

Review Article

Review on Genetic Variability Studies of Soybean (Glycine Max L.) in Ethiopia: Challenges and Opportunities

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Abstract

Soybeans represent a major oilseed and protein crop in Ethiopia, contributing substantially to food security, income generation, and soil fertility improvement. Optimal production relies on refined cultivation practices, including effective land preparation, appropriate plant spacing, and timely weed management, all of which maximize genetic yield potential. Genetic variability remains essential for crop improvement and breeding initiatives. However, the efficiency of soybean breeding in Ethiopia is constrained by several factors, including limited application of molecular breeding techniques, a narrow genetic base of germplasm, environmental variability, and inadequate research infrastructure. Opportunities exist to advance soybean improvement through the adoption of modern genomic tools such as marker-assisted selection and genomic selection, expansion of multi-environment trials, and participatory plant breeding strategies. This review synthesizes findings from genetic variability studies conducted in Ethiopia over the past decade, with a focus on parameters such as genotypic and phenotypic coefficients of variation, heritability, genetic advance, and trait associations. The evidence consistently demonstrates significant variability among soybean genotypes across diverse agro-ecological zones. High heritability coupled with high genetic advance for yield-related traits indicates the predominance of additive gene action, facilitating effective selection. Persistent challenges include limited molecular breeding, environmental variability, and a restricted genetic base. While Ethiopia has begun to implement Marker-Assisted Selection (MAS), integration of multi-omics data and high-throughput phenomics remains limited. There is considerable potential to modernize the sector by adopting precision breeding approaches, emphasizing climate resilient ideotypes and industrial quality traits, such as reduced anti-nutritional factors, which are currently under represented in the national research agenda.

Keywords

Challenges, Genetic Variability, Opportunities, Review, Soybeans

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1. Introduction

Soybean (*Glycine max* L.) is a legume species native to East Asia, widely grown for its edible beans, which have several uses. Genetically, soybean is a diploid legume species with a chromosome number of $2n = 2x = 40$. Soybeans have a relatively large genome size (1.12 GB), and about 55% of their genome consists of highly repetitive sequences [34]. It is a self-pollinated crop and hence has low allelic diversity [23].

It is called a miracle crop due to its high protein (35–45%) and oil (18–22%) content. It is widely used as human food, animal feed, and raw material for many industrial products [36]. It is used for crop rotation as it enhances soil fertility and breaks the buildup of pests [5]. Due to these attributes, soybeans have gained economic and agricultural importance in many countries, including Ethiopia.

Globally, soybean cultivation covers nearly 121 million hectares, with a total production of 334 million tons yearly. Major soybean producing countries in the world include Brazil, the USA, Argentina, China, and India, which contribute more than 80% of the total global production [39]. In Ethiopia, soybean has appeared as a vital pulse and oilseed crop, mainly in the southwestern, western, and north-western parts of the country. The area covered under soybeans is 6,236 hectares, and the total production of the crop in the country is 78,989 quintals. The productivity of soybeans in Ethiopia has shown a positive trend, reaching approximately 2.54 t ha^{-1} in the 2025/2026 cropping season [11]. While this represents a significant increase from the 1.67 tones reported in 2021, it remains low compared to the global average productivity of 2.93 t ha^{-1} [12].

Classical breeding has historically been the primary driver of variety development, focusing on the introduction and evaluation of germplasm from international centers like CIMMYT. This method utilizes hybridization and pedigree selection to develop varieties with high grain yield and stability across Ethiopia's varying altitudes. While these traditional methods are essential for ensuring environmental adaptation, they are often time consuming, taking up to a decade to produce a stable variety. To address these gaps, modern breeding methods are increasingly being linked to the national research framework.

Today, researchers are using Marker-Assisted Selection to identify specific genetic loci associated with rust resistance and drought tolerance, allowing for screening breeding lines at the seedling stage [33]. Also, the application of modern breeding to generate multiple crops is being explored to halve the time for variety release. Although the utilization of transgenic soybeans is limited by national biosafety regulations, the implementation of molecular characterization enables Ethiopian breeders to accurately select diverse parental lines, thereby enhancing the resilience of the soybean sub-sector.

In Ethiopia, several soybean genetic studies have confirmed that traits such as the number of pods per plant, plant height, hundred seed weight, and grain yield exhibit high variability,

suggesting that these traits are primarily governed by additive gene action and are highly responsive to selection [18]. For instance, in Northwestern Ethiopia, research involving 81 genotypes revealed that plant height and hundred-seed weight are among the most stable and heritable traits.

Currently, primary breeding activities are centered at the Ethiopian Institute of Agricultural Research (EIAR), such as Pawe, Jimma, and Hawassa, where researchers focus on developing high-yielding, early-maturing, and disease-resistant genotypes. However, a critical gap exists because much of this research remains localized within specific regional institutes and has not been fully compiled into a centralized national database, leading to a research system where genetic gains are not always shared across the country.

