# Biotechnological Approaches in Soybean (*Glycine max* L.) Improvement: Advances, Challenges and Future Prospects

**Dr. Pradip P. Patil**
Associate Professor
Department of Botany,
KVPS Kisan Arts Commerce and Science College Parola Dist Jalgaon (MS) 425 111

**Abstract**

Soybean (*Glycine max* L.) is a globally important oilseed and legume crop, valued for its high oil and protein content. Conventional breeding methods have contributed significantly to soybean improvement; however, progress is often limited by narrow genetic variability, long breeding cycles, and environmental constraints. Recent advances in biotechnology have opened new avenues for soybean crop improvement through plant tissue culture, genetic engineering, molecular breeding, and genome editing technologies. These approaches have enabled the development of high-yielding, stress-tolerant, pest-resistant, and nutritionally improved soybean varieties. This review highlights major biotechnological strategies applied in soybean improvement, focusing on tissue culture techniques, transgenic technology, marker-assisted selection, CRISPR/Cas-based genome editing, and future prospects for sustainable soybean production.

**Keywords:** Soybean, Biotechnology, Genetic engineering, Tissue culture, CRISPR/Cas9, Oilseed crops

## 1. Introduction

Soybean (*Glycine max* L. Merrill) is one of the most economically important oilseed and leguminous crops in the world, serving as a major source of vegetable oil, high-quality protein**,** and bioactive compounds. It is cultivated across diverse agro-climatic regions and plays a vital role in global food security, livestock feed industries, and several non-food sectors such as biodiesel, pharmaceuticals, and bioplastics. Soybean seeds typically contain 18–22% oil and 38-42% protein**,** making them nutritionally superior compared to many other oilseed crops (Hartman et al., 2011; Wilson, 2004).

Globally, soybean contributes nearly 60% of the world's oilseed production**,** highlighting its dominance among oilseed crops (FAO, 2022). In developing countries like India, soybean has emerged as a **"**golden bean**"** due to its increasing importance in edible oil production and its ability to improve soil fertility through biological nitrogen fixation**.** Despite its agronomic and economic importance, soybean productivity remains constrained by several biotic stresses such as insect pests, nematodes, bacterial, fungal and viral diseases, as well as abiotic stresses including drought, salinity, heat, and nutrient deficiencies (Hartman et al., 2015).

The conventional breeding approaches have contributed significantly to soybean improvement; however, their effectiveness is often limited due to the crop's narrow genetic base**,** self-pollinating nature**,** and long breeding cycles**.** Furthermore, complex traits such as stress tolerance, yield stability, and oil quality are

typically governed by multiple genes, making their improvement through traditional breeding methods slow and inefficient (Singh et al., 2019). These challenges necessitate the integration of advanced biotechnological tools to accelerate genetic gains and enhance crop resilience.

Biotechnology offers innovative solutions for soybean improvement by enabling precise manipulation of genetic material**,** rapid multiplication of elite genotypes, and early selection of desirable traits. Techniques such as plant tissue culture, genetic transformation, marker-assisted selection (MAS), RNA interference (RNAi), and genome editing technologies like CRISPR/Cas9 have revolutionized soybean breeding programs worldwide (Somers & Samac, 2004; Haun et al., 2014). Among these, tissue culture-based regeneration systems form the foundation for genetic transformation and large-scale propagation of improved cultivars.

The successful commercialization of genetically modified (GM) soybean, particularly herbicide-tolerant and insect-resistant varieties, represents a landmark achievement in agricultural biotechnology. GM soybean has significantly reduced dependency on chemical pesticides, improved weed management, and enhanced crop productivity, especially in countries such as the USA, Brazil, and Argentina (James, 2016). In addition, recent advances in genome editing have enabled the development of soybean varieties with improved oil composition**,** enhanced nutritional value, and increased tolerance to environmental stresses without introducing foreign DNA (Zhang et al., 2020).

Given the increasing demand for edible oils, climate change challenges, and the need for sustainable agricultural practices, biotechnological interventions in soybean improvement have become more relevant than ever. This review aims to comprehensively summarize the major biotechnological approaches applied in soybean**,** highlighting their role in enhancing productivity, oil quality, and stress tolerance, while also discussing the challenges and future prospects of soybean biotechnology.

