



Brazil as a Global Leader in Soybean Production: Historical Trends, Current Status, and Future Perspectives

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Abstract

Soybean (*Glycine max* L.) is the most widely cultivated oilseed globally due to its nutritional value, versatility, and economic importance. It accounts for nearly 25% of global vegetable oil production and is a key component in animal feed, making it strategic for food and energy security. Brazil has emerged as the world leader in production and exports, contributing ~40% of the 2024/25 harvest with approximately 171.5 million tons over ~47.4 million ha. This expansion has been driven by public policies, research investments, territorial expansion, and the widespread adoption of genetically modified (GM) varieties, now covering over 99% of the cultivated area. The transformation of the Cerrado into a major agricultural frontier, combined with technological advances, has resulted in substantial increases in area, production, and yield (~3.6 t ha⁻¹ in 2024/25). Despite these gains, yields remain far below the crop's potential (>8.9 t ha⁻¹ in experimental fields), highlighting the presence of a persistent yield gap between current and attainable productivity levels. This review synthesizes the historical evolution of soybean production in Brazil and examines the main production drivers, structural constraints, and emerging innovation pathways shaping future productivity. Particular attention is given to the challenges associated with climate variability, environmental regulation, and increasing global demand for sustainable supply chains. The analysis highlights that future production gains will depend on the transition from expansion-driven growth to sustainable intensification, supported by technological innovation, improved management strategies, and effective governance.

Keywords Agricultural innovation · Biotechnology · Crop management · Sustainable intensification · Tropical agriculture · Yield gap

Introduction

Soybean [*Glycine max* (L.) Merr.] is recognized as both an economic and nutritional resource, and is currently the most widely cultivated oilseed globally (Sugiyama, 2019; Sugiyama et al., 2023). Soybean grains are rich in protein (44–48%) and oil (15–25%), and contain relevant amounts of carbohydrates, fatty acids, and micronutrients (Perkins,

1995; Bueno et al., 2018; Dilawari et al., 2022). It accounts for ~25% of global vegetable oil production and is a major component of global agri-food systems (Snyder et al., 2009; Klein & Luna, 2021). Approximately 85% of global production is processed into meal and oil, with soybean meal predominantly used in animal feed (>95%), reinforcing its importance as the most economically relevant legume worldwide (Dilawari et al., 2022; Modgil et al., 2021; USDA, 2025).

During the 2023/24 growing season, global soybean production reached 395 million metric tons. For 2024/25, production exceeded 420 million metric tons (~7% increase) (USDA, 2025; CONAB, 2025a). This expansion has been driven by increasing global demand for protein and vegetable oil, with production rising by more than 15% over the past decade (USDA, 2025). South America has emerged as the leading soybean-producing region, with Brazil consolidating its position as the world's largest producer and

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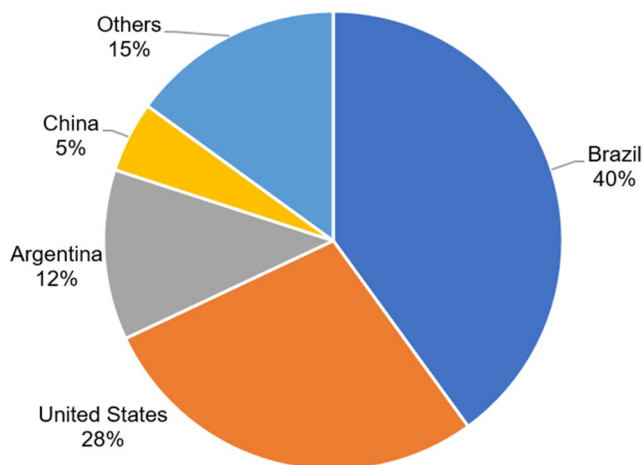


Fig. 1 Top soybean-producing countries in the season of 2024/2025. Adapted from USDA (2025)

exporter (~40% of global output), followed by the United States (29%) and Argentina (12%) (Fig. 1) (USDA, 2025). The widespread adoption of genetically modified (GM) crops has further enhanced grain production through the use of herbicide- and insect-resistant varieties, increasing management flexibility and contributing to productivity gains.

In Brazil, GM soybean adoption began in the early 2000s and was later formalized through national biosafety legislation, enabling rapid expansion of transgenic cultivation (Brazil, 2003; Brazil, 2005). GM soybean adoption began in the early 2000s and was later formalized through national biosafety legislation, enabling rapid expansion of transgenic cultivation (Brazil, 2003; Brazil, 2005). Following its introduction, GM soybean rapidly expanded from limited initial adoption to near-total coverage, contributing to increases in cultivated area and yield.

