



Review Article

The Multifunctional Role of *Soybean (Glycine max L.)*: Its Nutritional Value, Industrial Potential, and Future Projections

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Abstract: Soybean (*Glycine max L.*) has been a cornerstone of East Asian cuisine throughout human history, but in the last century, it has become a global agricultural commodity and economic powerhouse. It holds strategic importance as both a direct food source for human consumption and a key protein source for the livestock sector. The rising global population, changing dietary habits, and increasing demand for animal protein further underscore the importance of soybeans. The plant's high-quality protein and oil content, along with its full complement of essential amino acids, make it an indispensable source of protein in both human nutrition and the animal feed industry. The versatility of its uses, ranging from food products (such as tofu and soy milk) to industrial applications (including biodiesel and bioplastics), highlights its multifaceted economic value. This review examines the broad applications, importance, and future potential of the soybean, one of the most significant cultivated plants globally, within our food systems. In the face of challenges posed by population growth and climate change, innovative approaches such as genetic engineering, smart farming, and agroecological methods will help maximize the economic potential of soybeans while minimizing their environmental footprint. These approaches will ensure that soybeans remain a vital resource for our food security in the future.

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1. Introduction

Soybean (*Glycine max L.*), native to East Asia and cultivated for thousands of years, is one of the world's most economically and nutritionally essential plants. Archaeological evidence shows that soybeans were farmed in China as early as the 11th century BC. From that time onward, it became a staple food source on the Asian continent, and by the late 18th century, it had spread to Europe and America (Modgil, 2020).

Soybean, a member of the Fabaceae family, is an annual herbaceous plant that can grow to a height of 30 to 150 cm. The plant's root system has nodules that form a symbiotic relationship with

Rhizobium bacteria, which enrich the soil by fixing atmospheric nitrogen. This feature enables soybeans to enhance soil fertility and reduce the need for nitrogen fertilizer (Anderson et al., 2019). Its leaves are typically trifoliate and hairy. The small, white or purple flowers bloom in clusters along the plant's stem. The fruit of the plant is a short, hairy pod containing 2 to 4 seeds (Bastidas et al., 2008). Soybeans are a plant that thrives in warm climates. The most suitable temperature range for soybean germination is 18-25°C. During the plant's vegetative growth period, the ideal temperature range is from 20°C to 30°C. Temperatures should be above 25°C during critical phenological stages, such as flowering and pod formation. High temperatures, especially those exceeding 35°C, can lead to flower abortion and negatively affect pod development, resulting in yield losses. The plant is severely damaged by frost events below -2°C (Singh et al., 2005). Soybeans require regular and sufficient rainfall throughout their growing season. The flowering and seed-filling stages are the most sensitive periods to water stress. A lack of water during these critical periods has a direct and negative impact on seed size and, consequently, yield. An annual average of 600-750 mm of rainfall can be sufficient for good soybean development. Still, this rainfall must be evenly distributed across the periods when the plant needs it. Soybeans are classified as short-day plants, although most modern cultivated varieties are less sensitive to day length. Sufficient sunlight maximizes photosynthetic efficiency, ensuring healthy growth and high yields (Ahmad et al., 2014).

Soybeans yield best in well-drained, deep, and loamy soils. Heavy clay or waterlogged soils negatively affect plant development by preventing roots from getting enough oxygen. Similarly, sandy soils can be inefficient at retaining water and nutrients (Sharma et al., 2014). Good soil aeration is vital for the nitrogen fixation activity of Rhizobium bacteria in the root nodules. The optimal pH for soybeans is slightly acidic to neutral (pH 6.0-7.0). This pH range allows the plant to absorb nutrients from the soil effectively and enhances the functionality of the root nodules (Singh et al., 2005). In overly acidic or alkaline soils, nutrient uptake is impaired, and some minerals (primarily aluminum and manganese) can reach toxic levels. Soybeans require macronutrients such as phosphorus (P), potassium (K), and sulfur (S). Most of the plant's nitrogen (N) needs are met through biological nitrogen fixation from the atmosphere, facilitated by soil-based Rhizobium bacteria. This process helps enrich the soil, resulting in a lower need for nitrogen fertilizer compared to other crops (Shahid et al., 2009).