## 2. Plant Tissue Culture Techniques in Soybean

### Micropropagation

Micropropagation refers to the *in vitro* clonal multiplication of plants using small explants under aseptic and controlled environmental conditions. In soybean (*Glycine max* L.), micropropagation plays a crucial role in rapid multiplication of elite genotypes**,** maintenance of genetic uniformity, and as a prerequisite for genetic transformation and genome editing studies**.** Due to the recalcitrant nature of soybean to *in vitro* regeneration, significant efforts have been made to standardize efficient micropropagation protocols using suitable explants and growth regulators (Somers & Samac, 2004).

### Explants Used in Soybean Micropropagation

Various explants have been employed for micropropagation in soybean, including cotyledonary nodes, shoot tips, hypocotyls, epicotyls, and immature embryos**.** Among these, cotyledonary node explants have been reported as the most reliable and reproducible source for shoot induction and multiple shoot formation (Hinchee et al., 1988; Paz et al., 2006). The high regeneration potential of cotyledonary nodes is attributed to the presence of pre-existing meristematic tissues.

**Culture Media and Growth Regulators**

Murashige and Skoog (MS) basal medium is most commonly used for soybean micropropagation. Shoot induction is typically achieved by supplementing the medium with cytokinins such as 6-benzylaminopurine (BAP) **or** kinetin, either alone or in combination with low concentrations of auxins like Naphthalene Acetic Acid (NAA)**.** Optimal cytokinin concentration promotes multiple shoot formation, while excessive levels may cause vitrification and abnormal shoot development (Barwale et al., 1986).

**Shoot Multiplication and Elongation**

Following shoot induction, regenerated shoots are subcultured onto fresh medium to promote shoot multiplication and elongation. Repeated subculturing enables rapid clonal **propagation** of soybean plants within a short time. Gibberellic acid ($GA_3$) is sometimes used at low concentrations to enhance shoot elongation (Paz et al., 2006).

**Root Induction and Acclimatization**

Rooting of *in vitro*-regenerated soybean shoots is generally achieved on half-strength MS medium supplemented with auxins such as indole-3-butyric acid (IBA) **or** indole-3-acetic acid (IAA)**.** Successfully rooted plantlets are gradually acclimatized under greenhouse conditions before transfer to the field. Proper acclimatization is essential to ensure high survival rates and normal growth (Franklin et al., 2004).

**Applications of Micropropagation in Soybean Improvement**

Micropropagation has several important applications in soybean biotechnology like Rapid multiplication of elite and transgenic lines, production of disease-free planting material, conservation of valuable germplasm, serving as a foundation for *Agrobacterium*-mediated transformation and support for marker-assisted breeding and genome editing.

**Limitations and Challenges**

Despite its advantages, soybean micropropagation faces challenges such as genotype dependency**,** low regeneration efficiency in some cultivars, and the risk of somaclonal variation during prolonged culture. Continuous refinement of protocols and the use of optimized explants are necessary to overcome these limitations (Homrich et al., 2012).

**Callus Culture**

Callus culture is an important plant tissue culture technique involving the induction and maintenance of an unorganized mass of undifferentiated cells from plant explants under *in vitro* conditions. In soybean (*Glycine max* L.), callus culture has been extensively explored for plant regeneration, somaclonal variation, in vitro selection, and genetic transformation studies**.** Although soybean is considered recalcitrant to tissue culture, significant progress has been made in establishing reliable callus induction and regeneration protocols (Barwale et al., 1986; Somers & Samac, 2004).

**Explants used for Callus Induction**

Various explants have been employed for callus induction in soybean, including hypocotyls, cotyledons, leaves, immature embryos, and root segments**.** Among these, immature cotyledons and hypocotyl explants are widely reported to exhibit higher callogenic potential due to their active meristematic regions (Christianson et

al., 1983; Franklin et al., 2004). The choice of explant significantly influences callus induction frequency and regenerative capacity.