By 2024/25, the total area had more than doubled to 47.4 million ha, 99% under GM varieties, with an average

yield of 3.62 t ha⁻¹ (Fig. 2A), representing ~45% of global GM soybean acreage (AGBIOINVESTOR, 2025). Over the period (2002/03–2024/25), total soybean production rose from 52 to 171.5 million tons (Fig. 2B), representing a 3.3-fold increase. This growth reflects both expansion in cultivated area and improvements in yield. These gains were associated with the expansion of soybean cultivation into the Brazilian Cerrado under non-tillage systems (Bartz et al., 2025), combined with increasing global demand. Importantly, these gains cannot be attributed solely to GM adoption, but rather to the interaction between genetic, agronomic, and management innovations

Among the main biotechnological innovations, glyphosate-tolerant platforms such as Roundup Ready® (RR, 1998) and Roundup Ready 2® (RR2, 2010) marked the initial phase of GM soybean adoption. Subsequent stacked technologies, including Intacta RR2 PRO® (2010) and Intacta 2 Xtend® (2018), combined herbicide tolerance with Bt-mediated insect resistance and broadened pest and weed management strategies (Table 1). Other platforms, such as LibertyLink® (LL) and Enlist E3®/Conkasta E3®, further expanded tolerance to multiple herbicides (e.g., glyphosate, glufosinate, and 2,4-D), enhancing management flexibility. Additional traits targeting oil composition and herbicide tolerance have also been developed, although some remain restricted to specific markets or uses (Table 1). More recently, stacked-trait platforms such as Vyconic™ (Intacta 5⁺ in Brazil) aim to expand herbicide tolerance through multiple modes of action (Bayer, 2025). However, their commercial deployment remains contingent on international regulatory approvals and market acceptance, highlighting the increasing influence of global governance on technological adoption.

This review analyzes the evolution of soybean production in Brazil using an integrative framework based on

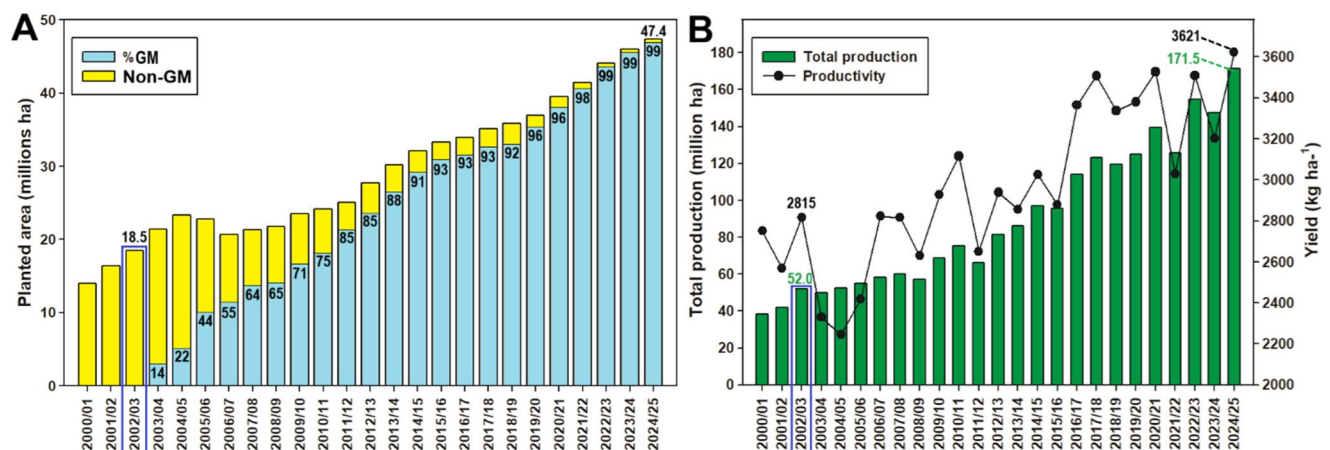


Fig. 2 Evolution of (A) soybean planted area, including the percentage adoption of genetically modified (GM) varieties, and (B) total production and average yield per hectare in Brazil between the 2000/01

and 2024/25 seasons. The blue box marks the last crop season without GM varieties. Adapted from AGBIOINVESTOR (2025) and CONAB (2025a)

Table 1 Chronological history of herbicide-tolerant transgenic technologies approved or under regulatory consideration for soybean cultivation in Brazil

