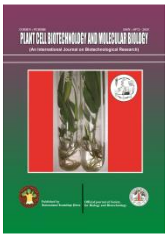

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Soybean (*Glycine max* L. Merrill): A Multipurpose Legume Shaping Our World

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Soybean (*Glycine max* L. Merrill), indigenous to East Asia, has assumed a pivotal role as a global substantial crop, substantially contributing to food security, a wide spectrum of product lines and rigorous scientific exploration. This unassuming legume, bearing the scientific nomenclature *Glycine max* L. Merrill, has transcended its East Asian origins to become a cornerstone in supplying 25% of the world's edible oil and approximately two-thirds of the global livestock protein concentrate. The significance of soybeans extends beyond their utility in direct human consumption; they serve as an indispensable component in crop rotation, thereby fostering soil health and averting erosion. This comprehensive review embarks on a profound exploration of

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soybeans, encompassing their historical significance, botanical attributes, geographical distribution, climatic influence and reproductive biology. Furthermore, it provides a detailed account of advancements in genetic enhancement and biotechnological applications within soybean breeding, emphasizing the importance of transgenic soybean production. Disease resistance efforts, including the identification of resistance loci, markers and mutations, are thoroughly discussed, with a specific focus on the improvement of Indian soybean varieties.

Keywords: Soybean; origin; distribution; reproductive biology; soybean breeding; genetic improvement.

1. INTRODUCTION

In the vast tapestry of agricultural crops that sustain human civilization, one legume stands out as an emblem of versatility, nutrition and economic significance – the soybean (*Glycine max* L. Merrill) [1]. This unassuming plant, native to East Asia, has emerged as a global agricultural powerhouse, playing a pivotal role in shaping modern agriculture, nutrition and industry [2]. The soybean, with its scientific name *Glycine max* L. Merrill, has transcended geographical boundaries, becoming a cornerstone of global food security, a source of diverse products and a subject of intense scientific exploration [3].

The term “soy” finds its etymological origin in the Japanese term “shoyu” and made its inaugural appearance within the lexicon in a Japanese dictionary dated back to the year 1597 [4-5]. It is the paramount seed legume on a global scale, playing a major role by supplying 25% of the world’s total edible oil production and serving as the primary source of approximately two-thirds of the world’s protein concentrate used in livestock nutrition [6-7]. For centuries, in regions such as China, Japan, Korea, Manchuria, Philippines and Indonesia, soybeans have served as a versatile dietary staple, providing essential components resembling meat, milk, cheese, bread and oil [8]. It is plausible that the prevalence of such multifaceted uses of soybeans in these cultures has led to colloquial designations such as ‘Cow of the field’ or ‘Gold from soil’ [9].

Soybean is an important crop worldwide, providing protein for human consumption directly and indirectly through processed foods or livestock products [10-11]. Its seeds possess an oil content ranging from 18% to 23% and a protein content ranging from 38% to 44% on a moisture-free basis [5]. Soybeans are also used in the production of a variety of products, including tofu, soy milk and soy sauce [12-13,6]. Due to its amino acid composition, soybean protein is often referred to as a complete protein [6].

Research has focused on the health effects of soybean, including its potential to reduce the risk of chronic diseases such as cardiovascular disease, cancer and osteoporosis [14]. Soybeans have also been studied for their potential to improve cognitive function, alleviate menopausal symptoms and reduce inflammation [15]. In addition to their nutritional benefits, soybeans are an important crop for farmers [16]. Soybeans are often used in crop rotation with other crops, as they can benefit other crops by fixing nitrogen into soil [17]. Soybeans are also used as a cover crop to prevent soil erosion and improve soil health [18]. However, soybean production has been linked to deforestation, particularly in the Amazonian region due to direct forest clearing for plantations and indirect impacts such as displacing cattle ranching, infrastructure development and meeting global demand for soy [19]. Soybean has been cultivated as a food crop in India for over a century and it goes by various regional names across different regions. These names include Bhat, Bhatman, Bhatmas, Ramkulthi, Bhut, Kalitur, Teliakulth and Garryakalay [20-21].

This review article explores a comprehensive journey through the world of soybeans, exploring their origins, historical significance and botanical characteristics that have propelled them to prominence. From its modest beginnings in the foothills of China, thousands of years ago, to its status as one of the most extensively cultivated crops on the planet earth, the soybean story is one of resilience, adaptability and transformation.

2. MATERIALS AND METHODS

This review paper synthesizes existing literature on soybean by conducting a comprehensive search and analysis of research papers, reports, reviews and studies available on various platforms including Google Scholar, Research

Gate and Academic Journals. By employing a rigorous methodology for data collection and analysis, this review paper provides a comprehensive and up-to date analysis of the existing literature on soybean, contributing to a better understanding of the subject matter.

3. RESULTS AND DISCUSSION

3.1 Taxonomical Classification

The genus *Glycine*, which belongs to the family Leguminosae/Fabaceae, falls under the subfamily Papilionoideae and the tribe Phaseolae. The name "*Glycine*" was originally coined by Linnaeus in the initial edition of his work, Genera Plantarum. The term "*Glycine*" has its roots in the Greek word "*Glykus"*, which likely referred to the sweet tubers produced by the plant *Glycine apios*, a species classified within this genus [20].

Currently, the genus *Glycine* is categorized into two subgenera: *Glycine* and *Soja*. Subgenus *Glycine* comprises 22 perennial wild species [22]. Subgenus *Soja* encompasses *Glycine max* (L.) Merrill, along with its wild annual counterpart *Glycine soja* Sieb. and Zucc. Additionally, subgenus *Soja* encompasses a form known as *Glycine gracilis*, which exhibits intermediate morphological characteristics between *Glycine max* and *Glycine soja* [20].

3.2 Area and Production

In the year 2021, worldwide soybean production achieved a historical peak, encompassing a global cultivation area exceeding 129 million hectares. Notably, Brazil and the United States accounted for 39 million and 34.9 million hectares respectively, while the European soybean production region encompassed approximately 5.5 million hectares, with only around 900,000 hectares allocated within the European Union [23-24]. During the agricultural year 2021-22, the global soybean production reached an aggregate output of 385.524 million metric tonnes (MMT) [25]. Brazil emerged as the predominant producer, cultivating a remarkable 144 MMT, closely followed by the United States with a production of 119.884 MMT [25]. Argentina secured the third ranking, contributing 52 MMT, while China occupied the fourth position with an output of 19 MMT. India occupied the fifth spot by producing 11.2 MMT of soybeans [25].