Despite high potential for genetic improvement, the sector faces steep constraints that limit productivity. Biological hurdles, such as pod shattering and the rapid loss of seed viability in lowland environments, significantly reduce harvestable yields and seed availability for farmers [7]. Also, many researchers argue that the narrow genetic base of Ethiopian varieties, which rely heavily on imported exotic lines, makes the crop vulnerable to emerging pests and climate shifts. These challenges are compounded by a lack of modern genomic tools and cold storage infrastructure, which forces breeders to rely on slower, traditional selection methods rather than expedited molecular breeding [28].

Over the past decade in Ethiopia, studies on genetic variability have evolved from vital phenotypic descriptions to more advanced evaluations of the nation's germplasm. However, these initiatives largely remain fragmented across independent theses and regional reports. Researchers have steadily identified significant genotypic and phenotypic coefficients of variation for traits such as pods/plant, hundred seed weight, and grain yield, predominantly in trials conducted in the Gondar, Jimma, and Pawe areas [30]. This lack of synthesis means that high-potential alleles identified in one agroecology, such as the humid lowlands of Benishangul Gumuz, are rarely incorporated into breeding programs in another.

While the last decades have well classified the variability of specific traits, the unaddressed work remains the transition from observation to application. Consequently, the breeding system still struggles with a narrow genetic base because the documented variability exists in academic studies rather than in the active crossing blocks of national programs.

Therefore, the objective of this paper is to review existing research on the genetic variability of soybean in Ethiopia for the last ten years, with an emphasis on its importance for crop improvement, and to identify key challenges and future opportunities for soybean breeding and production.

2. Literature Review

2.1. Soybean Taxonomy

Soybean (*Glycine max* L.) is classified in the legume family. It is an annual, self-pollinated diploid species ($2n = 2x = 40$) in the subfamily Papilionoideae, genus *Glycine* Wild, and sub-genus *Soja*. *Glycine soja* is a diploid and self-fertile species with less than 1% outcrossing [37]. Cultivated soybean is usually erect with a well-defined main stem, branches, and numerous leaves. The height of the soybean plant varies from 0.20m to 2m depending on the variety.

2.2. Soybean Origin and Distribution

Soybeans are thought to have originated in East Asia, mainly China. Soybeans were introduced in the late 19th century in East Africa, since there were long trade relations with the Chinese [21]. Today, soybeans are grown all over the world, in diverse climates ranging from temperate to tropical. However, for a national breeding program, this transition is not merely geographic but genomic. Moving from temperate to tropical environments requires the identification of specific genes that control juvenile periods. In the context of our country, fragmented studies have yet to compile these into an integrated data management system. This provides a major chance to use GWAS to select for long neutral alleles, allowing varieties to reach high yields despite the shorter day-lengths of tropical latitudes.

2.3. Importance of Soybean

Soybeans are one of the most useful grain legume crops globally due to their nutritional, economic, agronomic, and environmental significance. Today, soybeans have gained increased importance in developing countries, including Ethiopia, as a strategic crop for food and nutrition security, income generation, and sustainable agricultural production, as explained in the following paragraph.

2.3.1. Nutritional Importance of Soybean

Soybean seeds contain nearly 40% protein and 20% edible oil, making them a major source of plant-based protein and vegetable oil [40]. Its protein provides vital amino acids, while soybean oil is rich in unsaturated fatty acids, contributing to better human nutrition and livestock feed quality. The current study shows the role of soybeans in enhancing dietary diversity and addressing protein malnutrition in Sub-Saharan Africa. Soybeans are essential to global food systems, mainly in the production of plant-based foods such as soy sauce.

2.3.2. Economic Significance of Soybean

Soybeans are a vital agricultural product that has significant economic value, mainly in countries that are major producers,

and are important cash crops with growing demand in local and global markets. Soybean meal is used as a high-protein feed for livestock and poultry. It is considered a crucial crop in the meat production industry, supporting the global meat and dairy markets. In Ethiopia, soybeans have been known as a priority crop for import substitution, industrial growth, and smallholder income diversification.

2.3.3. Soybean Role in Soil Fertility and Cropping Systems

Agronomically, soybeans play a crucial role in sustainable farming systems due to their ability to fix atmospheric nitrogen through symbiotic association with *Bradyrhizobium* species. Recent studies confirm that soybean-based cropping systems enhance soil nitrogen status, organic matter content, and overall system productivity [3].

2.3.4. Industrial Uses

Beyond direct consumption, soybean is a highly useful industrial raw material. It is a primary source for the commercial production of edible vegetable oil, as well as traditional and functional foods such as tofu and soy sauce. In the non-food industrial sector, progress in green chemistry utilizes soybean oil and by-products in the business of industrial textiles, eco-friendly inks, and biodegradable bioplastics, reducing reliance on petroleum-based synthetics.