Technology	Herbicide/trait	Registered events	Gene	Donor species	Year
Roundup Ready®	Glyphosate tolerance	GTS 40–3–2	<i>cp4 epsps</i>	<i>Agrobacterium tumefaciens</i>	1998
LibertyLink®	Glufosinate tolerance	A2704-12, A5547-127	<i>pat</i>	<i>Streptomyces viridochromogenes</i>	2010
Roundup Ready 2®	Glyphosate tolerance	MON89788	<i>cp4 epsps</i>	<i>Agrobacterium tumefaciens</i>	2010
Intacta RR2 PRO®	Glyphosate tolerance	MON87701 ×MON89788	<i>cp4 epsps, cry1Ac</i>	<i>Agrobacterium tumefaciens</i> and <i>Bacillus thuringiensis</i>	2010
Intacta 2 Xtend®	Glyphosate + dicamba tolerance and insect resistance	MON87751 ×MON87708 ×MON87701 ×MON89788	<i>cp4 epsps, dmo, cry1A.105, cry2Ab2, cry1Ac</i>	<i>Agrobacterium tumefaciens, Stenotrophomonas maltophilia</i> and <i>Bacillus thuringiensis</i>	2018
Enlist E3®	Glyphosate + glufosinate + 2,4-D tolerance	DAS44406	<i>aad-12, pat, 2mEPSPS</i>	<i>Delftia acidovorans, Streptomyces viridochromogenes</i> and <i>Zea mays</i>	2015
Conkesta E3®	Glyphosate + glufosinate + 2,4-D tolerance and insect resistance	DAS81419 ×DAS44406	<i>aad-12, pat, 2mEPSPS, cry1Ac, cry1F</i>	<i>Delftia acidovorans, Streptomyces viridochromogenes, Zea mays</i> and <i>Bacillus thuringiensis</i>	2017
Plenish®	Modified oil profile + glyphosate tolerance	DP305423 ×GTS 40–3–2	<i>gm-fad2-1, gm-hra, cp4 epsps</i>	<i>Glycine max</i> and <i>Agrobacterium tumefaciens</i>	2018*
Treus®	ALS inhibitor tolerance + modified oil	DP305423	<i>gm-fad2-1, gm-hra</i>	<i>Glycine max</i>	2018*
Intacta 5 ⁺	Multiple herbicide tolerance (glyphosate, dicamba, mesotrione, glufosinate, 2,4-D) + insect resistance	MON87701 ×MON87751 ×MON89788 ×MON94313 ×MON94637	<i>cp4 epsps, dmo, pat, ft_t.1, cry1B.2, cry1A.2</i>	<i>Agrobacterium tumefaciens, Stenotrophomonas maltophilia, Oryza sativa, Streptomyces viridochromogenes, Sphingobium herbicidovorans</i> , and <i>Bacillus thuringiensis</i>	2024**

* Not approved for production, only for animal consumption. ** Approved in Brazil (CTNBio); specific event designations are not publicly disclosed; pending international approvals

production drivers, structural constraints, and innovation pathways. It aims to provide a critical assessment of the factors shaping productivity gains, yield gaps, and the long-term sustainability of soybean-based production systems under tropical conditions.

Methodological Approach

This study adopts a narrative, integrative, and critical review approach to examine the historical, agronomic, technological, and policy-related drivers of soybean production in Brazil. The review is structured around a conceptual framework that integrates production drivers, structural constraints, and innovation pathways, guiding both the selection and interpretation of the literature.

The literature survey was conducted using peer-reviewed articles indexed in international databases (e.g., Web of Science and Scopus), complemented by official datasets and institutional reports from organizations such as USDA, FAO, CONAB, EMBRAPA, IBGE, and MAPA. Searches were performed using combinations of keywords such as “soybean production,” “Brazil,” “yield gap,” “sustainable intensification,” “biotechnology,” and “agricultural policy.” The review primarily considered publications from 2000

to 2025, with emphasis on recent studies (2020–2025) to ensure an up-to-date analysis.

Given its narrative nature, exhaustive coverage was not intended; instead, emphasis was placed on studies that contribute conceptually or empirically to understanding yield dynamics, technological adoption, and sustainability trade-offs. Studies were selected based on relevance, methodological robustness, and alignment with the analytical framework adopted in this review. Information was synthesized qualitatively, focusing on identifying converging evidence, knowledge gaps, and emerging research fronts.

The analysis was organized into three interconnected dimensions: (i) production drivers, (ii) structural and environmental constraints, and (iii) innovation pathways. Although this approach enables a comprehensive and integrative assessment of the soybean production system, it is subject to limitations inherent to narrative reviews, including potential selection bias and limited reproducibility. These limitations were mitigated by prioritizing high-quality sources and cross-referencing evidence across multiple data types.

Soybean History

Soybean is a leguminous crop of Asian origin that has become one of the most important agricultural commodities worldwide due to its versatility and high nutritional value. It was domesticated more than 9,000 years ago from the wild species *Glycine soja* Sieb. & Zucc., native to East Asia, including China, Japan, Korea, Russia, and Taiwan (Hymowitz, 2008). Historical evidence indicates that soybean cultivation dates back to the Shang dynasty (1700–1100 BCE) (Hymowitz, 2008). Soybean cultivation subsequently spread throughout East Asia, becoming an important component of local diets.