In India, soybean cultivation encompassed an extensive expanse of 12.27 million hectares, resulting in a total production of 12.99 million metric tons and a yield of 1059 kg per hectare. Among the Indian states, Madhya Pradesh distinguished itself as the foremost soybean producer, earning the moniker "Soya State". Madhya Pradesh contributed significantly to India's soybean production, dedicating 5.51 million hectares of land to cultivation and achieving a yield of 5.39 million metric tonnes. This accounted for 44.94% of the total soybean cultivation area in the country and represented 41.50% of the national soybean production. Notably, the state attained a commendable productivity rate of 978 kg per hectare [26].

3.3 Origin, Domestication and Dissemination

Soybean originated and was cultivated from its wild progenitor, *Glycine soja* (previously designated as *G. formosana* Hosokawa; *G. ussuriensis* Regal & Maack). *Glycine soja* is an annual plant exhibiting weed-like characteristics, known for its climbing attributes and its role as a pioneer species in secondary successions [20]. The pods of *Glycine soja* contain black seeds that disperse upon maturity. This wild soybean is indigenous to regions including China (including Taiwan), far eastern Russia, the Korean peninsula and Japan [27]. Moreover, an intermediary hybrid species, *Glycine gracilis* Skvortz., had been identified by Skvortzow [28], demonstrating characteristics intermediate between *G. soja* and *G. max.* [29].

Linguistic, geographical, and historical evidence suggests that soybean (*Glycine max*) emerged as a domesticated plant during the Zhou dynasty in the eastern half of north China, possibly during the Shang dynasty (ca 1500–1100 B.C.) or earlier. The movement of soybean throughout this period was due to the establishment of sea and land trade routes, as well as the migrations of certain tribes from China (Fig. 1).

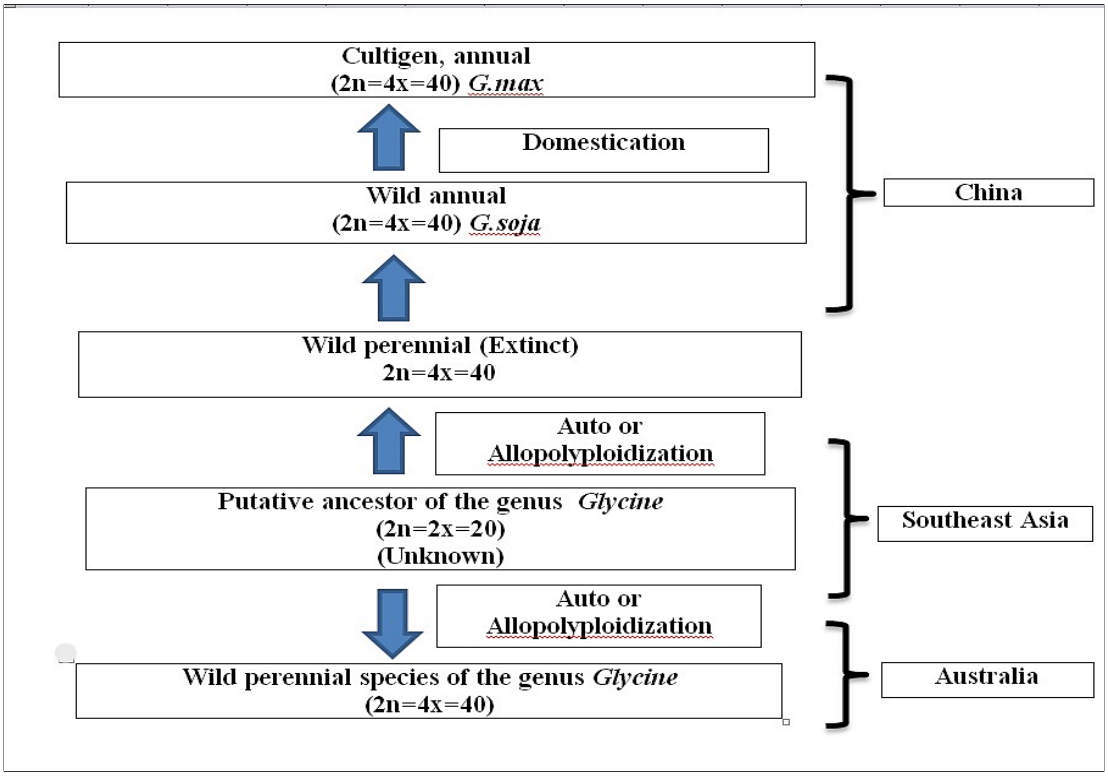

Fig. 1. The origin of genus *Glycine* [22]

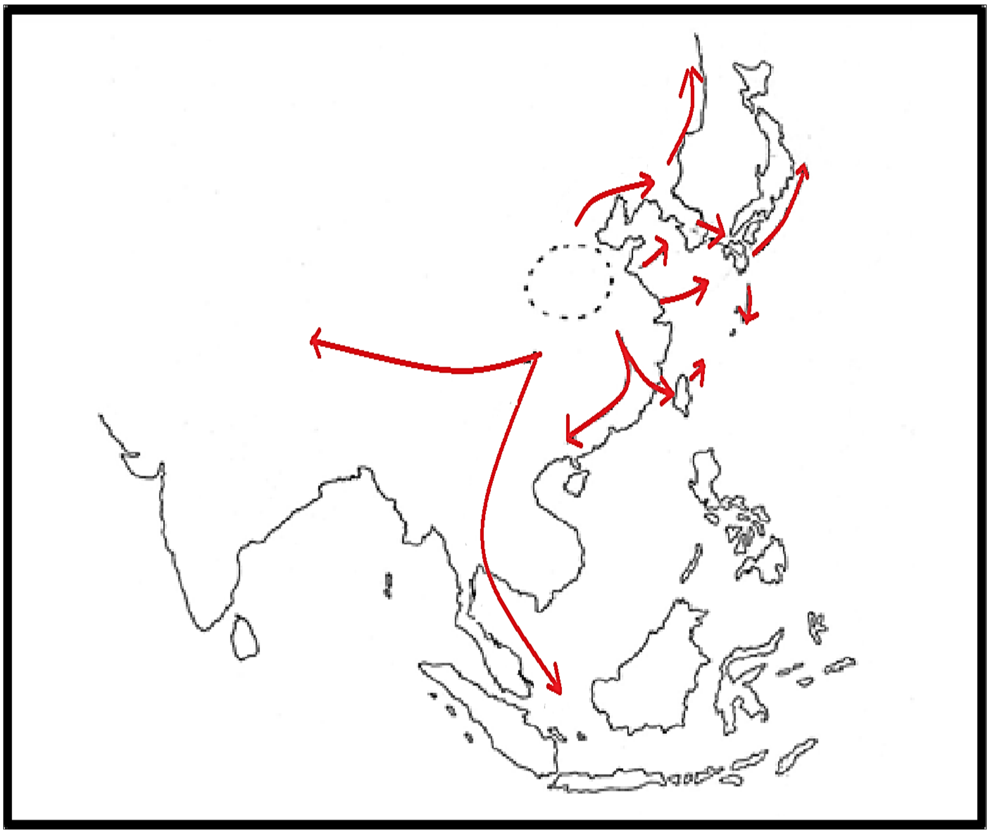

Fig. 2. Paths of dissemination of soybean from China [33-34,5]