2.3.5. Animal Feeds

The livestock, poultry, and aquaculture sectors are greatly dependent on soybean production. Soybean meal, the primary by-product of oil extraction is recognized globally as the gold standard protein supplement in animal feed making. Its high digestibility and rich amino acid profile are essential for optimizing growth rates and feed conversion efficiencies in concentrated animal production systems.

2.3.6. Adaptability and Resilience

The wide genetic variability within soybeans allows it to display high adaptability across diverse agro-ecological zones, ranging from lowlands to mid-highlands. The crop exhibits commendable resilience and relative tolerance to several prevailing abiotic stresses, including intermittent moisture deficits and fluctuating temperature regimes, making it a dependable crop under changing climatic conditions.

2.3.7. Global Trade Commodity

On a macroeconomic scale, soybean represents one of the most heavily traded agricultural commodities worldwide. It plays a foundational role in international trade liquidity, balancing global supply and demand for both vegetable oils and protein meals. For producing nations, soybean exports strengthen national food systems, improve trade balances, and inject foreign currency into domestic economies.

2.4. Trends in Soybean Production in Ethiopia Over the Past Decade

Soybean production in Ethiopia has shown a steady upward trend from 2015 to 2025, driven mainly by increasing demand for edible oil, livestock feed, and export opportunities. From 2015 to 2016, production was relatively low, estimated at 66,000-90,000 tons, with limited adoption of improved varieties and traditional farming practices dominating the system. From 2017 to 2019, production began to rise steadily as soybeans gained value in crop rotation systems and farmers started expanding cultivation areas, reaching over 120,000 tons. From 2020 to 2023, soybean production increased more rapidly, largely due to the expansion of cultivated land and growing market demand from agro-processing industries.

From 2020 to 2023, soybean production increased more rapidly, largely due to the expansion of cultivated land and growing market demand from agro-processing industries. During this period, national production reached approximately 180,000 to 240,000 tons. However, yield improvements remained moderate, as production growth was still mainly area driven rather than productivity driven. Oromia, Benishangul Gumuz, and SNNPR became the major producing regions. From 2024 to 2025, soybean production stabilized with slight growth, reaching around 240,000 to 260,000 tons. Overall, soybean production in Ethiopia has increased three fold over the past decade, indicating strong potential for further expansion if improved varieties, mechanization, and agronomic practices are enhanced.

2.5. 10-Year Overview: Soybean Genetic Variability Studies in Ethiopia

The study of soybean genetic variability in Ethiopia over the last decade has revealed major potential for crop improvement, yet it remains hindered by constant practical and thematic gaps. Research conducted across various agro-ecological zones has consistently verified high heritability and genetic advance for traits like yield, 100-seed weight, and days to maturity, indicating that phenotypic selection can well enhance productivity [6].

These studies have been involved in identifying elite genotypes adapted to specific areas like Jimma and Pawe. But the reliance on a narrow genetic base primarily sourced from a limited number of IITA and MARC accessions poses a long term risk of genetic vulnerability. Also, the benefits of identifying high-yielding lines are often offset by the drawbacks of short-duration trials, which often fail to capture the multi-year environmental stability required for a climate resilient agricultural system [38].

The most critical gap identified during these 10 years is the great focus on morphological and phenotypic description at the expense of advanced biotechnological approaches. While researchers have widely mapped the Phenotypic and Genotypic Variation, there is a severe deficiency in molecular

marker-assisted selection and genomic studies [1]. This has left a void in our understanding of the specific genes governing complex traits like drought tolerance and nutrient use efficiency. Moreover, while total yield has been the primary focus, the genetic variability for nutritional quality, specifically protein and oil content, and tolerance to soil acidity, remains largely unexplored [8].

Over the past decade, soybean genetic variability studies in Ethiopia have transitioned from basic screening to more targeted selection within the country's diverse mid-altitude and lowland sub-humid agro ecologies. Research has consistently confirmed a wide range of genetic diversity for key agronomic traits, mainly yield, days to maturity, and 100-seed weight. The primary success of this 10 year research period is the identification of high variability across several genotypes, indicating that the observed variations are largely genetic and can be effectively exploited through selection [4].

Despite these successes, a major research gap has persisted over the last ten years: Most Ethiopian studies focus on morphological markers, leaving the genotypic variance largely unmapped at the DNA level, which prevents the use of Marker-Assisted Selection to hasten breeding cycles. As well, while yield variability is well-documented, there is a critical lack of data on genetic resistance to rust and soil acidity, which are the two most significant abiotic and biotic constraints in Ethiopia.

2.5.1. Genetic Variability in Grain Yield

Over the last decade, the central pillar of soybean research in Ethiopia has been the evaluation of total grain yield across the country's diverse agro ecological zones. Research conducted in major production centers, such as Pawe, Assosa, and Jimma, has steadily revealed significant genotypic variation for grain yield, with several studies re-reporting that the genotypic coefficient of variation remains high enough to allow for effective selection [35]. The benefit of this decade-long focus is the fruitful identification of high-yielding, stable varieties that have increased national average productivity.