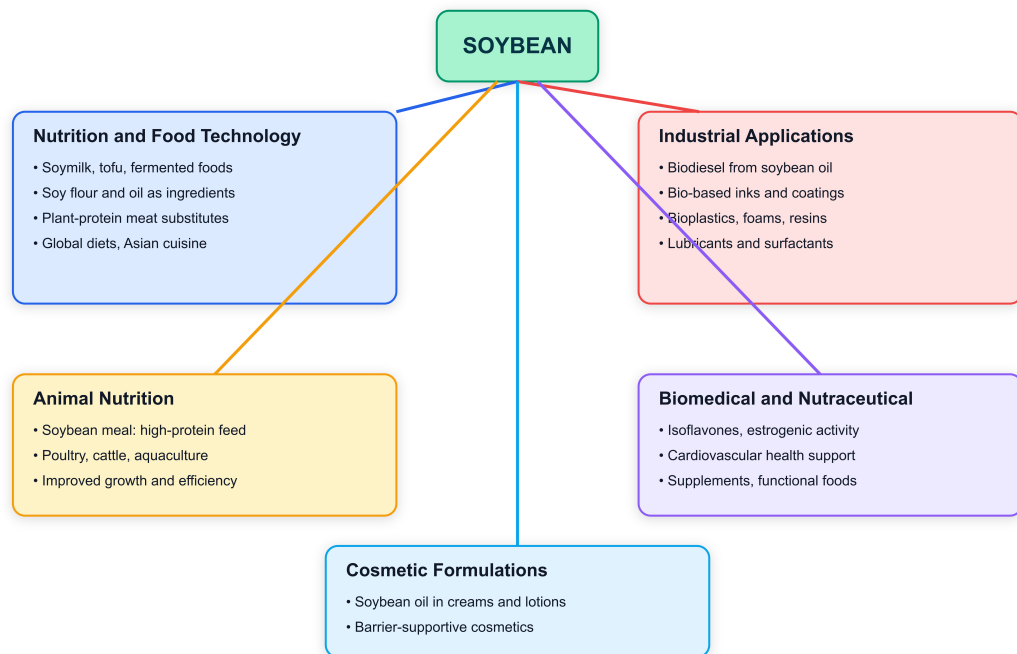
The nutritional content of soybeans makes them unique for both human and animal nutrition. Soybeans are a high-protein source, containing about 40% protein and 20% fat. This protein is a complete protein, meaning it contains all the essential amino acids that the human body requires. This gives it an exceptional place among plant-based proteins. The fat content is primarily composed of unsaturated fatty acids, such as linoleic acid (an omega-6 fatty acid) and oleic acid. Additionally, soybeans contain biologically active compounds, including isoflavones (such as genistein and daidzein), phytosterols, saponins, and phytoestrogens. These compounds are associated with potential health benefits, including improved heart health, bone density, and a reduced risk of certain types of cancer. Rich in fiber, vitamins (especially B vitamins and vitamin K), and minerals (including iron, calcium, and magnesium), soybeans hold strategic importance in global food security due to these properties (Singh et al., 2005).

The significance of this study lies in the fact that the soybean's role extends beyond being a high-nutritional-value product; it also holds a strategic position in terms of agricultural sustainability, food security, and industrial use. Soybeans are considered a critical resource for meeting the protein needs of the growing global population. They are gaining importance as a plant that must be comprehensively addressed due to its impacts on health, the economy, and ecological balance.

2. Importance and Uses of Soybeans

Soybeans have become a cornerstone of global agriculture, serving as both a high-value food product and a versatile industrial raw material. This importance stems from the plant's exceptional nutritional content, particularly its high protein (approximately 40%) and oil (around 20%) content. The protein found in soybean is considered a complete protein, containing all essential amino acids,

making it a valuable alternative to animal-derived proteins (Sharma et al., 2015). This characteristic is crucial for vegetarian and vegan diets, and it also holds strategic importance in the animal feed industry, where soybean meal is a primary protein supplement for cattle and poultry. Additionally, soybean is rich in bioactive compounds such as isoflavones, which are associated with potential health benefits, including a reduced risk of cardiovascular disease. The wide range of uses for soybean extends beyond direct consumption and feed to various industrial applications, such as biodiesel, lubricants, paints, and bioplastics. The plant's ability to perform symbiotic nitrogen fixation makes it a crucial component in sustainable agricultural practices, as it improves soil fertility and reduces the need for synthetic nitrogen fertilizers. This multifaceted value solidifies soybean's strategic role in ensuring global food security and promoting a more sustainable bioeconomy (Lee et al., 2011).