In 1765, soybean seeds were introduced to North America by a British colonist who brought them from China to the colony of Georgia. Soybean-derived products such as tofu, miso, tempeh, and soy sauce were already consumed outside Asia prior to its cultivation in the Americas and remain widely consumed today (Shurtleff & Aoyagi, 1983; Hymowitz, 2008).

Soybean cultivation remained largely confined to Asia until the mid-20th century, when production expanded significantly in the Western Hemisphere. Countries such as the United States, Brazil, and Argentina intensified production and are now the three largest soybean producers globally (Chang et al., 2015). Originally used as a forage crop, soybean became a major commodity during the mid-20th century, driven by technological advances and increasing market demand (Alves et al., 2008; Hart, 2017; Mishra et al., 2024).

The consolidation of soybean as a major global crop accelerated during the Green Revolution, supported by advances in fertilization, mechanization, and agricultural research (Langthaler, 2020; Nehring, 2022; Liu et al., 2020). In recent decades, soybean has exhibited one of the fastest increases in cultivated area among major crops (Hamza et al., 2024). These global transformations strongly influenced Brazilian agriculture, where soybean evolved from a marginal crop to one of the main pillars of the national agricultural economy. This transformation was driven by technological advances, institutional support, and land-use changes that enabled large-scale expansion under tropical conditions (Liu et al., 2019).

Brazilian Context

Soybean was introduced in Brazil in 1882, but it was only from the 1940s onward that the crop began to gain economic relevance. Initially cultivated in the southern region, particularly in Rio Grande do Sul, soybean gradually expanded to other regions, supported by agricultural

incentive policies and research investments (Oliveira, 2017; Rocha et al., 2022). The establishment of the Brazilian Agricultural Research Corporation (EMBRAPA) in 1973 was a key milestone, enabling the development of tropical-adapted varieties and the expansion of soybean cultivation into the Brazilian Cerrado (Santos et al., 2021; Umburanas et al., 2022; Boaventura et al., 2023).

The migratory movement known as the “southerners’ march,” primarily driven by farmers from Rio Grande do Sul, was a key process in the reconfiguration of Brazil’s agricultural geography in the late 1980s. Farmers migrated toward new agricultural frontiers characterized by lower land costs and greater availability of arable areas. This process led to the consolidation of key grain-producing regions across the Central-West and Southeast of Brazil. More recently, the MATOPIBA (Maranhão, Tocantins, Piauí, and Bahia) region has emerged as a prominent new agricultural frontier, characterized by favorable climatic conditions and increasing technological adoption. In the 2023/2024 season, MATOPIBA produced approximately 20.3 million tons of grains over 5.9 million hectares, with projections indicating continued expansion, further reinforcing its role as an agricultural frontier in Brazil (EMBRAPA, 2025). Emerging regions such as SEALBA (Sergipe, Alagoas, and Bahia) also present opportunities for expansion due to logistical advantages and diversified production systems.

Brazil consolidated its position as the largest soybean producer in 2019/2020, when it surpassed the United States (USDA, 2021; CONAB, 2025b). Since then, production has shown interannual variability driven by climatic conditions, but with a clear upward trend, reaching record levels in the last season (2024/2025), with planted area exceeding 47 million hectares and national production surpassing 170 million tons (CONAB, 2025b; Reis et al., 2025). Exports have followed this trend, exceeding 120 million tons and generating over USD 50 billion, supported by strong international demand (Toloi et al., 2021; Jraissati, 2025; USDA, 2025).

National productivity has fluctuated due to climatic variability and technology adoption, with average yields around 3.5 t ha⁻¹ and higher values in leading states such as Mato Grosso, which accounts for approximately 28% of national production, with output approaching 50 million tons (Fig. 3A) (Gusso et al., 2014; CONAB, 2025c; Carvalho et al., 2024; Leite-Filho et al., 2025).

