glycosides in soybeans are primarily secondary metabolites that play crucial roles in plant defense, nutrient storage, and human health. The most significant glycosides in soybeans are isoflavone glycosides, which contribute to both the nutritional benefits and potential anti-nutritional effects of soy products.	(Chen et al., 2021)
Polyphenols	0.2–1.5 mg/g	Polyphenols in soybeans primarily isoflavones, phenolic acids, tannins, and lignans play critical roles in plant defense, human health, and food quality.	Polyphenols effect in Soybean enzymatic hydrolysis chemical & solvent extraction genetic & breeding approaches	The complex nature and multiple roles of polyphenols in soybeans, from plant physiology to human nutrition. The dual nature of these compounds - as both beneficial nutrients and potential antinutrients - underscores the importance of proper processing and consumption practices.	(Sun et al., 2025)
Non-Starch Polysaccharides	15-25%	The multifaceted effects of soybean Non-Starch Polysaccharides, highlighting their dual role as both beneficial nutrients and potential anti-nutrients, with significant implications for human nutrition, animal feed efficiency, and food technology applications.	Physical Processing Methods Enzymatic Treatments Fermentation Techniques Chemical Methods Nutritional Impact Assessment	Soybean Non-Starch Polysaccharide structurally complex, functionally versatile components that significantly influence nutritional quality, processing behavior, and potential applications across multiple industries. Their unique composition bridges the gap between traditional food ingredients and novel biomaterials.	(Cheng et al., 2025)
Alkaloids	Low alkaloid concentrations	Soybean alkaloids present in relatively low concentrations, exert significant biological effects across multiple domains - from plant	Traditional Processing Methods (Soaking & Washing, Thermal Processing) Fermentation Techniques (Solid-	Soybean alkaloids represent a chemically diverse group of bioactive compounds with relatively low toxicity compared to other legumes. Their unique structural	(Hama et al., 2021)

		ecology to human nutrition. Their dual nature as both protective compounds and potential anti-nutrients underscores the importance of balanced approaches in soybean utilization, whether for food, feed, or pharmaceutical applications.	State Fermentation, Liquid Fermentation) Enzymatic Treatments (Commercial Enzyme Preparations, Endogenous Enzyme Activation) Physical Removal Methods (Dehulling, Fractionation) Chemical Treatments (Alkali Processing, Acid Modification)	features and biological activities make them important targets for both quality improvement in food applications and potential valorization in specialty chemical production.	
Metal Chelators	*13.9 mg/kg for Pb and 2.95 mg/kg for Cd*	Soybean metal chelators exert multifaceted effects spanning nutritional, biochemical, technological, and environmental domains. Their dual roles as both anti-nutrients and protective compounds necessitate careful management through processing and breeding approaches to optimize soybean utilization across various applications.	Enzymatic Degradation Methods (Phytase Treatment, Combined Enzyme Systems) Fermentation Techniques (Traditional Fermentation, Industrial-Scale Fermentation) Byproduct Valorization (Recovered Phytate, Mineral-Rich Fractions)	Description highlights the chemical diversity and functional importance of metal chelators in soybeans. Their dual roles in plant physiology and human nutrition make them critical components that influence both agricultural practices and food processing technologies.	(Shaffique et al., 2023)
Raffinose Family Oligosaccharides (RFOs)	*4-6%*	Raffinose Family Oligosaccharides in soybeans present both challenges and opportunities, with their effects being highly dependent on processing methods and intended use. While they can cause digestive issues in their intact form, proper processing can either mitigate these effects	Enzymatic Treatment Fermentation Processes Physical Processing Methods Thermal and Mechanical Treatments	RFOs represent a significant fraction of soybean carbohydrates with dual roles as both anti-nutritional factors and functional components. Their concentration and composition vary substantially depending on genetic and environmental factors, requiring tailored approaches for different food and feed applications. Modern analytical techniques allow precise characterization, enabling targeted modification through breeding	(Elango et al., 2022)

Global Soybean Production

Brazil, the United States of America, Argentina, and China are top-ranked soybean-producing countries. These countries' soybean productions are 121.80 million tonnes, 112.55 million tonnes, 48.80 million tonnes, and 19.60 million tonnes, respectively (IGC, 2023). Expected soybean worldwide production in 2023-24 is 399.5 metric tons, according to the United States Department of Agriculture (USDA, 2024). Brazil's soybean area production increased from 26.4 million hectares (Mha) to 55.2 million hectares (Mha), which is more than the 2 folds. Brazilian Amazon soybean cultivation area production increased from 0.4 hectares (Mha) to 4.6 hectares (Mha), which is 10-fold higher. Soybean has become the most-produced grain in Brazil in just 20 years, and this soybean market is continuously expanding in food and feed demand (Song et al., 2021). The U.S. soybean sector makes around 124billion dollars in the United States, viz., 85.7billion dollars in production and 9.8billion dollars in processed soybeans. It makes up 0.6 of the U.S. GDP. This industry supports about 0.37million people (LMC, 2019). It is mainly produced in East and Southeast Asia. Its nutritional traits and taste have also caught the attention of other countries. Its processed products also have high demand worldwide.