As a result, soybeans were introduced into several countries, including Japan, Indonesia, Philippines, Vietnam, Thailand, Malaysia, Myanmar, Nepal and North India, where landraces eventually developed, comprising a secondary gene center [30-31]. The introduction of soybeans to the Indian subcontinent can be traced back to approximately 1000 AD, facilitated by trade along the Silk Route, particularly originating from northeastern India and the Himalayan Mountains [20]. The Silk Road, a network of ancient trade routes, facilitated the spread of soybeans to other parts of Asia and eventually to Europe. By the 17th century, soybeans had made their way to the Americas, thanks to Portuguese and Spanish explorers. However, it was not until the 19th century that soybeans gained a foothold in the United States, where they were initially grown as a forage crop for livestock [32]. Its distribution can be traced as shown in Fig. 2.

3.4 Distribution

Soybean is grown in many countries around the world. Here are some of the areas where soybean is found in different countries (Fig. 2):

3.4.1 South America

South America is the largest producer of soybean in the world, with Brazil, Argentina and Paraguay being the top producers. The soybean expansion in South America has been massive since 2000, with the Cerrado biome being the most affected. The Cerrado biome is a tropical savanna ecoregion in Brazil that has been converted to soybean production, resulting in significant environmental impacts [35].

3.4.1.1 Brazil

In Brazil, soybean production is distributed across several key regions (Fig. 3). The largest contributor to the country's soybean production is Mato Grosso, accounting for 26% of the national output, followed by Parana (15%), Rio Grande do Sul (14%), Goias (10%) and Mato Grosso do Sul (8%) [36].

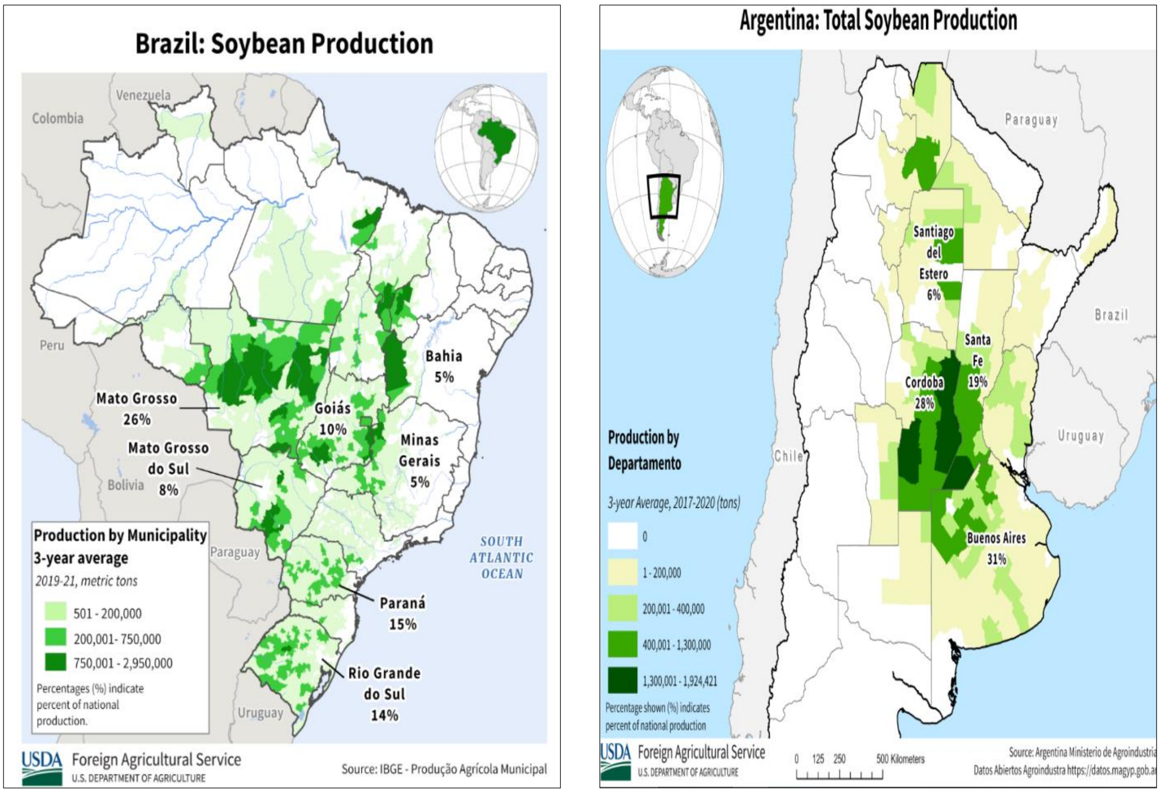

Fig. 3. Soybean Producing Areas in Brazil and Argentina [36]

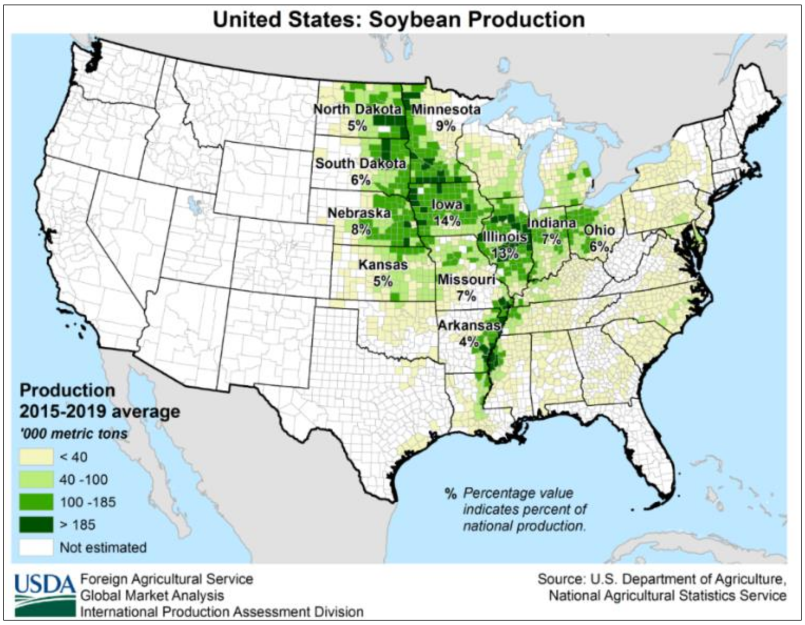

Fig. 4. Soybean Producing Areas in USA [36]

3.4.1.2 Argentina

Argentina's soybean production is primarily concentrated in Buenos Aires, which contributes 31% of the national production, followed by Cordoba (28%), Santa Fe (19%) and Santiago del Estero (6%) [36].