**Culture Media and Plant Growth Regulators**

Murashige and Skoog (MS) medium is commonly used as the basal medium for callus induction in soybean. High auxin concentrations, particularly 2,4-dichlorophenoxyacetic acid (2,4-D)**,** are essential for initiating callus formation. Auxins such as **NAA** and **IAA** are also used, either alone or in combination with cytokinins like BAP or kinetin, to regulate callus growth and differentiation (Barwale et al., 1986; Lazzeri et al., 1987).

**Types and Characteristics of Callus**

Soybean callus can vary in texture, color and regenerative ability:

- Friable callus, suitable for suspension cultures and genetic transformation
- Compact or nodular callus, often associated with higher regeneration potential

Embryogenic callus, capable of forming somatic embryos, is of particular importance in soybean biotechnology and is frequently induced from immature cotyledons (Lazzeri et al., 1987).

**Plant Regeneration from Callus**

Regeneration of soybean plants from callus occurs through either organogenesis or somatic embryogenesis, depending on the hormonal balance and culture conditions. A reduction in auxin concentration and an increase in cytokinin levels generally promote shoot differentiation. Regenerated shoots are subsequently rooted and acclimatized under greenhouse conditions (Christianson et al., 1983; Franklin et al., 2004).

**Applications of Callus Culture in Soybean**

Callus culture has several important applications in soybean improvement:

- Somaclonal variation for generating novel genetic variability
- *In vitro* selection for tolerance to abiotic stresses such as salinity and drought
- Genetic transformation and gene expression studies
- Secondary metabolite production
- Development of cell suspension cultures

**Limitations and Challenges**

Despite its wide applicability, callus culture in soybean faces limitations such as genotype dependency, low regeneration efficiency, and the occurrence of genetic instability during prolonged culture. Optimization of explant type, growth regulator concentration, and culture conditions is essential to improve callus-mediated regeneration systems (Homrich et al., 2012).

**Somatic Embryogenesis in Soybean (*Glycine max* L.)**

Somatic embryogenesis is a specialized plant tissue culture technique in which embryo-like structures are formed from somatic (non-reproductive) cells without fertilization. These somatic embryos closely resemble zygotic embryos in their morphological and developmental stages and have the potential to regenerate

into complete plants. In soybean (*Glycine max* L.), somatic embryogenesis is considered one of the most effective regeneration systems and serves as a cornerstone for genetic transformation, large-scale propagation, and genome editing studies (Christianson et al., 1983; Lazzeri et al., 1987).

**Explants Used for Somatic Embryogenesis**

In soybean immature cotyledons derived from developing seeds (usually 3-6 mm in length) are the most commonly used explants for inducing somatic embryogenesis. Other explants such as hypocotyls, embryonic axes, and leaf tissues have also been tested; however, immature cotyledons consistently show higher embryogenic competence (Lazzeri et al., 1987; Meurer et al., 2001). The embryogenic potential of explants is strongly influenced by genotype and physiological age.

**Induction of Somatic Embryos**

Somatic embryo induction in soybean is typically achieved on Murashige and Skoog (MS) medium supplemented with high concentrations of auxins, particularly 2,4-dichlorophenoxyacetic acid (2,4-D)**.** Elevated auxin levels promote cellular dedifferentiation and the formation of embryogenic callus. Prolonged exposure to auxin is often necessary for the establishment and maintenance of embryogenic cultures (Christianson et al., 1983).

**Development and Maturation of Somatic Embryos**

Following induction, embryogenic calli are transferred to media with reduced or no auxin concentration to allow embryo development and maturation. Somatic embryos pass through distinct developmental stages, including globular, heart-shaped, torpedo, and cotyledonary stages**,** similar to zygotic embryogenesis. Supplementation of abscisic acid (ABA), activated charcoal, or osmotic agents such as polyethylene glycol (PEG) has been reported to enhance embryo maturation and quality (Lazzeri et al., 1987; Bailey et al., 1993).

**Germination and Plant Regeneration**

Mature somatic embryos are transferred to hormone-free or low-hormone media to promote germination and conversion into plantlets. Successful germination results in the formation of complete soybean plants with well-developed shoots and roots. Regenerated plantlets are subsequently acclimatized and transferred to greenhouse or field conditions (Meurer et al., 2001).