Soybean is a multifunctional commodity in food, feed, industry, health, and cosmetics.

Figure 1. Uses of soybeans

2.1. Biochemical Content and Functional Properties

The strategic importance of the soybean (*Glycine max* L.) from a biochemical standpoint is closely related to its unique macro- and micronutrient profile. From an agricultural production perspective, the strategic role of soybeans is based on three key factors (Singh et al., 2005).

2.1.1. High-Quality and Complete Protein Source

Soybeans are one of the highest-protein plants and possess one of the highest-quality protein structures among all plant sources. Its ability to contain all nine essential amino acids (histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, valine) in sufficient amounts makes it equivalent to, and in some cases even superior to, animal protein sources (Singh et al., 2005).

This characteristic enables soybean to play a crucial role in addressing the protein gap, particularly in vegetarian and vegan diets. In response to the increasing global demand for meat and dairy products, soybean meal has become the primary protein source in animal feed formulations, thereby making a critical, indirect contribution to the sustainability of animal

protein production (Hildebrand, 1986). The quality of protein is determined by the presence of a sufficient and balanced amount of the nine essential amino acids that our bodies cannot produce and must obtain from food. Animal proteins are generally called "complete proteins" because they contain all the essential amino acids. Most plant proteins, however, are deficient in one or more essential amino acids and are therefore classified as "incomplete proteins." The degree to which a consumed protein is broken down, absorbed by the digestive system, and made available for use by body tissues determines its digestibility score (Thuzar, 2010).

The superior position of soybeans among plant proteins is based not only on their high protein content but also on scientific data, such as their balanced essential amino acid profile and high digestibility rate, which enable them to compete with animal proteins. These characteristics make soybean an indispensable protein source for global food security and healthy nutrition strategies Hellal and Abdelhamid, 2013).

2.1.2. Fatty Acid Composition

Soybean seeds contain approximately 20% oil. This oil is rich in polyunsaturated fatty acids, particularly linoleic acid (an omega-6 fatty acid) (Brar et al., 1993). The fatty acids found in it are essential for human health and play a vital role in the cardiovascular system's functionality. As one of the most consumed products in the global vegetable oil market, soybean oil is widely used in both kitchens and the food industry. This ensures that soybean plays a central role not only in the protein but also in the global supply chain of healthy fat sources (Nwokolo, 1996).

2.1.3. Bioactive Compounds

The nutritional value of soybeans extends beyond macronutrients. The isoflavones it contains, such as genistein and daidzein, are phytoestrogens that have antioxidant and anti-inflammatory properties. Scientific studies show that these compounds may have potential therapeutic benefits in reducing the risk of heart disease, osteoporosis, and certain types of cancer (Arshad et al., 2006). These bioactive compounds elevate soy from being merely a food item to a nutraceutical product. This characteristic reinforces soy's strategic importance in the fields of human health and nutrition. With all these features, soybean is an indispensable strategic resource for meeting the protein and fat needs of the growing global population, ensuring food security, and supporting healthy nutrition. Soybean's multifaceted nutrient profile guarantees its place in global food systems (Bau et al., 1993).

2.2. INDUSTRIAL AREAS OF USE

Due to its rich protein and oil content, soybeans have become a primary raw material not only for the food industry but also for various industrial sectors, including chemistry, energy, and biomedicine. This versatile industrial use solidifies soybean's strategic position in the global economy (Sobko et.al., 2020).