Worldwide perspective of soybean

Soybean is the world's second-largest producer of vegetable oil, with the United States leading in production. Soybeans are a globally consumed crop yielding a variety of products essential in everyday life (Mahanta et al., 2022). The crop's versatility is evident in its wide range of applications, including food products, biofuels, and animal feed (Gaonkar et al., 2019). When processed for consumption, soybean seeds are transformed into several key products, particularly for animal nutrition (Patel et al., 2020). Soybean meal, a significant byproduct, is produced by dehulling seeds of varying particle sizes, which are then extracted and expelled (Janocha et al., 2022). Currently, soybean cultivation covers approximately 75.5million hectares worldwide, accounting for nearly 6% of the world's arable land. The United States stands out as the leading producer of soybeans, reflecting the crop's significant role in the agricultural sector of this country and its contribution to global soybean supply (Kezar et al., 2023). By 2017, Brazil had emerged as the world leader in soybean exports by value, generating USD 26.1billion. The United States followed closely with exports valued at USD 22.8billion, and Argentina contributed USD 3 billion. This impressive export performance underscores the pivotal role of South America in the global soybean market. The largest importers of soybeans were China, with a staggering import value of USD 38.1 billion, followed by Mexico at USD 1.7billion and the Netherlands at USD 1.6 billion (Mcclain et al., 2018). The historical and projected trends in soybean production highlight the complex interplay between agricultural expansion, global demand and environmental sustainability. The growth of soybean cultivation in South America has been a response to market needs and economic opportunities.

Challenges in soybean production

One of the most important viral diseases that destroy soybeans is Soybean Mosaic Virus (SMV). In Pakistan, attack of pests is also a huge problem. Multiple insect pests like whitefly (*Bemisia tabaci*), armyworm (*Spodoptera litura*), Green clover worm Caterpillars (*Hypenas cabra*) and grasshoppers, etc. Weeds also cause a severe reduction in the production and yield of soybeans. The yield of soybean ranges from 12-20mounds per acre in different areas of Pakistan (Khurshid et al., 2017). Pakistan faces challenges in edible oil supply due to lower oil production (Hagely et al., 2020). It is the second-highest oil-producing crop (Akmalovna, 2022). Soybean production and yield are affected by ecological factors, viz., rainfall, sunlight, and climate change. These factors affect plants' height, size, and number of pods, as well as the size of the pods. These factors directly affect all the morphology of the plant (Shahin et al., 2023). Nonetheless, the poultry industry in Pakistan heavily depends on soymeal as a primary ingredient in poultry feed. According to the United States Department of Agriculture (U.S.D.A.), soymeal imports in Pakistan are expected to reach a record high of 2.5 million metric tons (MMT) in the current fiscal year. The experiences and challenges associated with soybean cultivation in Pakistan include several key areas; the introduction and adaptation of soybean germ plasm, breeding and varietal development, regional adaptability and management of biotic and abiotic stresses (Kandil et al., 2019). These factors collectively influence the success and sustainability of soybean farming in the region (Asad et al., 2020). The global significance of soybeans, coupled with the specific challenges faced in regions like Pakistan, underscores the need for continued research and development. Efforts to enhance genetic and breeding programs, improve regional adaptability and manage stress factors are essential for maximizing the potential of soybean cultivation. These advancements could help overcome current limitations and ensure that soybeans continue to be a valuable crop for food security and economic stability worldwide.

However, future projections indicate potential challenges for soybean production in South America, particularly in Brazil. Climate modeling research conducted by the World Bank suggests that soybean yields in Brazil could decline by 30% or more by 2050 due to climate change. This anticipated reduction poses significant concerns for global soybean supply, given Brazil's leading role in the industry. It also faces the looming threat of climate change. Addressing these challenges will require adaptive strategies and innovations in agricultural practices to sustain soybean production and meet future demands while mitigating environmental impacts.

Conclusion

Soybean (*Glycine max*) remains one of the most economically and nutritionally significant crops worldwide, serving as a critical source of plant-based protein, oil, and bioactive compounds. Its high nutritional value is counterbalanced by the presence of anti-nutritional factors, which can be effectively reduced through thermal and enzymatic processing. Additionally, soybean-derived isoflavones contribute to human and animal health, offering protective benefits against chronic diseases. However, global soybean production faces mounting challenges, including climate change, pest pressures, and regional cultivation constraints, particularly in countries like Pakistan, where yield limitations persist despite growing demand. The projected decline in productivity due to climate variability underscores the urgent need for resilient soybean varieties and sustainable agricultural practices.

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