**Applications of Somatic Embryogenesis in Soybean**

Somatic embryogenesis has several important applications in soybean biotechnology:

- Efficient plant regeneration for genetic engineering
- *Agrobacterium*-mediated transformation and gene stacking
- Production of synthetic seeds
- Large-scale propagation of elite and transgenic lines
- Study of embryo development and gene expression

This system is particularly valuable because it allows the regeneration of whole plants from single transformed cells, thereby minimizing the risk of chimerism (Homrich et al., 2012).

**Limitations and Challenges**

Despite its advantages, somatic embryogenesis in soybean is limited by genotype dependency**,** variable embryo-to-plant conversion rates, and the occurrence of abnormal embryo development. Additionally, prolonged culture may lead to somaclonal variation, which can affect genetic stability. Continuous optimization of culture conditions and the use of responsive genotypes are essential to improve efficiency (Somers & Samac, 2004).

**3. Genetic Engineering and Transgenic Soybean**

Genetic engineering involves the direct manipulation of an organism's genome using recombinant DNA technology to introduce, modify, or silence specific genes. In soybean (*Glycine max* L.), genetic engineering has emerged as a powerful tool to overcome limitations of conventional breeding by enabling precise and targeted trait improvement. The development of transgenic soybean represents one of the most significant achievements in agricultural biotechnology, contributing to enhanced crop productivity, improved quality traits, and sustainable agricultural practices (Somers & Samac, 2004; Homrich et al., 2012).

**Methods of Genetic Transformation in Soybean**

***Agrobacterium*-mediated Transformation**

*Agrobacterium tumefaciens*–mediated transformation is the most widely used and efficient method for producing transgenic soybean plants. This bacterium naturally transfers a segment of its Ti plasmid (T-DNA) into the plant genome, which can be engineered to carry genes of interest. In soybean, explants such as cotyledonary nodes, immature embryos, and embryogenic calli are commonly used for transformation (Hinchee et al., 1988; Paz et al., 2006).

This method offers advantages such as:

- Stable gene integration
- Low copy number insertions
- Minimal gene rearrangements

**Particle Bombardment (Biolistic Method)**

The biolistic method involves the physical delivery of DNA into plant cells using high-velocity gold or tungsten microprojectiles**.** Although less frequently used than *Agrobacterium*-mediated transformation, it is effective for:

- Transforming recalcitrant genotypes
- Introducing multiple genes simultaneously

However, this method often results in multiple gene insertions and complex integration patterns (Christou, 1997).

**Development of Transgenic Soybean**

**Herbicide-Tolerant Soybean**

One of the earliest and most commercially successful transgenic soybean traits is herbicide tolerance**.** Introduction of the 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) gene confers resistance to

glyphosate-based herbicides. Herbicide-tolerant soybean allows effective weed control, reduces production costs, and increases crop yield (Padgette et al., 1995; James, 2016).

**Insect-Resistant Soybean**

Transgenic soybean expressing *Bacillus thuringiensis* (Bt) Cry genes provides resistance against major lepidopteran pests. Bt soybean reduces the need for chemical insecticides, thereby minimizing environmental pollution and improving farmer safety (Macrae et al., 2005).

**Disease-Resistant Soybean**

Genetic engineering has enabled the development of soybean varieties resistant to viral, fungal, and bacterial pathogens. Techniques such as RNA interference (RNAi) have been effectively used to silence pathogen-related genes and confer resistance to soybean mosaic virus and nematodes (Zhang et al., 2011; Klink et al., 2009).

**Quality and Nutritional Improvement**

Transgenic approaches have also been employed to modify soybean seed composition. Alteration of fatty acid biosynthesis pathways has resulted in soybean varieties with:

- Increased oleic acid content
- Reduced linolenic acid levels

Such modifications enhance oil stability and nutritional quality (Haun et al., 2014).

**Advantages of Transgenic Soybean**

- Increased yield and productivity
- Reduced pesticide and herbicide usage
- Improved oil quality and nutritional value
- Enhanced tolerance to biotic and abiotic stresses

**Biosafety, Regulatory and Public Concerns**

Despite the benefits, transgenic soybean faces challenges related to biosafety regulations, environmental risk assessment, and public acceptance**.** Rigorous testing and regulatory frameworks are essential to ensure the safe deployment of genetically engineered soybean varieties (Bawa & Anilakumar, 2013).