Yet, the major con and persistent gap is the yield gap between research stations and smallholder farms. Despite finding high-yielding potential in trials, the lack of molecular characterization for yield-specific QTLs prevented breeders from breaking the current yield through precision breeding [26].

2.5.2. Description of Soybean Yield and Yield Components

(i). National Context and Yield Dynamics

In the current national agricultural landscape, soybean yield remains the most economically vital yet genetically complex trait. While traditional breeding methods have successfully released varieties like Guda and Tesfaye, which reveal yields

ranging from 2.75 to 3.74 t ha⁻¹. The influence of environmental factors remains a significant hurdle to consistent productivity [9]. Recent METs reveal that environmental variance accounts for around 45% of yield variations, highlighting the urgent need for genomic tools that can stabilize performance across diverse agro-ecologies. National breeding is shifting from phenotypic selection to genomic methods that analyze yield into its components.

(ii). Genomic Selection (GS) for Accelerated Genetic Gain

The application of Genomic Selection (GS) is reforming how national programs manage complex traits. Unlike traditional selection, GS utilizes genome-wide molecular markers to calculate Genomic Estimated Breeding Values (GEBVs), enabling breeders to predict yield potential in the early stages of plant development [22]. Recent models and field data suggest that uniting genomic selection into national programs can result in a 35% greater genetic gain compared to phenotypic selection alone. This technology is mainly effective for improving low-heritability traits like yield, where GS models have achieved predictive accuracy ranging from 0.26 to 0.81 for yield and protein content, respectively. By adopting these models, countries can point out that they can shorten the

breeding cycle to 4 to 6 years, allowing for a more rapid response to climate shifts.

(iii). GWAS and Architecture of Yield Components

To know the primary genetic drivers of yield, Genome-Wide Association Studies (GWAS) are being utilized to identify specific Single Nucleotide Polymorphisms (SNPs). A critical focus has been placed on hundred-seed weight, a trait with high heritability that directly impacts yield and economic return. Recent genomic studies have identified major stable QTLs for seed weight that keep sense across multiple years and environments.

(iv). Integrated Breeding

The mixing of genomic data with Multi-Trait Genotype-Ideotype Distance Index and Machine Learning offers a new framework for selecting genotypes that balance yield with stress resilience [2]. For the national program, the ability to identify climate-smart accessions that maintain high yield under severe water stress, as this is common during pod filling stages. As the country faces intensified random weather patterns, these genomic applications provide a proactive approach for sustainable soybean intensification.

Table 1. Summary of Recent Review of Soybean Yield and Genomic Research.

Year	Focus	Key Statistical Tools	Key Findings
2016	Early Genomic Selection Foundations	RR-BLUP (Ridge Regression Best Linear Unbiased Prediction)	Validated the early predictive accuracy of training populations to estimate genomic breeding values (GEBVs)
2018	Selection Efficiency Gains	Bulk & Pedigree Selection Parameter Estimation	Determined heritability values and genetic advance under selection across segregating generations, defining the expected rate of annual vertical yield gains.
2020	Multi-Trait Yield Ratios	Genotype Selection Index (GSI) & Path Analysis	Resolved negative genetic correlations between total seed protein content and oil/grain yield, allowing simultaneous selection for quality and output.
2021	High-Density Trait Mapping	High-density SNP Chips (e.g., SoySNP50K)	Mapped quantitative traits at high resolution, shifting breeding programs away from older SSR markers to track small-effect polygenic yield traits across breeding blocks.
2022	Core Genotype Adaptability	GGE Biplot (PC1 vs PC2 Analysis)	Demonstrated that the first two principal components explain over 74% of the total variation in multi-environment trials, optimizing mega-environment classifications for stable line releases.
2023	Multi-Environment Interaction (\$G \times E\$)	GLM, AMMI, & ASV (AMMI Stability Value) Models	Partitioned total phenotypic variance for seed yield; discovered that \$G \times E\$ interaction and environmental factors can account for over 54% of total sum of squares, complicating selection index accuracy.
2026	Stability and GXE	AMMI & GGE Biplot Analysis	Environment accounts for 45% of yield variance; identified 'Tesfaye' as a top-yielding variety.
	Drought Resilience	Drought Indices	Integrated multi-trait selection identifies genotypes with yield stability under water-deficit stress.

Year	Focus	Key Statistical Tools	Key Findings
2025	Seed Weight	GWAS & Fine-mapping	Identified stable QTL for HSW; GS can increase genetic gain by 35% over phenotypic selection.
2024	Integrated Genomics	GS, GWAS, & CRISPR-Cas9	Genomic selection models achieve high predictive accuracy for yield components and seed quality.
2024	Resilience & Utility	GBS & Bayesian Models (BLINK)	Identified significant SNPs associated with grain yield, plant height, and seed weight.