Soybean is cultivated across most Brazilian states, reflecting its adaptability to diverse edaphoclimatic conditions. Goiás and Mato Grosso exhibit the highest productivity levels (~4,183 and 4,028 kg ha⁻¹, respectively), while Paraná remains above the national average (~3,739 kg ha⁻¹). In contrast, Rio Grande do Sul shows the lowest yields (~2,342 kg ha⁻¹), likely due to recurrent climatic constraints. Across

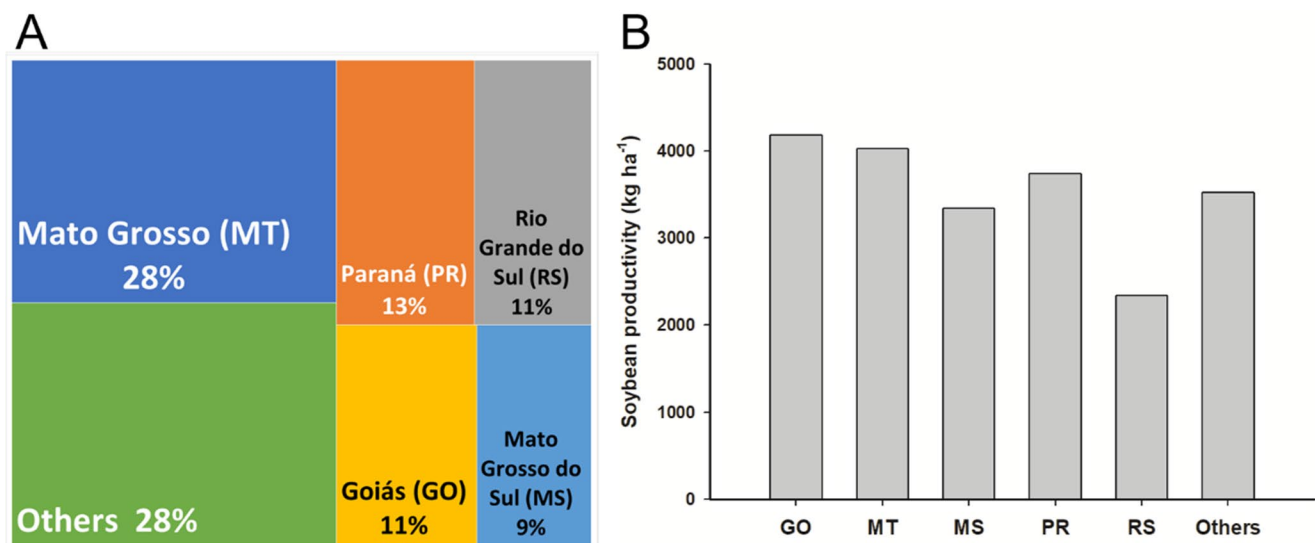


Fig. 3 Percentage of agricultural production and productivity by state in Brazil. source: adapted from USDA (2025) and CONAB (2025a)

other regions, productivity ranges from $\sim 3,000$ to $4,100 \text{ kg ha}^{-1}$, with a national average of $\sim 3,500 \text{ kg ha}^{-1}$ (Fig. 3B) (CONAB, 2025b). These patterns highlight the importance of region-specific strategies to improve efficiency and stability in national production.

Brazil exhibits structural advantages compared to the United States, particularly due to the rapid expansion of arable land, superior edaphic conditions, favorable climatic patterns, and lower production costs (Williams, 2025). The expansion of soybean production between 2019 and 2023 was driven by multiple factors, including the advancement of the agricultural frontier over the Cerrado, investments in biotechnology, genetic improvement programs, efficient soil management, and optimized input use (Benites et al., 2023; Klein & Luna, 2023; Voora et al., 2024).

External demand, particularly from China, has remained the main driver of the crop, stimulating increases in cultivated area and overall production. Projections for the 2025/2026 season suggest production in the range of approximately 175–178 million tons, with cultivated area approaching 49 million hectares, according to official estimates (CONAB, 2026). However, these projections remain sensitive to climatic variability and methodological differences among data sources, with some estimates exceeding 180 million tons under favorable conditions. This reinforces soybean's central role in Brazil's agro-export economy (Voora et al., 2024).

Soybean production in Brazil involves a large number of smallholder farms; however, these represent the majority in number rather than in production volume. Among approximately 236,000 soybean-producing farms, most are concentrated in the South (83%). In contrast, production is predominantly concentrated in medium- and large-scale

operations, particularly in the Central-West region, which accounts for the majority of national output. Despite the wide distribution of farms, the South, Central-West, and Southeast regions together account for approximately 98% of national production (MAPBIOMAS).

Vision 2030: Trajectory of Brazilian Agriculture

The Brazilian agricultural system has evolved from a traditional model, characterized by limited adoption of modern technologies, to one of the largest and most competitive agricultural systems worldwide (Pereira et al., 2012; Martha & Lopes, 2023). This transformation, driven by technological innovation and institutional support, has positioned Brazil as a leading global producer and exporter.

The *Vision 2030* represents a strategic and analytical framework aligned with the United Nations Sustainable Development Goals (SDGs), aiming to coordinate science, innovation, public policy, and territorial management (EMBRAPA, 2018). However, as an institutionally driven agenda, it is primarily based on prospective scenarios and internal projections, which may not fully capture the complexity and heterogeneity of Brazil's agricultural systems. From a scientific standpoint, *Vision 2030* offers a useful framework to assess whether Brazil's production model can reconcile yield growth with increasing environmental and market constraints; nevertheless, its assumptions require independent validation and should be interpreted with caution, particularly under rapidly changing climatic and geopolitical conditions.