**Development of Genetically Modified (GM) Soybean**

The development of genetically modified (GM) soybean represents one of the most significant milestones in agricultural biotechnology. GM soybean is produced by introducing specific foreign genes (transgenes) into the soybean genome using recombinant DNA technology to confer desirable agronomic traits such as herbicide tolerance, insect resistance, disease resistance, improved oil quality, and enhanced stress tolerance**.** Since the commercialization of the first GM soybean in the mid-1990s, transgenic soybean has been widely adopted and has substantially contributed to global soybean productivity and sustainability (Padgette et al., 1995; James, 2016).

**Steps Involved in the Development of GM Soybean**

The development of GM soybean involves several critical steps, including gene identification, gene cloning, plant transformation, selection, regeneration, and biosafety evaluation**.** Genes of interest are first isolated and inserted into suitable expression vectors under the control of appropriate promoters. These vectors are then introduced into soybean cells using *Agrobacterium*-mediated transformation or particle bombardment techniques**.** Transformed cells are selected using selectable marker genes and regenerated into whole plants through tissue culture-based regeneration systems such as somatic embryogenesis or organogenesis (Somers & Samac, 2004; Paz et al., 2006).

**Major Traits Introduced in GM Soybean**

**1. Herbicide-Tolerant Soybean**

Herbicide tolerance is the most widely adopted GM trait in soybean. The introduction of the 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) gene confers resistance to glyphosate, a broad-spectrum herbicide. Glyphosate-tolerant soybean allows efficient weed control without damaging the crop, leading to reduced production costs and increased yield (Padgette et al., 1995). This trait has been extensively cultivated in countries such as the United States, Brazil, and Argentina (James, 2016).

**2. Insect-Resistant Soybean**

GM soybean expressing *Bacillus thuringiensis* (Bt) Cry genes provides resistance against major insect pests, particularly lepidopteran larvae. Bt soybean reduces reliance on chemical insecticides, thereby lowering environmental pollution and improving ecological sustainability (Macrae et al., 2005).

**3. Disease-Resistant Soybean**

Genetic modification has been used to enhance resistance to viral, fungal, and nematode pathogens in soybean. RNA interference (RNAi) technology has been successfully employed to silence pathogen-related genes, resulting in resistance to soybean mosaic virus and soybean cyst nematode (Klink et al., 2009; Zhang et al., 2011).

**4. Improved Oil Quality**

GM soybean has been developed with altered fatty acid composition to improve oil stability and nutritional quality. Modification of genes involved in fatty acid biosynthesis, particularly fatty acid desaturase (FAD2) genes, has led to increased oleic acid content and reduced linolenic acid levels in soybean oil (Haun et al., 2014).

**5. Abiotic Stress Tolerance**

Although still under development, genetic engineering approaches have introduced genes related to drought, salinity, and heat tolerance into soybean. These traits are increasingly important in the context of climate change and environmental stress (Singh et al., 2019).

**Commercialization and Global Adoption of GM Soybean**

GM soybean was first commercialized in 1996, and since then, its adoption has increased rapidly. GM soybean currently accounts for a significant proportion of the global soybean cultivation area. The widespread

adoption of GM soybean reflects its economic benefits, including improved yield, simplified crop management, and reduced chemical inputs (James, 2016).

**Abiotic Stress Tolerance Enhancement**

**1.1 Drought Stress Tolerance**

Drought is one of the most severe abiotic stresses limiting soybean yield, particularly under rainfed conditions. Biotechnological strategies to enhance drought tolerance involve the introduction or regulation of genes associated with osmotic adjustment, water-use efficiency, and stress-responsive signaling pathways**.** Transgenic soybean plants expressing transcription factors such as **DREB** (Dehydration-Responsive Element Binding proteins) and genes encoding late embryogenesis abundant (LEA) proteins have shown improved drought tolerance (Manavalan et al., 2009; Tran et al., 2009).

**1.2 Salinity Stress Tolerance**

Salinity stress affects soybean growth by disrupting ion homeostasis and water uptake. Genetic engineering approaches have introduced genes involved in ion transport, osmolyte biosynthesis, and antioxidant defense mechanisms. Overexpression of genes encoding $Na^+/H^+$ antiporters and compatible solute-producing enzymes has enhanced salt tolerance in soybean under controlled conditions (Zhang et al., 2014).