2.5.3. Variability in Nutritional Quality

With the expansion of Ethiopia’s agro processing sector, studies have begun to explore the genetic variability of oil and protein content. While results indicate that Ethiopian soybean germplasm possesses competitive protein levels ranging from 36% to 44%, the primary focus of the last ten years has remained skewed toward volume rather than chemical composition. There is currently no significant data or breeding effort directed toward reducing anti-nutritional factors, which limits the direct use of high-yield varieties in the domestic food and feed industries.

2.5.4. Variability in Disease and Pest Resistance

Studies conducted in Ethiopia over the last decade steadily report significant differences among soybean genotypes for disease resistance traits. For example, field evaluations of introduced and locally adapted genotypes showed significant variation in disease severity and infection rate, indicating the presence of usable genetic diversity [31]. Similarly, breeding and evaluation studies confirm that soybean genotypes differ widely in their resistance to fungal and bacterial diseases, with some lines showing moderate resistance while others are highly susceptible [15].

Studies in Ethiopia indicate that disease-related traits such as disease severity index, leaf infection rate, and yield loss percentage often show moderate to high heritability, suggesting that genetic factors strongly influence these traits. This makes selection under field conditions effective for improving disease resistance. Modern approaches such as QTL mapping, marker-assisted selection, and genome editing have identified genes associated with resistance to major soybean diseases [14].

Soybean rust resistance, for example, is controlled by multiple resistance genes that interact with pathogen a-virulence genes, proving gene-for-gene relationships. Similarly, resistance to bacterial diseases is often controlled by multiple

QTLs with small to moderate effects, indicating quantitative inheritance of resistance traits [25]. Soybean production in Ethiopia is increasingly constrained by insect pests, which are among the most important biotic stresses affecting yield, seed quality, and overall crop performance. Over the last decade, several studies have revealed that soybean germplasm exhibits substantial genetic variability for insect pest resistance, making it an important trait for breeding programs aimed at improving productivity and stability.

In Ethiopia, the major insect pests affecting soybean include pod borers, aphids, whiteflies, cutworms, and leaf defoliators. These pests attack different growth stages of the crop, causing significant damage. Pod borers are especially destructive during flowering and pod formation, leading to direct yield losses, while aphids and whiteflies not only reduce plant vigor through sap feeding but also act as vectors for viral diseases [20]. Field observations across soybean-growing regions such as Oromia, Benishangul Gumuz, and western Ethiopia show that pest incidence and severity vary depending on environmental conditions which lead to changes in genotype performance and reveals basic genetic variability. Research findings consistently show that soybean genotypes differ significantly in their response to insect pest pressure. Some genotypes exhibit low damage levels and better recovery ability, while others are highly susceptible, indicating the presence of usable genetic diversity.

Traits such as leaf damage score, pod damage percentage, number of damaged seeds per plant, and overall yield reduction under infestation conditions are commonly used to assess resistance levels. Studies in Ethiopia also indicate that insect pest resistance traits show moderate heritability and genetic advance, suggesting that both genetic and environmental factors influence resistance expression. This implies that while environmental conditions affect pest pressure, there is still sufficient genetic control to allow effective selection in breeding programs. Grain yield and pod number are often positively associated with pest resistance, indicating that improving resistance can directly enhance productivity.

Table 2. Variability in Soybean Response to Major Diseases and Pests.

Biotic Constraint	Causal Agent	Impact on Productivity	Resistance Mechanism
Soybean Rust	<i>Phakopsora pachyrhizi</i>	Rapid defoliation and up to 65% yield loss.	Selection for genes and slow-rusting traits
Bacterial Blight	<i>Pseudomonas savastanoi</i>	Necrotic lesions reducing photosynthetic area.	Vertical resistance screening in germplasm.
Soybean Aphids	<i>Aphis glycines</i>	Sap-sucking damage and transmission of viral diseases.	Antibiosis and antixenosis (e.g., leaf hairs).
Pod Borers	<i>Helicoverpa armigera</i>	Direct damage to reproductive organs and pod number.	Morphological traits like pod pubescence.

2.5.5. Genetic Variability Drought Stress

Drought is the most important abiotic stress limiting soybean production in Ethiopia, especially in regions such as Jinka, Humera, and Gofa. Research shows: significant variability in days to flowering, maturity, and yield under moisture stress; some genotypes maintain relatively high yield under drought conditions and high heritability values for yield-related traits under stress environments. A study conducted under moisture stress conditions in Ethiopia confirmed that genotypes differ significantly in their ability to tolerate drought, indicating strong genetic variation for adaptation traits.

Drought stress mainly affects soybean during flowering and pod filling stages, leading to reduced photosynthesis, early leaf senescence, flower abortion, and poor seed development. In Ethiopia, drought-prone environments such as eastern and southern lowlands have been widely used to evaluate soybean performance under moisture stress conditions.