3.4.2 Sub-saharan Africa

Soybean is an important crop in Sub-Saharan Africa, with Nigeria, Tanzania and Uganda being the top producers [37]. The crop is grown in various agro-ecological zones, including the savannas, highlands, and coastal regions [38]. Inoculation with rhizobium bacteria has been found to significantly increase soybean yields in Sub-Saharan Africa [39].

3.4.3 United States

In the United States, soybean cultivation is prominent in various states (Fig. 4). Leading the production is Illinois and Iowa, each contributing 14% to the national total, followed by Minnesota (9%), Nebraska (8%) and Indiana (7%) [36].

3.4.4 Canada

Soybean is grown in various regions of Canada typically in the southern parts of the country, where the climate is suitable for soybean production [39]. In Canada, soybean cultivation is prominent in Ontario, contributing 55% of the national production, followed by Manitoba (24%) and Quebec (16%) [36].

3.4.5 India

India is the fifth-largest producer of soybean in the world (Fig. 5), with Madhya Pradesh and Maharashtra being the top soybean-producing states [39]. Soybean is grown in various agro-climatic zones in India, including the tropical, sub-tropical and temperate regions [37]. India's soybean production centers around Madhya Pradesh, the largest contributor, responsible for 44% of the national output, followed by Maharashtra (39%) and Rajasthan (8%) [36].

3.4.8 China

China is the fourth-largest producer of soybean in the world, with Heilongjiang being the top soybean-producing province which accounts for 42% of the national production (Fig. 6) followed by Nei Mongol (11%), Anhui (7%), Sichuan (6%) and Henan (4%) [34]. The crop is also grown in other provinces, including Anhui, Sichuan and Henan [39].

3.5 Climatic Conditions

Soybean exhibits a moderate salt tolerance with a reported salinity threshold of approximately 5 Deci Siemens per meter. The manifestation of this tolerance is contingent upon various factors, including the timing of exposure, the specific soybean variety, and the prevailing environmental conditions [40-43]. Despite its categorization as a warm-season crop, soybean cultivation is not restricted solely to tropical regions; it extends to latitudes as high as 52 degrees north, typically at altitudes below 1,000 meters. Soybean growth is notably influenced by photoperiod and light intensity[44].

Soybean water requirements exhibit considerable variability, but, in general, the crop necessitates between 330 and 825 millimeters of rainfall during its growth season to achieve optimal yields [44-47]. The period from flowering to seed filling imposes the highest demands for water. It is essential to note that soybeans are susceptible to both waterlogging and drought stress [48]. Particularly, arid conditions, predominantly during the months of July and August, can result in the retention of green coloration in soybean seeds at harvest, even when the seed moisture content is less than 13% [49].

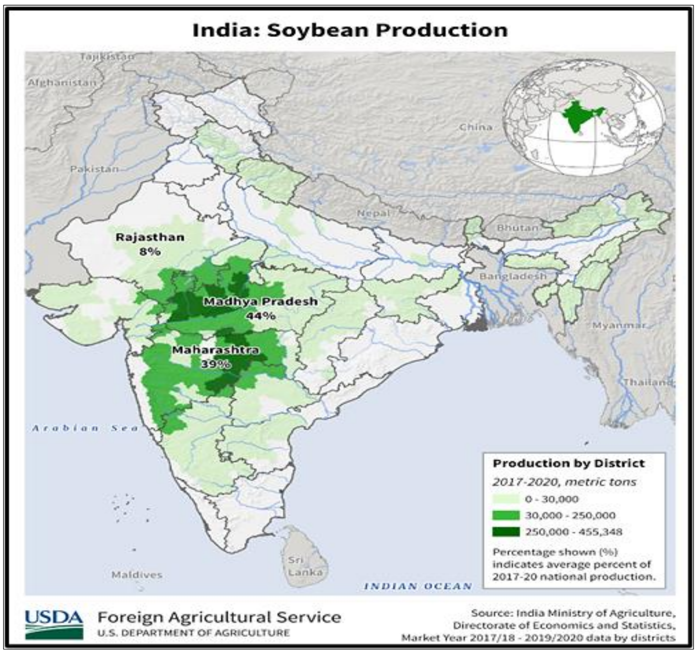

Fig. 5. Soybean Producing Areas in India [36]

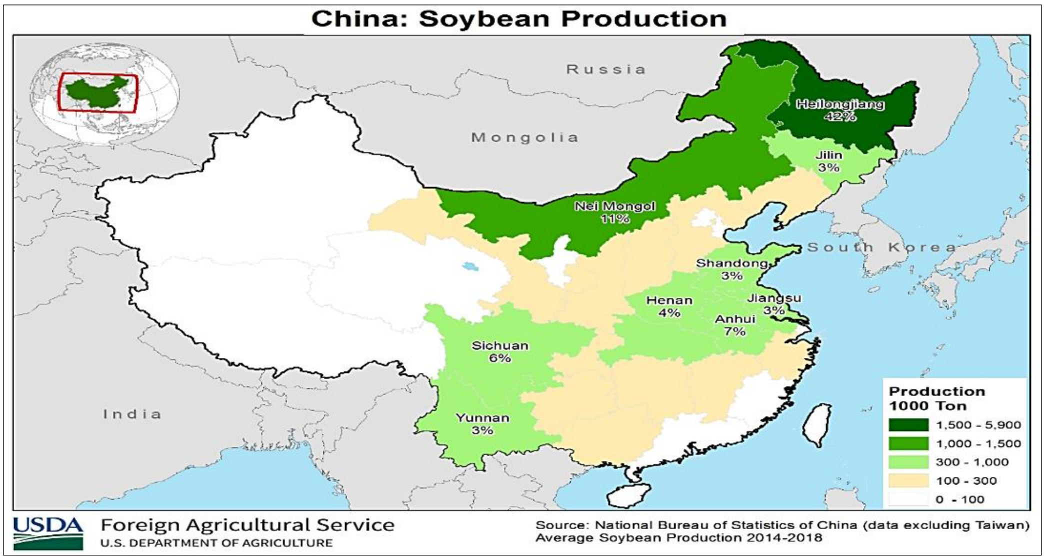

Fig. 6. Soybean Producing Areas in China [36]

Soybeans exhibit optimal growth in soils characterized by a neutral to slightly acidic pH, with a tolerance range spanning approximately 5.5 to 7.8 [36]. The cultivation of soybeans is widespread across a diverse array of well-drained soil types, although clay loam soils are considered the most favorable [44]. While heavy clay soils may pose challenges during seeding and initial plant emergence, once established, soybeans tend to perform reasonably well. In contrast, sandy or gravelly soils render plants more susceptible to drought-induced stress and are therefore less conducive to soybean production.