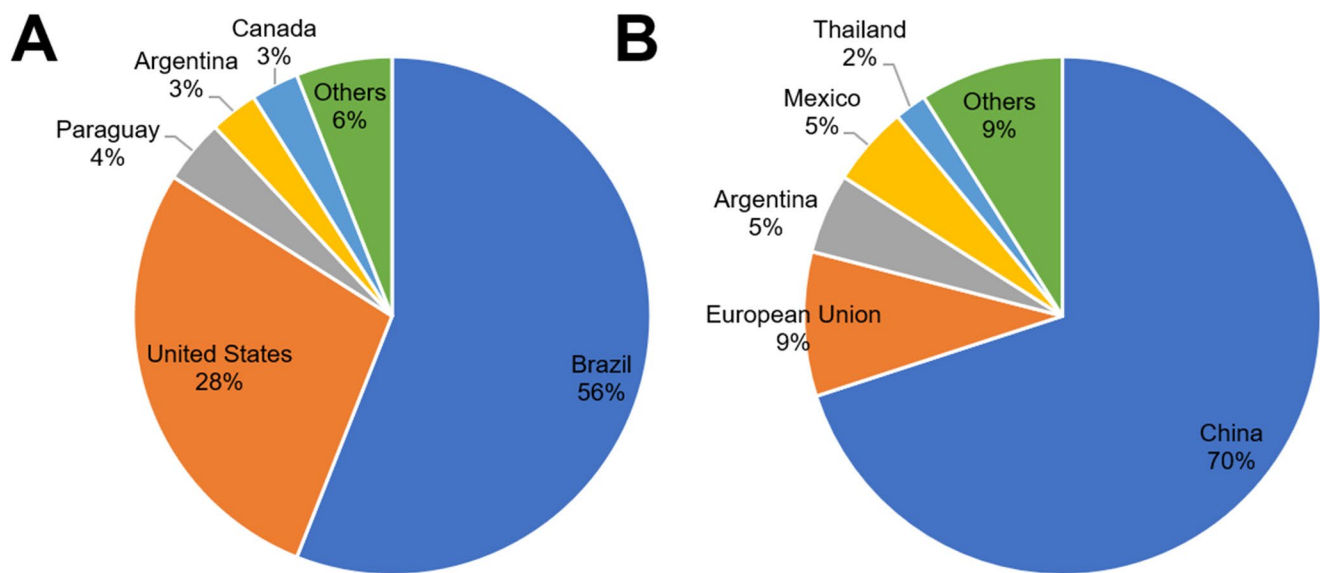


Fig. 4 A. Top soybean exporting (A) and importing (B) countries. Adapted from USDA (2025)

Historically, Brazilian economic development has been closely linked to commodity-based export cycles, resulting in recurrent exposure to external market volatility. By the late 1990s, soybeans and iron ore still represented a relatively small share of total exports (Rada & Valdés, 2012; Søndergaard et al., 2023). Subsequent decades marked a structural shift, with agriculture (particularly grain production) becoming central to economic growth (EMBRAPA, 2018). In response to increasing global demand and market integration, the Brazilian government implemented policies aimed at enhancing agricultural productivity, including investments in research and development, rural extension, and subsidized credit (Chaddad, 2015). These policies strengthened the national innovation system, facilitating technology transfer and accelerating the adoption of improved crop management and genetic technologies (Buainain et al., 2020; Klein & Luna, 2021). This model, however, has reinforced dependence on commodity exports, increasing vulnerability to price volatility and external demand shocks.

Economic policies also promoted investments in energy and transport infrastructure, particularly road networks, strengthening the integration between agricultural production areas and domestic and international markets. Although this reduced transaction costs and facilitated market integration, persistent logistical bottlenecks and regional disparities still limit efficiency, particularly in frontier regions.

Between 2000 and 2024, the expansion of cultivated land and productivity gains occurred simultaneously, reflecting territorial expansion and technological intensification (CONAB, 2025b). Soybeans remain the leading commodity, benefiting from shifts in the global agricultural trade landscape. Trade disputes, particularly between the United

States and China, have periodically reshaped demand patterns, temporarily favoring Brazilian exports. These advantages are, however, circumstantial and volatile, and do not constitute a stable basis for long-term competitiveness, which will depend on sustained productivity gains, cost efficiency, and compliance with sustainability standards (Reuters, 2025).