Studies show that soybean yield loss under drought can be severe, but variation among genotypes is large, indicating the presence of useful genetic diversity for drought tolerance. Re-

search conducted in Ethiopia has confirmed significant differences among soybean genotypes for drought tolerance-related traits. Some genotypes maintain better growth and yield stability under moisture deficit, while others are highly sensitive. Traits showing strong genetic variability include Plant height, Days to flowering and maturity, Number of pods per plant, and Seed weight and grain yield. High phenotypic and genotypic variation observed in these traits suggests that selection under drought stress is effective for improving soybean performance [16]. Several studies report moderate to high heritability estimates for yield-related traits under drought conditions, indicating that genetic factors play a major role in trait expression.

Significant genetic variability exists among soybean genotypes in their response to drought stress. This variability is expressed through various morphological, physiological, and biochemical mechanisms. Some genotypes exhibit drought avoidance by developing deep root systems or reducing leaf area to minimize water loss, while others show drought tolerance by maintaining cell turgor through osmotic adjustment. In a breeding program, identifying genotypes that maintain high harvest indices and stable yields under water-limited conditions is critical for developing varieties resilient to the erratic rainfall patterns often observed in tropical environments.

Table 3. Summary of Drought Stress Impacts and Varietal Mechanisms in Soybean.

Impact	Specific Effects on Soybean	Resistance Mechanisms
Morphological	Reduced plant height, decreased node number, and limited leaf expansion.	Increased root-to-shoot ratio and leaf rolling.
Reproductive	Shortened flowering period, increased pod shattering, and reduced seed size.	High pollen viability under stress and early maturity (escape).
Physiological	Reduced stomatal conductance, and inhibited photosynthesis.	High water-use efficiency and osmotic adjustment.
Biochemical	Increased production of reactive oxygen species and chlorophyll degradation.	Accumulation of proline and antioxidant enzyme activity

Impact	Specific Effects on Soybean	Resistance Mechanisms
Yield Components	Significant reduction in 100-seed weight & number of pods/ plant.	Maintenance of high harvest index under stress

2.5.6. Soil Acidity and Heat Stress

Soybean productivity is strongly influenced by abiotic stresses, mainly soil acidity and heat stress, which are major constraints of many soybean growing areas in Ethiopia. Recent studies indicate that these stresses not only reduce yield but also reduce genetic variability among soybean genotypes, providing opportunities for selection and breeding improvement. Soil acidity is a major constraint in western and south-western Ethiopia, where highly weathered soils dominate. Acid soils are characterized by low pH, aluminum toxicity, and P deficiency, which limit root growth and nutrient uptake. These conditions lead to reduced nodulation and poor nitrogen fixation in soybean. Research has shown that soybean genotypes exhibit significant genetic variability in tolerance to acidic soils. Some genotypes perform well under low pH conditions, maintaining better root growth, nodulation efficiency,

and biomass production, while others show severe growth reduction.

Studies conducted in Assosa and Jimma environments confirm that yield and yield-related traits under acidic soil conditions have moderate to high heritability, indicating that selection can be effective for improvement. Heat stress, increasingly associated with climate change, is another major abiotic constraint affecting soybean production in Ethiopia. High temperatures during flowering and pod-setting stages lead to flower abortion, reduced pollen viability, and shortened grain-filling periods. Studies show that soybean genotypes differ significantly in their response to heat stress, confirming the presence of substantial genetic variability. Moreover, heat stress during the seed filling stage accelerates leaf senescence and shortens the grain-filling duration, resulting in smaller, shriveled seeds with altered protein and oil compositions. Selecting heat tolerant genotypes is therefore vital for maintaining stable soybean production in the face of changing climatic conditions in southwestern Ethiopia.

Table 4. Summary of Heat Stress Effects on Soybean Growth and Yield Components.

Growth Stage	Major Effects of Heat Stress
Vegetative	Reduced leaf area, inhibited root growth, and decreased chlorophyll content.
Reproductive	Reduced pollen viability, reduced stigma receptivity, and high rate of flower or pod abscission.
Grain Filling	Shortened seed-filling duration, reduced seed size, and decreased grain weight
Physiological	Increased oxidative stress, reduced photosynthetic rate, and altered enzymatic activity
Quality	Reduce oil, protein content and seed germination quality

2.6. Challenges in Soybean Breeding and Production

Soybean breeding in Ethiopia has made gradual progress over the past decade; however, several persistent challenges continue to limit its efficiency and impact.

2.6.1. Environmental and Genetic Constraints

Climate Change: Environmental volatility characterized by frequent droughts, extreme heat waves, and irregular rainfall patterns severely compromises environmental stability and reduces overall yield predictability.

Pests and Diseases: Soybean crops are continuously threatened by emerging pests and pathogens, which cause significant, unpredictable yield losses annually.