**1.3 Temperature Stress Tolerance**

Extreme temperatures, particularly heat stress, adversely affect soybean flowering, pod set, and seed development. Biotechnological interventions focus on genes encoding heat shock proteins (HSPs) and transcription factors involved in thermal tolerance. Enhanced expression of such genes helps stabilize cellular proteins and membranes under high-temperature stress (Bita & Gerats, 2013).

**2. Biotic Stress Tolerance Enhancement**

**2.1 Insect Pest Resistance**

Biotechnological approaches have successfully enhanced soybean resistance to insect pests through the introduction of Bt (Cry) genes derived from *Bacillus thuringiensis*. Bt soybean provides effective protection against lepidopteran pests, reducing yield losses and minimizing pesticide use (Macrae et al., 2005).

**2.2 Disease Resistance**

Genetic engineering has enabled the development of soybean varieties resistant to viral, fungal, and bacterial diseases. RNA interference (RNAi) technology has been particularly effective in silencing pathogen genes and conferring resistance to soybean mosaic virus and fungal pathogens (Zhang et al., 2011). Additionally, resistance genes (R genes) have been manipulated to strengthen plant defense responses.

**2.3 Nematode Resistance**

Soybean cyst nematode (*Heterodera glycines*) is a major constraint in soybean cultivation. Transgenic approaches using RNAi to target nematode-specific genes have resulted in significant reductions in nematode infestation and improved plant performance (Klink et al., 2009).

## Challenges and Future Prospects

Despite remarkable progress in the application of biotechnology for soybean improvement, several technical, biological, regulatory, and socio-economic challenges continue to limit its full potential. Addressing these challenges while harnessing emerging technologies will be crucial for the future of sustainable soybean production.

### 1. Challenges

#### 1.1 Genotype Dependency and Regeneration Constraints

One of the major technical challenges in soybean biotechnology is its genotype-dependent response to tissue culture and regeneration**.** Many elite soybean cultivars exhibit low regeneration efficiency, particularly in callus culture and somatic embryogenesis systems. This limits the successful recovery of transgenic and genome-edited plants and increases the time and cost of cultivar development (Somers & Samac, 2004; Homrich et al., 2012).

#### 1.2 Complexity of Stress Tolerance Traits

Stress tolerance traits such as drought, salinity, and heat resistance are polygenic and highly influenced by environmental factors**.** Single-gene modifications often provide limited or inconsistent improvements under field conditions. Gene–environment interactions further complicate the stable expression of stress-tolerant traits in soybean (Manavalan et al., 2009).

#### 1.3 Biosafety and Regulatory Constraints

The development and commercialization of genetically modified (GM) soybean are governed by stringent biosafety regulations and lengthy approval processes. Regulatory frameworks vary across countries, leading to delays in the adoption of biotech soybean varieties. In addition, biosafety assessments and compliance increase the overall cost of development (Bawa & Anilakumar, 2013; James, 2016).

#### 1.4 Public Acceptance and Ethical Concerns

Public perception and acceptance of GM crops remain major challenges. Concerns regarding food safety, environmental impact, and ethical issues often influence policy decisions and market access, particularly in developing countries (Bawa & Anilakumar, 2013).

#### 1.5 Intellectual Property and Access to Technology

Biotechnological innovations in soybean are often protected by intellectual property rights (IPRs), limiting access for public-sector institutions and smallholder farmers. This can restrict technology dissemination and widen the gap between developed and developing agricultural systems (Singh et al., 2019).

### 2. Future Prospects of Soybean Biotechnology

#### 2.1 Genome Editing and Precision Breeding

The advent of CRISPR/Cas9 and related genome-editing tools has opened new possibilities for precise and efficient soybean improvement. Genome editing allows targeted modification of genes controlling yield, oil quality, and stress tolerance without introducing foreign DNA, potentially reducing regulatory hurdles and increasing public acceptance (Zhang et al., 2020).