International agricultural trade reinforces this scenario. The United States and Brazil account for a substantial share of global agricultural exports, while China and the European Union represent the main importers (Fig. 4A, B) (FAO, 2024). Although supported by Brazil's capacity to expand supply under tropical conditions, this position is increasingly conditioned by environmental regulations, carbon requirements, and traceability demands, which may constrain future expansion.

In 2024/2025, Brazil ranked among the world's largest producers of soybeans (171 million t), maize (132 million t), and sugarcane (578 million t). This productive base supports large-scale animal protein production, including beef, poultry, and pork (IBGE; ABPA; ABIEC, 2025). The strong integration between grain and livestock systems reinforces soybean's central role in the agri-food system, but also intensifies pressure on land use and natural resources, raising concerns about long-term sustainability.

Over the past two centuries, innovation has been consolidated as a cornerstone of Brazilian agriculture (Andrade et al., 2020). More recently, it has shifted toward sustainability-oriented strategies, including low-carbon agriculture, recovery of degraded pastures, and integrated production systems. It is estimated that approximately 28 million hectares of planted pastures in Brazil show intermediate to severe levels of degradation (EMBRAPA, 2024). These areas represent both a

structural challenge and a potential opportunity for agricultural expansion without further deforestation. A substantial share of future expansion may occur through pasture recovery, particularly in the Cerrado, where nearly 32 million hectares of cultivated pastures exhibit some degree of degradation (Bolfé et al., 2024; Reis et al., 2025). However, large-scale implementation remains constrained by economic feasibility, access to technology, and institutional capacity.

Soybean expansion in the Cerrado between 2000 and 2021 increased nearly threefold, from 7.43 million to 21.43 million hectares (Agrosatélite Geotecnologia Aplicada Ltda, 2022), driven by tropical-adapted cultivars, biological nitrogen fixation, and improved soil management (Hungria et al., 2020). Despite these advances, expansion has been associated with land-use change and ecosystem pressure, increasingly scrutinized in global markets.

Overall, the *Vision 2030* framework highlights that Brazil's future leadership in soybean production will depend less on continued territorial expansion and more on sustainable intensification, innovation, and effective governance. Achieving this transition, however, will require overcoming structural constraints related to climate variability, infrastructure limitations, and the enforcement of environmental regulations, which remain key challenges to long-term sustainability.

Innovations to Enhance Productivity

In the 2024/25 growing season, the national average soybean yield in Brazil reached 3,560 kg ha⁻¹, slightly exceeding the previous cycle (2023/24: 3,527 kg ha⁻¹) (CONAB, 2025). Despite this advancement, a substantial gap remains relative to the potential yield observed in high-performing areas, which can reach 8,945 kg ha⁻¹ (Battisti et al., 2018; Zambon et al., 2023). This yield gap represents a central challenge for Brazilian soybean production and underscores the need for improved management and technological integration.

Technological innovation plays a key role in improving soybean productivity and resilience, particularly through advances in biotechnology, precision agriculture, and improved crop management (Santos et al., 2023; Şimşek, 2025; Vasavi et al., 2025). Genetic breeding has contributed to the development of high-yielding, stress-tolerant cultivars with improved disease resistance (Vargas-Almendra et al., 2024).

The adoption of low-carbon agriculture practices, including those promoted by the ABC and ABC+ Plans, is essential to mitigate climate risks and improve system resilience (Bigolin & Talamini, 2024). In parallel, digital agriculture tools (e.g., AI, big data, IoT) enable more efficient and precise management decisions (Viola & Mendes, 2022). They

also support the optimization of input use and the integration of production systems, including crop–livestock systems (Bueno et al., 2023).

Biological responses such as hormesis have also been investigated, although their practical relevance remains limited. Hormesis is defined as a biphasic dose–response phenomenon in which low doses of a stressor stimulate biological processes, while higher doses are inhibitory (Belz & Duke, 2014). Herbicides, particularly glyphosate, are among the most commonly reported agents inducing hormetic responses in plants under controlled conditions. In soybean, low-dose glyphosate applications have been associated with increases in vegetative growth and biomass in specific experimental settings, with occasional yield responses reported (Velini et al., 2008; Silva et al., 2019; Krenchinski et al., 2024). However, these responses are highly context-dependent, varying according to genotype, environmental conditions, and application timing, which limits their reproducibility under field conditions. While alternative application strategies may improve response consistency, the overall evidence remains variable and insufficient to support large-scale agronomic adoption (Krenchinski et al., 2024; Milosevic et al., 2025). Therefore, hormesis should be interpreted as an experimental phenomenon with limited practical relevance compared to established productivity-enhancing technologies.