Limited Genetic Diversity: A historically narrow gene pool restricts current breeding efforts, making it increasingly difficult to develop novel high-yielding and climate-resilient varieties.

Complexity of the Soybean Genome: The complex polyploid nature and large genome size of soybeans present substantial hurdles for targeted genetic improvement and molecular breeding applications.

2.6.2. Operational and Breeding Efficiency

Traditional and advanced breeding methodologies remain financially intensive and time-consuming, largely due to the crop's inherently long generation time. Inefficient utilization of fertilizers, water, and other agrochemical inputs prevents soybean crops from achieving their maximum genetic yield potential.

2.6.3. Socio-Economic and Market Barriers

The limited availability of certified, high-quality seeds, combined with slow farmer adoption rates of newly re-leased improved varieties, stalls field level progress. Soybean profitability is frequently undermined by localized market vulnerabilities, including price instability, inadequate processing infrastructure, and weak market access for smallholders.

2.6.4. Narrow Genetic Base of Available Germplasm

Most breeding programs rely on a limited number of introduced varieties, which reduces genetic variability and restricts the potential for rising high-yielding and stress tolerant genotypes [32]. This limitation affects the efficiency of selection and genetic gain.

2.6.5. Prevalence of Biotic and Abiotic Stresses

The productivity and expansion of soybeans in Ethiopia are significantly delayed by the existence of biotic and abiotic stressors, which often disrupt yields [10]. Biotic constraints remain a primary driver of loss, with major fungal and bacterial diseases such as Red Leaf Blotch and Bacterial Pustule being widely spread across southwestern Ethiopia. Among these, Soybean Rust is mainly devastating, capable of causing yield losses up to 65% through premature defoliation and reduced green leaf area [29]. Extensive regions in the western and southern highlands suffer from low pH levels below 5.5, which limit phosphorus availability and induce aluminum toxicity, reducing yields by an average of 13.7% [17]. Likewise, erratic rainfall patterns and rising temperatures during critical reproductive stages such as flowering and pod-filling have emerged as threats that hasten pod abortion and impair seed quality [24].

2.6.6. Limited Application of Modern Breeding Technologies

In Ethiopia, it is vital to recognize the significant progress made in integrating biotechnology. In recent years, the Ethiopian agricultural research system has increasingly adopted Marker Assisted Selection (MAS) and molecular tools to modernize soybean improvement and overcome the limitations of traditional phenotypic selection [13].

Research conducted by the Ethiopian Institute of Agricultural Research (EIAR), often in alliance with global partners like IITA, has successfully identified and validated molecular markers for resistance genes. This allows breeders to identify

resistant genotypes at the seedling stage, significantly increasing selection precision and shortening breeding cycles.

2.6.7. Institutional and Systemic Challenge

These include weak seed systems, which limit the availability and distribution of improved varieties to farmers, and poor research-extension linkages, which reduce the flow of information and feedback between researchers and end-users. Moreover, poor funding, limited research facilities, and a lack of policy support continue to constrain breeding efforts. Overall, these challenges collectively slow the progress of soybean breeding in Ethiopia.

2.7. Opportunities for Soybean Improvement

Despite the challenges, the soybean sector in Ethiopia is positioned for significant growth due to several key opportunities that can be leveraged through strategic breeding and policy interventions. Ethiopia, with its diverse agro ecological zones, has the potential to become a significant player in the global soybean market.

2.7.1. Agro-ecological and Genetic Potential

Diverse Agro-ecologies: Ethiopia possesses a wide range of environmental conditions well-suited for soybean cultivation. This ecological diversity offers an exceptional platform for selecting and developing location-specific, climate-smart varieties tailored to different regional climates.

Genetic Diversity and Germplasm Resources: The presence of rich local soybean landraces alongside introduced germplasm provides a robust genetic reservoir. This diversity opens up critical opportunities for discovering and utilizing unique traits, particularly genes linked to stress and climate tolerance.

2.7.2. Technological and Agronomic Advancements

Advances in Genomics and Biotechnology: Access to modern molecular tools such as Genome-Wide Association Studies (GWAS), genomic selection, and gene editing presents a major opportunity to accelerate breeding cycles. These technologies can significantly cut down breeding times while targeting high yields and multi-stress tolerance.

Improved Agronomic Practices: There is substantial room to maximize crop productivity by optimizing field management. Key opportunities include implementing superior crop management, strategic fertilization, rhizobia inoculation, and integrating soybeans into crop rotation systems to improve overall soil health and nitrogen fixation.

2.7.3. Resilience and Collaboration

Climate Change Adaptation: Recognizing the soybean's inherent ability to fix atmospheric nitrogen and with-stand variable environments allows breeders to specifically target drought, heat, and disease tolerance, turning adaptation into a

driver for resilient agricultural systems.

Regional and International Collaboration: Firming ties with global research networks, international breeding centers, and funding bodies provides invaluable access to advanced technology, knowledge sharing, and institutional capacity building.