### 2.2 Integration of Omics Technologies

The integration of genomics, transcriptomics, proteomics, and metabolomics will enhance the identification of key genes and pathways involved in complex traits. Omics-driven approaches combined with bioinformatics and artificial intelligence are expected to accelerate trait discovery and soybean breeding programs (Manavalan et al., 2009).

### 2.3 Gene Stacking and Trait Pyramiding

Future soybean varieties are likely to incorporate multiple beneficial traits through gene stacking and trait pyramiding strategies. Combining herbicide tolerance, pest resistance, improved oil quality, and stress tolerance in a single cultivar will improve productivity and resilience under diverse environmental conditions (Somers & Samac, 2004).

### 2.4 Development of Climate-Resilient Soybean

Climate change poses a significant threat to soybean cultivation. Biotechnology-based approaches focusing on climate resilience, such as tolerance to drought, heat, and flooding, will be essential for maintaining yield stability and ensuring food security (Boyer, 1982; Manavalan et al., 2009).

### 2.5 Sustainable and Environment-Friendly Agriculture

Biotechnological advancements in soybean can contribute to sustainable agriculture by reducing chemical inputs, improving nutrient-use efficiency, and minimizing environmental impact. The development of eco-friendly biotech soybean varieties aligns with global goals for sustainable development and environmental conservation (James, 2016).

## Conclusion

Biotechnological approaches have emerged as powerful and indispensable tools for the improvement of soybean (*Glycine max* L.), one of the world's most important oilseed and legume crops. Traditional breeding methods, although successful to a certain extent, are often constrained by limited genetic variability, long breeding cycles, and the complex inheritance of key agronomic traits. In contrast, modern biotechnology has enabled precise, efficient, and targeted manipulation of the soybean genome to enhance productivity, quality, and resilience.

Techniques such as plant tissue culture, including micropropagation, callus culture, and somatic embryogenesis, have laid a strong foundation for large-scale propagation and successful genetic transformation. Genetic engineering and transgenic technologies have led to the development of commercially successful soybean varieties with herbicide tolerance, insect resistance, disease resistance, and improved oil quality. Furthermore, molecular breeding tools **and** marker-assisted selection have accelerated the identification and introgression of desirable traits, improving the efficiency of breeding programs.

Recent advances in genome editing technologies, particularly CRISPR/Cas-based systems, have opened new possibilities for precise trait improvement without the introduction of foreign DNA, addressing biosafety and public acceptance concerns. In addition, biotechnological interventions aimed at enhancing abiotic and

biotic stress tolerance are particularly relevant in the context of climate change, as they contribute to yield stability and sustainable soybean production.

Despite existing challenges related to regeneration efficiency, regulatory frameworks, and socio-economic acceptance, the future of soybean biotechnology remains highly promising. The integration of omics technologies, precision breeding, and sustainable agricultural practices is expected to further accelerate soybean improvement. Overall, biotechnology will continue to play a crucial role in ensuring **food** and nutritional security, environmental sustainability, and economic viability of soybean cultivation, making it a key component of future agricultural systems.

**Acknowledgement**

The authors also express their sincere thanks to teachers, mentors, and colleagues for their guidance, encouragement, and constructive suggestions during the preparation of this manuscript. Special appreciation is extended to the publishers and reviewers of the cited journals for maintaining high academic standards and making relevant research accessible to the scientific community.