Soybeans are typically cultivated within regions where growing-season temperatures range from 10 to 40 degrees Celsius (°C) [50-51]. Soil temperature of at least 10°C is prerequisite for the germination and nodulation of soybean seeds [48]. For adequate nodulation and nitrogen fixation, a root zone temperature of at least 15°C to 17°C is essential, with an optimal temperature of 25°C [52].

3.6 Botanical Description

3.6.1 Morphological overview

Soybean is an annual dicotyledonous plant that can vary in size from small, bushy varieties to tall, vine-like cultivars, depending on the intended use and environmental conditions. The plant typically reaches a height of 1 to 1.5 meters. It follows a distinctive pattern of root development (Table 1). Initially, it demonstrates primary taproot growth, succeeded by the subsequent proliferation of an extensive network of secondary roots. These roots establish a mutually beneficial symbiotic association with the nitrogen-fixing bacterium *Bradyrhizobium japonicum* by initiating the formation of specialized root nodules, a pivotal mechanism for enhancing nitrogen fixation [29].

3.6.1.1 Leaves

In the realm of its foliar morphology, soybean exhibits four distinct leaf types, namely cotyledons, representing the initial seed leaves during epigeal germination; primary leaves, signifying the basic foliage emerging post-germination; trifoliolate leaves, which are characteristic of soybeans and feature a pinnate arrangement of three leaflets; and prophylls, a pair of diminutive, simple leaves, each measuring approximately 1 millimeter in length and situated at the base of every lateral branch [29].

3.6.1.2 Flower

The soybean possesses a characteristic papilionaceous flower structure (Table 2). The floral anatomy comprises a tubular calyx consisting of five sepals with unequal lobes. The corolla is five-parted, composed of a posterior banner petal, two lateral wing petals and two anterior keel petals that are in contact but not fused. Within the androecium, there are ten stamens arranged in a diadelphous pattern. Nine stamens have their filaments fused and elevated as a single structure, while the posterior stamen remains separate. The gynoecium is composed of a single unicarpellate pistil, housing one to four campylotropous ovules that alternate along the posterior suture. The style, approximately half the length of the ovary, curves backward towards the free posterior stamen and terminates in a capitate stigma. Trichomes are present on the pistil and cover the outer surfaces of the calyx tube, bract and bracteoles, but are absent on the petals and stamens. This floral structure is characteristic of the papilionaceous flowers observed in the Fabaceae family, to which soybean belongs [54-57].

3.6.1.3 Stem

Soybean plants exhibit two distinctive stem growth habits: indeterminate and determinate growth. In the case of indeterminate stem growth, the terminal buds maintain their vegetative growth activity throughout a significant portion of the growing season. Inflorescences in this category take the form of axillary racemes. At maturity, the plant displays a scattering of pods across all its branches, with a gradual decrease in frequency toward the branch tips. Conversely, the determinate stem growth habit is characterized by the cessation of vegetative growth in the terminal bud as it transforms into an inflorescence. Plants of this type feature both axillary racemes and a central terminal raceme. At maturity, pods are distributed along the stem, with a notable concentration of pods in a dense cluster at the apex of the stem. This distinction in stem growth patterns influences the overall plant architecture and pod distribution, imparting valuable traits for various agricultural and breeding purposes [57].

Table 1. Different growth stages of soybean [53]

Growth Stage	Description
Vegetative stages	
V1	Completely unrolled leaf at the unifoliate node
V2	Completely unrolled leaf at the first node above the unifoliate node
V3	Three nodes on main stem beginning with the unifoliate node
V(N)	N nodes on the main stem beginning with the unifoliate node
Reproductive stages	
R1	One flower at any node
R2	Flower at node immediately below the uppermost node with a completely unrolled leaf
R3	Pod 0.5 cm (1/4 inch) long at one of the four uppermost nodes with a completely unrolled leaf
R4	Pod 2 cm (3/4 inch) long at one of the four uppermost nodes with a completely unrolled leaf
R5	Seeds begin to develop (can be felt when the pod is squeezed) at one of the four uppermost nodes with completely unrolled leaf
R6	Pod containing full size green beans at one of the four uppermost nodes with a completely unrolled leaf
R7	Pods yellowing; 50% of leaves yellow, physiological maturity
R8	90% of pods browning, harvest maturity

Table 2. Chronology of development of flower and ovule of soybean [57]

Days before flowering	Morphological and anatomical features
25	Initiation of floral primordium in axil of bract and sepal differentiation.
20-14	Petal, stamen and carpel initiation.
14-10	Ovule initiation; maturation of megasporocyte; meiosis; four megaspores present.
10-7	Anther initiation; male archesporial cells differentiate; meiosis; microsporogenesis.
7-6	Functional megaspore undergoes first mitotic division.
6-2	Second mitotic division results in 4-nucleote embryo sac. Third mitotic division results in 8-nucleate embryo sac. Development of 7-celled and 8-nucleate embryo sac. Single vascular bundle in ovule extends from chalaza through funiculus and joins with the carpellary bundle.
1	Embryo sac continues growth; antipodals disorganized and difficult to identify. Synergids with filiform apparatus; one synergid degenerating. Tapetum in anthers almost gene. Pollen grains mature; some are germinating. Nectary surrounding ovary reached maximum height.
0	Flower opens; usually day of fertilization; resting zygote; primary endosperm nucleus begins dividing.