2.2.1. Biofuel and Energy Sector

One of the most significant industrial uses of soybean oil is in the production of biodiesel. Thanks to its high oil content (20%), soybean (*Glycine max* L.) has become a strategic raw material in the global energy and chemical industries. In this regard, a primary industrial application of soybean is the production of biodiesel, which serves as a sustainable alternative to fossil fuels. Biodiesel is obtained by processing soybean oil through a transesterification process. In this process, triglycerides are converted into methyl esters (biodiesel) and byproducts, such as glycerin. Soybean-based biodiesel offers several advantages, including being a renewable resource, producing lower sulfur emissions, and being compatible with diesel engines with only minor modifications. This has played a crucial role

in the growth of the biodiesel market, particularly in major soybean-producing countries such as the United States and Brazil (Kim et al., 2017).

Biodiesel is a methyl ester fuel produced by processing fats and oils from biological sources through a chemical reaction called transesterification. Soybean oil is an ideal raw material for this process. During transesterification, the triglyceride molecules in soybean oil react with an alcohol (typically methanol) in the presence of a catalyst, converting them into fatty acid methyl esters (biodiesel) and glycerin as a by-product (Stupar and Specht, 2013). This process transforms the long-chain triglycerides found in soybean's natural structure into shorter-chain esters that can burn more efficiently in standard diesel engines. The industrial and environmental importance of soybean-based biodiesel stems from multiple factors:

Renewability and Sustainability: Unlike petroleum-based diesel, soybean oil biodiesel is a renewable resource. This helps to increase energy security by reducing dependence on fossil fuels and contributes to the preservation of natural resources.

Environmental Benefits: The combustion of soybean biodiesel produces lower emissions of carbon monoxide, particulate matter, and sulfur oxides compared to fossil diesel fuel. This helps to reduce air pollution and acid rain. Furthermore, the soybean plant's ability to absorb carbon dioxide from the atmosphere through photosynthesis during its growth creates a carbon-neutral cycle, contributing to the fight against climate change.

Economic and Strategic Value: As one of the most widely produced vegetable oils globally, soybean oil provides a significant and stable raw material source for biodiesel production. This significantly contributes to the economic development of major soybean-producing countries, such as the United States, Brazil, and Argentina, by strengthening their biodiesel industries. Additionally, biodiesel production diversifies the agricultural economy by adding value to soybean in a non-food sector.

Technological Compatibility: Soybean biodiesel can often be used directly in diesel engines with no modifications or only minor adjustments. This is a critical technological advantage that supports the widespread adoption of biodiesel by facilitating compatibility with existing infrastructure (Stupar and Specht, 2013).

2.2.2. Chemical Industry

Components derived from soybean are used in the production of a wide range of chemical products.

•**Plastics and Polymers:** Proteins and oils from soybeans are used in the synthesis of bio-based plastics and polymers. These bioplastics offer an environmentally friendly alternative to petroleum-based plastics and are utilized in a range of applications, from single-use products to automotive components. Soybean protein isolate can be used in the production of adhesives and coating materials.

•**Inks and Paints:** Soybean oil is the main component of soybean-based inks, which are more environmentally friendly compared to traditional petroleum-based inks. These inks offer more vibrant colors, are less abrasive to printing equipment, and allow for easier ink removal during the production of recycled paper. Similarly, soybean oil is also used in some types of paints and varnishes.

•**Cleaning Products and Cosmetics:** Soybean oil derivatives and glycerin are included in the formulation of soaps, detergents, and other surface cleaners. In the cosmetics industry, soybean is utilized in products such as lotions, creams, and shampoos due to its moisturizing and antioxidant properties (Sobko et al., 2020).

2.2.3. Biomedical and Pharmaceutical Fields

The bioactive compounds found in soybean have also attracted the interest of the pharmaceutical and biomedical industries. Isoflavones are known as phytoestrogens, which are compounds that may have potential benefits in alleviating menopausal symptoms or reducing the risk of osteoporosis. These compounds are used in the production of dietary supplements and some medications. Additionally, proteins and peptides isolated from soybeans are included in clinical nutrition products and nutritional supplements. The economic value of soybean is not limited to its

use in food. Soybean oil is used as an industrial raw material in the production of biodiesel, paints, inks, plastics, and soaps. This versatility shows that soybean supports not only food security but also the biofuel and chemical industries (Stupar and Specht, 2013).