**References**

- Bailey, M. A., Boerma, H. R., & Parrott, W. A. (1993). Genotype-specific optimization of plant regeneration from somatic embryos of soybean. Plant Cell Reports, 12, 413–417.
- Barwale, U. B., Kerns, H. R., & Widholm, J. M. (1986). Plant regeneration from callus cultures of several soybean genotypes. Planta, 167, 473–481.
- Bawa, A. S., & Anilakumar, K. R. (2013). Genetically modified foods: Safety, risks and public concerns. Journal of Food Science and Technology, 50, 1035–1046.
- Bita, C. E., & Gerats, T. (2013). Plant tolerance to high temperature in a changing environment. Plant Science, 1–2, 356–367.
- Boyer, J. S. (1982). Plant productivity and environment. Science, 218, 443–448.
- Christianson, M. L., Warnick, D. A., & Carlson, P. S. (1983). A morphogenetically competent soybean suspension culture. Science, 222, 632–634.
- Christou, P. (1997). Rice transformation by bombardment. Plant Molecular Biology, 35, 197–203.
- FAO. (2022). *FAOSTAT Statistical Database*. Food and Agriculture Organization of the United Nations.
- Franklin, G., Sheeba, C. J., & Lakshmisita, G. (2004). Regeneration of soybean (*Glycine max* L. Merrill) from cotyledonary node explants. Plant Cell, Tissue and Organ Culture, 76, 1–7.
- Hartman, G. L., Rupe, J. C., Sikora, E. J., Domier, L. L., Davis, J. A., & Steffey, K. L. (2015). Compendium of Soybean Diseases and Pests. APS Press.
- Hartman, G. L., West, E. D., & Herman, T. K. (2011). Crops that feed the world 2. Soybean-worldwide production, use, and constraints. Food Security, 3, 5–17.
- Haun, W., Coffman, A., Clasen, B. M., et al. (2014). Improved soybean oil quality by targeted mutagenesis of the fatty acid desaturase 2 gene family. Plant Biotechnology Journal, 12, 934–940.
- Hinchee, M. A. W., et al. (1988). Production of transgenic soybean plants using *Agrobacterium tumefaciens*. Bio/Technology, 6, 915–922.
- Homrich, M. S., et al. (2012). Soybean genetic transformation: A review. Brazilian Journal of Plant Physiology, 24, 79–94.
- James, C. (2016). Global status of commercialized biotech/GM crops. ISAAA Brief No. 52.

- Klink, V. P., et al. (2009). RNA interference-mediated resistance to soybean cyst nematode. Plant Physiology, 151, 149–161.
- Lazzeri, P. A., Hildebrand, D. F., & Collins, G. B. (1987). Soybean somatic embryogenesis: Effects of hormones and culture manipulations. Plant Cell, Tissue and Organ Culture, 10, 197–208.
- Macrae, T. C., et al. (2005). *Bacillus thuringiensis* toxins: Mode of action and use in crop protection. Microbiology and Molecular Biology Reviews, 69, 1–40.
- Manavalan, L. P., Guttikonda, S. K., Tran, L. S. P., & Nguyen, H. T. (2009). Physiological and molecular approaches to improve drought resistance in soybean. Plant and Cell Physiology, 50, 1260–1276.
- Meurer, C. A., Dinkins, R. D., & Collins, G. B. (2001). Factors affecting soybean somatic embryo maturation and conversion. Plant Cell, Tissue and Organ Culture, 66, 123–131.
- Murashige, T., & Skoog, F. (1962). A revised medium for rapid growth and bioassays with tobacco tissue cultures. Physiologia Plantarum, 15, 473–497.
- Padgette, S. R., et al. (1995). Development, identification, and characterization of a glyphosate-tolerant soybean line. Crop Science, 35, 1451–1461.
- Paz, M. M., Martinez, J. C., Kalvig, A. B., Fonger, T. M., & Wang, K. (2006). Improved cotyledonary node method for *Agrobacterium*-mediated soybean transformation. Plant Cell Reports, 25, 206–213.
- Singh, G., Kumar, S., & Singh, P. (2019). Advances in soybean breeding through molecular and biotechnological approaches. Journal of Oilseed Research, 36, 1–10.
- Somers, D. A., & Samac, D. A. (2004). Genetic engineering of soybean. Plant Breeding Reviews, 24, 317–354.
- Tran, L. S. P., et al. (2009). Functional analysis of soybean DREB genes in drought and salt stress tolerance. Plant Biotechnology Journal, 7, 554–565.
- Wilson, R. F. (2004). Seed composition. In Soybeans: Improvement, Production, and Uses (3rd ed.). ASA, CSSA, SSSA.
- Zhang, C., et al. (2011). RNAi-mediated resistance to soybean mosaic virus. Plant Biotechnology Journal, 9, 1–10.
- Zhang, J., Zhang, H., Botella, J. R., & Zhu, J. K. (2020). Genome editing in plants: Advances and applications in soybean. Plant Biotechnology Journal, 18, 186–188.
- Zhang, X., et al. (2014). Genetic engineering for salt tolerance in soybean. Plant Cell Reports, 33, 123–134.