3.6.1.4 Pods

The number of pods within a single inflorescence of soybeans ranges from 2 to over 20, and a single plant can bear up to 400 pods. Each pod typically contains one to five seeds, with most common cultivars usually having two or three seeds per pod [58-59]. The shape of soybean pods is predominantly straight or slightly curved and their length varies from less than 2 cm to 7 cm or more in certain cultivars. The mature pods exhibit a spectrum of colors, including light yellow, yellow-grey, brown or black. The coloration of the pods is influenced by the presence of carotene and xanthophyll pigments, the trichome color, and the presence or absence of anthocyanin pigments [54,57]. The peak length of soybean pods is achieved relatively early in their development, occurring approximately 20 to 25 days after the onset of flowering [60-61]. During this phase, the seeds have grown to approximately 4% of their ultimate dry weight [62]. The maximum width and thickness of the pod are attained around 30 days after flowering, coinciding with the period when the seeds achieve their maximum size in all dimensions (Table 3; Fig. 7; Fig. 8). The highest fresh seed weight and the maximum seed dimensions are typically reached within 5 to 15 days following this stage. As the maturing seeds lose moisture, their shape transitions from an elongated, kidney-shaped form to the more typical oval or spherical shape characteristic of fully mature seeds [57].

Fig. 7. Glabrous pods of soybean

Fig. 8. Pubescent pods of soybean

Table 3. Chronology of development of seed in pod of soybean [57]

Days after flowering	Morphological and anatomical features
0	Resting zygote. Numerourous divisions of primary endosperm nucleus (PEN).
1	Two-celled proembryo. Endosperm with approx. 20 free nuclei.
2	4-8 celled proembryo.
3	Differentiation into proembryo proper and suspensor. Endosperm in peripheral layer with large central vacuole.
4-5	Spherical embryo with protoderm and large suspensor. Endosperm surrounding embryo is cellular but elsewhere it is mostly acellular and vacuolated.
6-7	Initiation of cotyledons. Endosperm mostly cellular.
8-10	Rotation of cotyledons begins. Procambium appears in cotyledons and embryo axis. All tissue systems of hypocotyl present. Root cap present over root initials. Endosperm completely cellular.
10-14	Cotyledons finished rotation and are in normal position with inner surfaces of cotyledons parallel with sides of ovules. Cotyledons elongate toward chalazal end of ovule. Primary leaf primordial present. Endosperm occupies about half of seed cavity. Extensive vascularization of seed coat.
14-20	Continued growth of embryo and seed. Reduction of endosperm tissue by assimilation into cotyledons.
20-30	Primary leaves reach full size. Primordium of first trifoliate leaf present. Cotyledons reach maximum size. Endosperm almost gone.
30-50	Continued accumulation of dry matter and loss in fresh weight of seeds and pod. Maturation of pod.
50-80	Various maturity times depending on variety and environmental factors

3.6.1.5 Seeds

Soybean seeds exhibit a spectrum of coloration, ranging from yellow, green, brown to black and can display monochromatic, bicolored or variegated patterns (Table 4). The pigments within the seed coat, primarily situated in the palisade layer, comprise anthocyanins found in the vacuole, chlorophyll within plastids and various permutations of their degradation products [11]. The cotyledons of mature embryos can manifest as green, yellow or a pale yellow with a chalky appearance, although in most genotypes, they appear yellow

[62]. The diverse amalgamation of pigments presents in both the seed coat and cotyledons accounts for the extensive array of colors observed in wild and cultivated soybean varieties [57].

3.7 Reproductive Biology

During stamen maturation, the anthers and pollen of soybean plants exhibit a yellow hue. The typical diameter of the pollen grains ranges from 21 to 30 μm [63,54]. At the time of pollination, the diadelphous stamens undergoes a significant elevation, leading to the formation of a circular arrangement of anthers around the stigma. This specific arrangement facilitates the direct deposition of pollen onto the stigma, resulting in a notably high rate of self-fertilization [59]. The occurrence of natural cross-pollination ranges from less than 0.5% to approximately 1%. Notably, it has been documented that pollination events can take place as early as one day before the complete opening of the flower [54]. The wild annual soybean, *G. soja*, primarily undergoes self-pollination. On the other hand, the perennial wild relative, *G. argyrea* (Ting.) and its closely related species, *G. clandestine* (Wendl.), exhibit both self-fertilized cleistogamous flowers and chasmogamous flowers on the same plant [64-65]. Chasmogamous flowers are often visited by insect pollinators, promoting cross-pollination [66].

Table 4. List of soybean DUS characteristics, states and stage of observation

S.No.	Characteristics	States	Stage of observation
1.	Hypocotyl: Anthocyanin pigmentation	Absent Present	10-15 Days After Sowing
2.	Plant: Growth type	Determinate Semi-Determinate Indeterminate	About 77% pods attained full length
3.	Plant: Days to 50% flowering	Early (<35 days) Medium (36-45 days) Late (>45 days)	Flowering: about 50% plants have at least one flower open
4.	Leaf Shape	Lanceolate Pointed ovate Rounded ovate	Flowering: about 50% plants have at least one flower open
5.	Leaf Colour	Green Dark green	Flowering: about 50% plants have at least one flower open
6.	Plant: Growth habit	Erect Semi-erect	Flowering: about 50% plants have at least one flower open
7.	Flower: Colour	White Violet	Flowering: about 50% plants have at least one flower open
8.	Plant: Height (cm)	Short (<40) Medium (41-60) Tall (>60)	Advance ripening: about 50% of pods are ripe
9.	Pod: Pubescence	Absent (Glabrous) Present (Pubescent)	About 77% pods attained full length
10.	Pod: Pubescence Colour	Grey Tawny (Brown)	About 77% pods attained full length
11.	Pod: Colour	Yellow Brown Black	Advance ripening: about 50% of pods are ripe
12.	Pod: Shattering	Shattering Non-Shattering (up to 10 days)	Full maturity: About 95% pods are ripe
13.	Days to maturity	Early Medium Late	Full maturity: About 95% pods are ripe
14.	Seed : Size (100 seed weight)	Small (≤10) Medium (10.1-13) Large (>13)	Harvested product (seeds)
15.	Seed : Shape	Spherical Elliptical	Harvested product (seeds)
16.	Seed : Colour	Yellow Yellow green Green	Harvested product (seeds)

S.No.	Characteristics	States	Stage of observation
		Black	
17.	Seed : Hilum colour	Yellow Grey Brown Black Variegated	Harvested product (seeds)
18.	Seed: Lustre	Shiny Dull	Harvested product (seeds)
19.	Seed : Coloration due to peroxidase activity in seed coat	Absent Present	Harvested product (seeds)
20.	Seed: cotyledon colour	Yellow Green	Harvested product (seeds)
21.	Seed: oil content (%)	Low (≤ 15.0) Average (15.1-18.0) Medium (18.1-20.0) High (>20.0)	
22.	Seed: Protein content (%)	Low (≤ 38.0) Medium (38.1-40.0) High (>40.0)	