3. Future Projections of Soybean

The increasing global demand for protein and the challenges posed by climate change are reshaping the future role of soybean. As the global population grows and consumption habits shift, the demand for protein is increasing at an unprecedented rate, while environmental challenges related to climate change are forcing agricultural production systems to undergo significant reshaping. At the intersection of these dynamics, the future role of the soybean (*Glycine max* L.) is at the heart of scientific and economic strategies. Thanks to its high nutritional value and versatile uses, soybean is positioned as a potential solution to these global challenges. The future of soybean is primarily being shaped by genetic engineering, sustainable production methods, and biotechnological innovations (Stupar and Specht, 2013).

Soybean cultivation in Turkey over the past decade has been characterized by fluctuations in cultivated area and production volume, alongside a relatively stable yield performance. While the extent of land allocated to soybean production experienced periodic expansions and contractions, productivity per unit area remained steady, with only modest year-to-year variations.

This relative yield stability suggests that technological advances and farming practices have been effective in mitigating adverse conditions to a certain degree. However, production volumes were more strongly influenced by shifts in the total cultivated area, rather than by improvements in yield efficiency. The close alignment between acreage and output underscores the dependence of national soybean production on land-use decisions.

Taken together, these trends indicate that the Turkish soybean sector is resilient and capable of recovery when cultivated area expands, yet its long-term growth remains constrained by the extent of available farmland. Sustained land allocation, supported by gradual technological improvements, appears to be essential for ensuring the sector's stability and for meeting potential future demand (Table 1.).

Table 1. Soybean Production in Turkey over the Last Decade (2014–2024)

Year	Cultivated Area (da)	Yield (kg/da)	Production (tons)
2014	343,178	437	150,000
2015	367,323	440	161,000
2016	381,804	432	165,000
2017	316,695	442	140,000
2018	328,483	426	140,000
2019	352,947	425	150,000
2020	351,343	442	155,225
2021	438,917	415	182,000
2022	380,090	408	155,000
2023	326,840	421	137,500
2024	437,113	412	180,000

3.1. Genetic Enhancements and Breeding Programs

To ensure future food security, increasing soybean production efficiency is essential. In this context, genetic engineering and modern breeding techniques are playing a critical role in enhancing soybean's adaptability and yield potential (Bau et al., 1997).

•**Drought and Heat Stress Tolerance:** The increasing drought and erratic rainfall patterns associated with climate change pose serious risks to soybean production. Scientific efforts are focused on developing genotypes that have higher water-use efficiency and greater resistance to drought and high temperatures. Gene-editing technologies, such as CRISPR-Cas9, are accelerating this process by enabling the precise modification of specific genes (Devi et al., 2011).

•**Disease and Pest Resistance:** Growing global trade and climate change facilitate the spread of new diseases and pests. The development of genetically resistant soybean varieties will minimize environmental impact by reducing the use of chemical pesticides and will also prevent yield losses.

•**Improved Nutritional Profile:** Future soybean varieties will not only be yield-oriented but also nutritionally enhanced. In addition to efforts to improve protein quality, research is ongoing to enhance the fatty acid composition for greater benefit to human health and to increase the amount of bioactive compounds (e.g., isoflavones). This will strengthen soybean's position in the functional food and nutraceutical markets (Singh et al., 2005).

3.2. Sustainability and Alternative Production Methods

The strategic role of soybeans (*Glycine max* L.) in meeting the global demand for protein and oil has brought the environmental sustainability of their agricultural production to the forefront. Problems caused by conventional soybean farming, such as deforestation, soil degradation, and water pollution, have led the scientific and industrial communities to research alternative production methods that are more sustainable and minimize environmental impact. These approaches cover a wide range, from biotechnological solutions to innovative farming Technologies (Kim et al., 2017).

3.2.1. Smart Farming and Digitalization

The future of soybean production relies on innovative farming practices that optimize resource use and reduce environmental impact.

•**Data-Driven Management:** Digital technologies like satellite imagery, drones, and ground sensors continuously monitor soil moisture, plant health, and nutrient levels. This data enables farmers to precisely determine the exact amount of fertilizer and water needed for their crops, thereby preventing waste of resources. This precision management also minimizes the use of pesticides and herbicides, which prevents the pollution of water sources.