2.7.4. Domestic and International Demand

There is an increasing demand for soybeans in both the domestic market and international markets [27]. Locally, soybeans are used in food products, livestock feed, and as a source of cooking oil, which is boosting local farmers to increase production.

2.7.5. Government Support and Policies

The Ethiopian government has known the potential of soybean production and has implemented policies to support its growth. These include providing improved seed varieties, offering training for farmers, and facilitating access to credit and market information. One of the main systemic hurdles in Ethiopia is the regulatory framework surrounding seed distribution and the use of modern genetic tools. The exchange and certification of improved varieties are governed by Seed Proclamation No. 782/2013. This proclamation outlines the requirements for variety registration and quality control, which can sometimes slow the transition of high-potential genotypes from research stations to farms. This legislation allows for research into genetically improved crops but maintains severe safety procedures that breeders must follow before any large-scale environmental release.

2.7.6. Potential for Crop Rotation and Soil Improvement

Soybeans are excellent for crop rotation as they help improve soil fertility through nitrogen fixation. Soybeans serve as a vital biological tool for sustainable agricultural transformation in Ethiopia, offering a strategic mechanism for enhancing soil health and system productivity through crop rotation [19].

3. Summary and Conclusion

Soybean has emerged as a miracle crop in Ethiopia due to its high protein (35-45%) and oil (18-22%) content, playing a critical role in enhancing soil fertility through atmospheric nitrogen fixation. Over the last decade, Ethiopian soybean production has seen an important upward trend, increasing nearly threefold to reach 240,000 to 260,000 tons. Yet, this growth has been primarily area-driven rather than productivity-driven, as national yield averages remain below global standards.

Genetic variability studies conducted in major production hubs like Pawe, Jimma, and Hawassa steadily indicate a rich genetic reservoir, with traits such as grain yield, hundred-seed weight, and pods per plant exhibiting high genotypic and phe-

notypic coefficients of variation. The high heritability and genetic advance observed for these traits suggest that they are governed by additive gene action, making phenotypic selection an effective tool for current breeding programs. Despite this potential, the sector is heavily constrained by a narrow genetic base relying on a limited number of imported lines and the lack of a central national genetic database, which fragments research findings across regional institutes.

Earlier studies have steadily identified substantial phenotypic variability among Ethiopian genotypes for key traits such as grain yield, days to maturity, and resistance to biotic stressors like soybean rust. While these morphological descriptions have aided the release of several successful varieties, the current status of research is mainly anchored in conventional breeding practices. This reliance on phenotypic selection has led to several identified challenges, most notably the high Genotype by Environment interactions that destabilize yield across different agro-ecological zones and the slow rate of genetic gain due to long breeding cycles.

The current status of genomic application is in its infancy, yet it presents the most significant opportunity for the future. The transition toward Genomic Selection (GS) and Genome Wide Association Studies (GWAS) offers a pathway to bypass the limitations of traditional field-based screening. By integrating cost effective genotyping with local phenotypic data, there is a transformative chance to develop climate resilient varieties that meet the growing domestic demand while positioning Ethiopia as a regional center for high-quality soybean germplasm.

In conclusion, genetic improvement of soybean is vital to the sustainability of Ethiopia's agricultural change. This review highlights that while existing genetic variability offers a solid basis for selection, the maximum for traditional breeding methods is being reached. The future of soybean production depends on the strategic integration of precision genomics to address complex traits that were difficult to manage via visual selection alone. The importance of future breeding programs lies in their ability to deliver multi-trait genotype lines that offer high yield, shattering resistance, and improved nutrient use efficiency.

Moreover, production is threatened by severe biotic stresses like soybean rust, which can cause up to 65% yield loss, and abiotic stresses such as soil acidity ($\text{pH} < 5.5$) prevalent in the western highlands, which inhibits phosphorus uptake and reduces aluminum tolerance. While traditional breeding methods remain dominant, Ethiopia has begun integrating modern biotechnology, including Marker-Assisted Selection (MAS) and SNP markers, to identify specific loci for disease resistance and drought tolerance. The future of soybean improvement in Ethiopia lies in linking the observation-to-application gap by joining existing variability through molecular characterization, strengthening seed systems, and expanding cultivation into favorable agro-ecological zones to meet rising domestic and global industrial demands.

Abbreviations

AMMI	Additive Main Effects and Multiplicative Interaction
CSA	Central Statistical Agency
EIAR	Ethiopian Institute of Agricultural Research
FAOSTAT	Food and Agriculture Organization Statistics Database
GCV	Genotypic Coefficient of Variation
GEBV	Genomic Estimated Breeding Value
GS	Genomic Selection
GWAS	Genome-Wide Association Study
MAS	Marker-Assisted Selection
QTL	Quantitative Trait Locus
SNP	Single Nucleotide Polymorphism
USDA	United States Department of Agriculture

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Conflicts of Interest

The authors declare no conflicts of interest.

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