3.8 Advances in Soybean

3.8.1 Genetic improvement

Soybean, a prominent crop with a history spanning centuries, has undergone substantial advancements in genetic enhancement from the 19th century to the present day. The discovery of Mendelian genetics in the late 19th and early 20th centuries marked a significant milestone, catalyzing advancements in soybean maturity through genetic manipulation. Since then, the progression of soybean genetic improvement has been noteworthy, notably with the advent of CRISPR/Cas9 gene editing technology, enabling precise modifications for enhancing traits like disease resistance [67]. Genetic engineering techniques have been effectively utilized to elevate soybean protein quality by modifying biosynthetic feedback pathways to increase lysine and sulfur-containing amino acids. Soybean transformation has been pivotal in augmenting various aspects, including yield, grain quality and tolerance to both biotic and abiotic stress, as well as economic attributes like oil and biofuel quality. Additionally, the integration of high-throughput canopy phenotyping has significantly improved the efficiency of selecting high-yielding soybean lines [68]. Research studies have demonstrated considerable genetic gains in soybean grain yield, attributed to factors such as increased seeds per plant and per pod, enhanced resistance to lodging, and a shortened vegetative period [69-71]. Recent research endeavors have particularly emphasized the improvement of soybean's phosphorus efficiency through strategic genetic approaches [68]. Genome editing in soybean is rapidly advancing, culminating in the commercialization of the first genome-edited plant product, notably high-oleic-acid soybean oil [72]. Collectively, the progress in genetic enhancement of soybean has yielded varieties possessing desirable traits such as high yield, superior quality and enduring disease resistance. These advancements have been achieved through the adept application of gene editing technology, genetic engineering and soybean transformation [73-75].

3.8.2 Biotechnological advancement

Recent advancements in biotechnology and molecular biology have revolutionized the enhancement of agronomic traits in soybean. These advancements encompass transgenic methodologies [76], genome editing technologies, and innovative transformation techniques utilizing cotyledonary-node and immature embryos as explants [77-80]. These scientific progressions have culminated in the development of soybean varieties exhibiting optimal characteristics, including high yield, superior quality and enduring disease resistance. Below are some recent strides in biotechnology and molecular biology in soybean and their applications in ameliorating agronomic traits:

1. Refinement of Traits through Genetic Approaches: Transgenic methodologies have been instrumental in elevating various soybean agronomic attributes. These encompass enhancements in yield components, grain quality, resilience to biotic and abiotic stresses, and economic traits such as the quality of oil, biofuels and specific chemical contents in seeds for human health. Recent research endeavors have notably concentrated on optimizing soybean's phosphorus utilization efficiency through genetic strategies [81].

2. Genome Editing Technologies: The advent of genome editing technologies, including CRISPR/Cas9, has ushered in a new era of innovation in soybean breeding. These groundbreaking techniques enable the simultaneous editing of multiple genes, thereby augmenting traits such as yield, disease resistance, and drought tolerance [82].

3. Cotyledonary-Node-Based Transformation: The cotyledonary-node-based transformation method has emerged as a cornerstone in soybean transformation, significantly enhancing transformation efficiency. Various research laboratories have contributed to the optimization of soybean transformation using cotyledonary-node explants [83,84].

4. Immature Embryos-Based Transformation: The utilization of *Agrobacterium*-mediated transformation with immature embryos as explants has demonstrated notable improvements in soybean transformation efficiency [83,84].

5. Multi-omics techniques: Novel multi-omics methodologies have emerged as indispensable tools for molecular-level breeding. These techniques encompass a spectrum of molecular domains, including soybean genomics, transcriptomics, proteomics, metabolomics and phenomics research. Their application has catalyzed significant progress in soybean transcriptomics, proteomics and molecular biology [85], offering comprehensive insights into the molecular underpinnings of soybean improvement.

3.8.3 Disease resistance

Soybean breeders have diligently endeavored to create disease-resistant soybean cultivars, aiming to ensure sustainability and amplify global soybean production. However, the escalating impacts of global climate change pose formidable challenges for these breeders in mitigating diseases [86,87]. The major diseases and insect-pests of soybean are depicted in Table 5 and Table 6. A comprehensive research effort has identified over 800 loci/alleles conferring resistance and closely associated markers for 28 distinct soybean diseases caused by nematodes, fungi, bacteria and viruses (Figs. 9-11). Noteworthy advancements have been made in delineating the soybean disease resistance gene atlas, employing techniques such as Quantitative Trait Loci (QTL) mapping and analysis of epistatic interactions to elucidate field resistance against sudden death syndrome (*Fusarium virguliforme*) in soybean. Effective management of soybean diseases entails a multifaceted approach, encompassing cultural practices, chemical applications, with the paramount strategy being the deployment of resistant cultivars. These cultivars can possess either vertical resistance, horizontal resistance, or a combination of both [86]. Additionally, researchers have pinpointed specific mutations in viral genes that enable the circumvention of resistance mechanisms. Notably, Indian soybean varieties have been successfully enhanced to bolster resistance against Phytophthora rot and powdery mildew diseases. These improved soybean lines exhibit varying degrees of resistance against powdery mildew and Phytophthora rot while also demonstrating proficient nodulation capacity. These advancements hold immense promise in bolstering soybean breeding initiatives in India and other soybean-growing nations, facilitating the development of disease-resistant varieties [88].

3.9 Future Breeding Strategies

3.9.1 Genetic enhancement

Soybean, a short-day plant highly responsive to day length, currently faces limited adaptability across different latitudes and planting periods [89]. The further genetic improvement of soybean, with an emphasis on enhancing yield and its stability under rainfed conditions, is of paramount importance [6,90]. The ideal high-yield soybean plant should exhibit determinate or semi-determinate growth habits (suited for short growing seasons), upright and non-lodging architecture, rapid development of Leaf Area Index (LAI), a suitable seed-filling duration, and maturity within the 95–100-day range [91]. In addition to yield, essential traits for soybean in tropical regions include resistance to pod shattering and robust seed longevity [92]. Major biotic stressors reducing soybean productivity in Indian conditions include diseases like yellow mosaic, rust, rhizoctonia, anthracnose and pests such as girdle beetles and various defoliators.

Given that soybean is a rainfed crop, drought represents a significant abiotic stress limiting productivity in India [92,6]. Therefore, breeding programmes will prominently focus on enhancing drought tolerance. Considering the impending challenges posed by climate change, breeding programs may also prioritize the development of varieties tolerant to high-temperature conditions and responsive to elevated CO_2 levels [93]. Early maturity will remain a crucial breeding objective, enabling integration into multi-crop systems and mitigating late-season moisture stress [94]. Considering diminishing phosphorus and micro-nutrient reserves in soils worldwide, future breeding programs will be oriented towards developing varieties with improved nutrient utilization and extraction efficiency [95]. In addition to conventional breeding methods, advanced molecular techniques such as allele mining, marker-assisted selection, functional genomics, genetic engineering and leveraging hybrid vigor should be actively pursued [96].