•**Automation:** In future soybean fields, many operations—from planting to harvesting—can be automated with robotic systems. This increases the efficiency of agricultural operations while reducing human error and environmental risks (Kim et al., 2017).

3.2.2. Agroecological Approaches

To mitigate the adverse effects of monoculture farming, agroecological methods are being increasingly adopted for sustainable soybean production.

Crop Rotation: The soybean plant's ability to fix nitrogen in the soil makes it an ideal part of crop rotation systems. Planting soybean improves the soil's nutrient balance, allowing subsequent crops to require less nitrogen fertilizer. This method preserves soil health while reducing the use of chemical fertilizers.

Intercropping, which involves growing different crops, such as soybeans with corn or wheat, simultaneously increases biodiversity, helps maintain the soil's nutrient balance, and assists in the natural control of pest populations (Kim et al., 2017).

3.2.3. Alternative Production Systems

In addition to traditional field farming, alternative systems are being explored to further reduce the environmental impact of soybean production.

•**Vertical Farming and Controlled Environments:** Vertical farming can make soybean production possible in areas with limited land, especially in cities. In closed and controlled systems, water and nutrients can be recycled, resulting in significantly reduced water consumption. This method also minimizes crop losses by providing a production environment that is independent of external weather conditions.

•**Hydroponic and Aeroponic Systems:** These systems, which use water-based nutrient solutions instead of soil, have the potential to maximize water efficiency while nearly eliminating the need for pesticides and herbicides (Stupar and Specht, 2013).

3.2.4. Integration into the Bioeconomy

Sustainability is not limited to production methods alone. The integration of soybean with non-food industries plays a significant role in reducing its overall environmental impact. Biodiesel and bio-based plastics derived from soybean contribute to the sustainability of the energy and chemical industries by reducing dependence on fossil fuels. The use of soybean by-products in these industrial processes also increases resource efficiency. In conclusion, the role of soybean in the global food system is being reshaped by a growing sense of ecological responsibility. Smart farming, agroecological approaches, and alternative production systems are replacing traditional farming methods. These integrated strategies reduce the environmental impact of soybean, ensuring both food security and the preservation of the planet's long-term health (Kim et al., 2017).

4. Conclusion

Due to its unique nutritional profile and versatile applications, soybeans have been positioned as one of the most critical agricultural commodities of the 21st century. This review shows that soybean not only offers a solution to current food security problems but will also play an indispensable role in meeting future global needs for protein, oil, and industrial raw materials.

Soybean stands out among plant-based proteins as a complete protein source with high biological value. The presence of all essential amino acids and valuable polyunsaturated fatty acids makes it a strategic component in both human nutrition and the animal feed sector. This highlights the key role soybean plays in closing the protein gap for the growing global population and increasing the efficiency of animal protein production.

With its high protein and oil content, the soybean plant is one of the main pillars of global food security. Thanks to its wide range of uses, it makes significant contributions to both agricultural economies and various industries. However, to meet future demand and minimize environmental impact, innovative genetic and sustainability approaches are needed. Soybean will continue to be a vital tool in the fight against global challenges, such as climate change and population growth. Still, environmental responsibilities must not be overlooked in this process. Sustainable production methods and scientific advancements will ensure soybean remains an indispensable part of our food system in the future.

In the future, soybean's role will be further strengthened by genetic engineering and technological innovations. Smart farming (precision agriculture) technologies and agroecological approaches will optimize the use of water, fertilizers, and pesticides, thereby reducing the environmental footprint of soybean production. At the same time, gene-editing techniques like CRISPR-Cas9 will enable the development of soybean varieties that are more resistant to drought, diseases, and pests, thereby ensuring stability and efficiency in production.

In conclusion, the soybean will remain a cornerstone of global food systems. In the future, to meet the increasing demand for areas such as food, feed, and industrial biofuels, a combination of scientific innovation and environmental responsibility principles is essential. This integrated approach

will both maximize the economic value of soybean and secure the planet's long-term sustainability. The multifaceted importance of soybean makes it an indispensable strategic resource for not only today's but also tomorrow's food systems.

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