Biological inputs (bioinputs) represent another component of sustainable intensification strategies. Co-inoculation with *Bradyrhizobium* spp. and plant growth-promoting rhizobacteria (*Azospirillum*), as well as beneficial fungi (*Trichoderma* spp.), entomopathogenic/endophytic fungi such as *Purpureocillium lilacinum*, *Bacillus* inoculants, and arbuscular mycorrhizal fungi (AMF) constitute an integrated strategy for sustainable intensification. These approaches can enhance nodulation, root biomass, nutrient use efficiency, and, under specific conditions, increase grain yield and profitability (Barbosa et al., 2021; Prando et al., 2024). Field studies report consistent improvements in nodulation and root development (e.g., ~10–12% increases), with modest and variable effects on grain yield (~3% on average), depending on environmental conditions and management practices (Barbosa et al., 2021; Zeffa et al., 2020; Prando et al., 2024). Yield responses remain context-dependent, with variability across environments and management systems (Rigobelo et al., 2024, 2024).

Mechanistically, bioinputs operate via multiple pathways, including biological nitrogen fixation, phosphorus solubilization, phytohormone production, and pathogen suppression. Their effectiveness depends on environmental conditions, soil characteristics, native microbial populations and management practices (Zeffa et al., 2020; Prando et al., 2024). AMF can enhance phosphorus (and, in some cases,

nitrogen) acquisition and improve plant performance under limiting conditions; however, benefits vary with soil context and prior management (Thioub et al., 2019; Wu et al., 2024).

At the regulatory and public policy level, Brazil has consolidated initiatives to accelerate R&D and production of biological inputs. In 2020, the National Bioinputs Program was established (MAPA, Decree No. 10,375/2020), and further advanced through the legal framework of Law No. 15,070/2024, defining categories such as biofertilizers, biostimulants, semiochemicals, and biological control agents. These policies have supported research, innovation, and sector expansion (Brazil, 2024). Global markets for biological inputs continue to expand steadily, reflecting increasing demand for sustainable agricultural solutions (Medina et al., 2024; Barbosa et al., 2025).

Despite these advances, challenges remain, including limited access to technology, especially among smallholders, and the need for solutions adapted to diverse tropical conditions. Overall, closing yield gaps will depend on the effective integration of genetic, digital, biological, and management innovations under increasingly constrained environmental conditions.

Final Considerations and Future Perspectives

The trajectory of soybean production reflects a continuous process of scientific, technological, and structural transformation. In Brazil, the combination of territorial expansion, public policies, genetic improvement, and biotechnology has consolidated the country as the world's leading producer and exporter. However, the factors that historically sustained this growth—particularly land expansion and favorable market conditions—are progressively losing relative importance as environmental, climatic, and regulatory constraints intensify.

Future gains in soybean production will depend less on horizontal expansion and increasingly on the capacity to reduce yield gaps through sustainable intensification. Despite average yields around 3.5–3.6 t ha⁻¹, experimental systems indicate a potential exceeding 8 t ha⁻¹, highlighting a substantial opportunity for productivity gains. Closing this gap will require the integration of advanced breeding strategies (including climate-resilient cultivars), precision agriculture tools, improved soil and nutrient management, and more efficient pest and weed control systems.

Climate variability represents one of the most critical sources of uncertainty for future production. Increasing frequency of droughts, irregular rainfall patterns, and temperature extremes may limit yield stability, particularly in

regions already exposed to climatic risks. In this context, adaptive management strategies and resilient production systems will be essential to sustain productivity under changing environmental conditions.

Market and regulatory pressures are also expected to play an increasingly decisive role. The growing demand for low-carbon supply chains, traceability, and deforestation-free production—particularly from major importers such as the European Union and China—will impose additional constraints on expansion and production practices. These requirements may reshape competitiveness, favoring production systems capable of combining high productivity with environmental compliance.

Brazil's continued reliance on commodity exports reinforces its exposure to global market volatility. Trade dynamics, including geopolitical tensions and tariff policies, may generate short-term opportunities but do not provide a stable basis for long-term growth. Therefore, strengthening competitiveness will depend on improving efficiency, reducing production costs, and increasing value generation within the production chain.

The recovery of degraded pastures emerges as a key pathway for reconciling production growth with environmental sustainability. However, its large-scale implementation will depend on economic viability, access to technology, and effective public policies, which remain uneven across regions.

Overall, Brazil's future leadership in soybean production will depend on its ability to transition from an expansion-driven model to one based on sustainable intensification, technological innovation, and robust governance of natural resources. This transition is not guaranteed and will require coordinated advances in science, policy, and market integration. A critical challenge moving forward will be to balance productivity gains with increasingly stringent environmental and socio-economic constraints, ensuring that growth remains both competitive and sustainable in a rapidly evolving global agricultural system.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing Interests The authors declare no competing interests.

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