Fig. 9. Yellow Mosaic

Fig. 10. Rhizoctonia Aerial Blight

Fig. 11. Charcoal Rot

Table 5. Major diseases of soybean and their causal organisms

S. No	Name of Disease	Causal organism	Type
1.	Soybean Rust	*Phakopsora pachyrizi*	Fungi
2.	Soybean Cyst Nematode	*Heterodera glycines*	Nematode
3.	Soybean Stem Canker	*Diaporthe phaseolorum*	Fungus
4.	Yellow Mosaic	*Soybean Mosaic Virus/ Mungbean Yellow Mosaic Virus*	Virus
5.	Soybean Bacterial Pustule	*Xanthomonas axonopodis* pv. *glycines*	Bacteria
6.	Rhizoctonia aerial Blight	*Rhizoctonia solani*	Fungus
7.	Charcoal Rot	*Macrophomina phaseolina*	Fungus
8.	Soybean Anthracnose	*Colletotrichum truncatum*	Fungus
9.	Soybean Leaf Blight/ Purple seed stain	*Cercospora kikuchii*	Fungus

Table 6. Major pests of soybean

S. No	Pest	Scientific name	Order
1.	Bihar hairy caterpillar	*Spilosoma obliqua*	Lepidoptera
2.	Gram Pod Borer	*Helicoverpa armigera*	Lepidoptera
3.	Tobacco Caterpillar	*Spodoptera litura*	Lepidoptera
4.	Thrips	*Thrips tabaci*	Thysanoptera
5.	White Fly	*Bemisia tabaci*	Hemiptera
6.	Soybean Aphid	*Aphis spp.*	Hemiptera
7.	Girdle Beetle	*Obereopsis brevis*	Coleoptera
8.	Stem Fly	*Melanagromyza sojae*	Diptera
9.	Jassids	*Apheliona maculosa*	Hemiptera

Fig. 12. Purple seed stain of soybean

Fig. 13. Tobacco caterpillar attack on soybean leaves

3.9.2 Improved production technologies

The soybean production system confronts significant challenges, including impending climatic changes, shifts in cropping patterns, and the introduction of new technologies promising higher yields [97,98]. Thus, it is imperative to develop production technologies that inherently adapt to unpredictable climatic anomalies, seamlessly integrate with evolving crop patterns, and synergize with emerging genetic technologies [99]. Consequently, the refinement of existing production methods and the development of novel technologies that augment productivity while reducing cultivation costs are necessary to improve farmer's incomes [100].

3.9.3 Biotic stresses

Like other *Kharif* season crops, soybean faces a multitude of biotic stressors. Among the 35 reported soybean diseases, 20 are considered major, with eight exhibiting pandemic prevalence, while others are regionally confined [91]. Diseases like yellow mosaic, soybean mosaic, Indian bud blight, rust, anthracnose and pod blight, alongside *Cercospora* blight (Purple seed stain), *Sclerotium* blight, *Rhizoctonia* root rot, aerial blight, and bacterial pustule, regularly affect soybean crops across a broad geographic range [101,91]. Insects like girdle beetles, tobacco caterpillars, and Bihar hairy caterpillars are significant crop-damaging pests [102] (Figs. 12-13). Changes in temperature, rainfall and CO_2 levels have led to shifts in the disease landscape, necessitating a well-structured system for surveillance, monitoring, forecasting and control [103,104]. Moreover, there is a pressing need to develop novel control strategies and enhance existing recommendations for future research endeavors.

3.9.4 Nanotechnology in soybean

The integration of nanotechnology into soybean agriculture holds substantial promise for elevating crop management efficacy and bolstering overall productivity [105,106]. Diverse facets of nanotechnology, encompassing nano sensors, nano fertilizers, nano pesticides, nano herbicides and gene delivery systems, present avenues for addressing multifaceted challenges inherent to soybean cultivation, thereby optimizing yield outcomes [107]. Nanosensors assume a pivotal role in the contemporaneous monitoring and administration of soybean crops. Specifically, in soybean cultivation, nanosensors prove invaluable for scrutinizing soil conditions, encompassing parameters such as temperature and moisture levels within the rhizosphere [108]. Such real-time data acquisition is indispensable for judicious irrigation management, ensuring the provision of optimal growth conditions for soybeans [109]. The deployment of nanofertilizers emerges as an intelligent and efficacious strategy for nutrient delivery to soybean plants. Through the encapsulation of essential nutrients within nanomaterials, nano fertilizers engender a controlled release mechanism, thereby facilitating a gradual and sustained supply of nutrients throughout the soybean growth cycle [110,111]. This innovative approach mitigates the constraints associated with conventional fertilizers, concurrently fostering sustainable agricultural practices within the soybean cultivation domain [112]. Tailoring nano pesticides and nano herbicides for soybean farming addresses nuanced challenges such as pest infestations and weed proliferation. These formulations, anchored in nanomaterial matrices, confer advantages such as heightened water solubility, target specificity, diminished environmental impact and regulated release kinetics [113]. The precision in the delivery of active ingredients underscores the potential for enhanced efficacy in pest and weed management within soybean fields [114]. Nanotechnology, through nanoparticle, nanofiber and nano-capsule modalities, facilitates the proficient delivery of genetic material for crop enhancement in soybeans. This novel approach, characterized by efficiency and minimal toxicity, enables strides in crop engineering by affording controlled gene delivery and the simultaneous introduction of multiple genes [115]. The amalgamation of these advancements contributes substantively to augmenting soybean crop traits and overall agricultural quality, as elucidated by recent research findings.

4. CONCLUSION

In conclusion, soybean (*Glycine max* L. Merrill) stands as a remarkable agricultural crop of immense global importance. It has evolved into a versatile and key crop, contributing significantly to food security, nutrition and industrial applications worldwide. Soybean's nutritional richness, providing essential proteins and oils, has made it a fundamental component of the human diet. Furthermore, its adaptability to diverse climates and its role in sustainable agriculture underscore its significance. Recent advancements in genetics and biotechnology promise further improvements, ensuring that soybean remains at the forefront of addressing the evolving demands of a growing population and changing environmental landscapes. The journey of soybean, from its ancient roots to its status as a global agricultural powerhouse, reflects its resilience, adaptability and enduring relevance.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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