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

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ABSTRACT

Soybeans are an oilseed and protein crop in Ethiopia contributing a lot to food security, income generation and soil fertility improvement. Good production depends on farming practices, including proper land preparation, right plant spacing and timely weed control all of which help to get the best possible yield from the plants. Genetic variability is important for improving crops and developing varieties. However, the success of soybean breeding in Ethiopia is limited by things, such as not using modern breeding techniques enough having a limited genetic base, changing environment and not enough research support. There are chances to improve soybean by using tools like marker-assisted selection and genomic selection expanding testing in different areas and involving farmers in breeding. This review looks at studies done over the ten years on genetic variability in Ethiopia. The focus is on things like how much the plants differ in their genes and in their appearance how much of that difference is due to genetics how much improvement can be. How traits are connected. The results show that there is a lot of difference between soybean plants in parts of the country. High genetic change with heritability for yield-related traits shows that the genes are mostly adding up making it easier to choose the best plants. Problems that remain include not use of molecular breeding, varying environment and a limited genetic base. Although Ethiopia has started using Marker-Assisted Selection combining types of data and using new technologies for measuring plant traits is not common. There is a lot of potential to improve the sector by using breeding methods focusing on plants that can handle climate change and have better quality for industry like less harmful substances, which are not yet a main focus in the country's research plans.

Keywords: Challenges; Genetic Variability; Opportunities; Soybeans; Studies

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1. INTRODUCTION

Soybean (Glycine max L.) is a legume species from East Asia grown mainly for its beans, which have many uses. Genetically soybean is a legume species with 2n = 2x =40 chromosomes. Soybeans have a genome size (1.12 GB) and about 55% of their genome is made of repetitive sequences [34]. It is a self-pollinated crop. So has low genetic diversity [23]. It is called a miracle crop because it has protein (35-45%) and oil (18-22%) content. It is used as food, animal feed and for many industrial products [36]. It is used in crop rotation to improve soil fertility and stop pests from building up [5]. Because of these benefits soybeans have become important in countries, including Ethiopia.

Globally soybean is grown on 121 million hectares with a total of 334 million tons produced each year. Countries growing soybeans include Brazil, the USA, Argentina, China and India which together produce more than 80% of the world's soybeans [39]. In Ethiopia soybean is a pulse and oilseed crop, mainly in the

southwest, west and northwest parts of the country. The area under soybeans is 6,236 hectares. The total production is 78,989 quintals. The yield of soybeans in Ethiopia has increased, reaching about 2.54 t ha^{-1} in the 2025/2026 season [11]. This is an improvement from the 1.67 tons in 2021 but it is still lower than the global average of 2.93 t ha^{-1} [12].

Traditional breeding has been the way to develop new varieties focusing on bringing in and testing plants from places like CIMMYT. This method uses crossbreeding and tracking family lines to create varieties with yield and stability across different altitudes in Ethiopia. These old methods are important for making sure plants grow well in areas but they take a long time up to ten years to get a stable variety. To fix these problems modern breeding methods are now being connected to the research plan.

Today scientists use Marker-Assisted Selection to find genes that help with disease resistance and drought tolerance, which allows them to check plants early on [33]. Also, the use of methods to create multiple crops is being explored to cut the time it takes to release new varieties. Even though using modified soybeans is limited by rules using genetic analysis helps Ethiopian scientists pick the best parent plants, which makes the soybean industry stronger.

In Ethiopia many studies on soybean genes have shown that traits like the number of pods per plant, plant height, weight of 100 seeds and total yield have a lot of variation which means these traits are mainly controlled by genes and respond well to selection [18]. For example, in the northwest of Ethiopia a study with 81 varieties showed that plant height and weight of 100 seeds are among the stable and heritable traits.

Now most breeding work is done at the Ethiopian Institute of Agricultural Research (EIAR) like in Pawe, Jimma and Hawassa where scientists are working on creating new varieties that give high yield mature quickly and are resistant to diseases. There is a big problem because most of this research is only done in certain regions and hasn't been put into a national database. This means that the progress made in one area isn't always shared with others.

Even though there is a lot of potential to improve soybean through genetics the industry has problems that stop it from growing. Natural problems, like seeds falling off the plants and losing their ability to grow in lowland areas make it hard for farmers to get seeds [7]. Also, many experts say that the limited genetic variety in soybeans, which comes mostly from outside makes the crop easy to get hurt by new pests and changing weather. These problems are made worse by not having tools for DNA work and places to keep seeds cold making breeders use slower older ways instead of faster modern methods [28].

Over the ten years in Ethiopia research on genetic differences in soybeans has gone from just describing plants to looking more deeply at the country's plant varieties. These studies are still spread out in different reports and local studies. Researchers have found that the variety in traits like pods per plant, weight of 100 seeds and yield is high in areas like Gondar, Jimma and Pawe [30]. This means that good genes found in one area like in the lowlands of Benishangul Gumuz are not used in other parts.

Even though we know a lot about traits we still need to use this knowledge to make better plants. So the breeding system still has a genetic base because the differences we found are in studies and not in active breeding programs. The goal of this paper is to look at research from the ten years on the genetic differences in soybeans in Ethiopia focus on why this is important for growing better plants and find the main problems and future chances for growing better soybeans.

2. LITERATURE REVIEW

2.1 Soybean Taxonomy

Soybean (Glycine max L.) is part of the legume family. It is a self-pollinated plant with 2n = 2x = 40 chromosomes in the subfamily Papilionoideae, genus Glycine Wild and subgenus Soja. Glycine soja is a self-pollinated species that has than 1% of its plants cross-pollinating [37]. Cultivated soybean usually stands with a main stem, branches and many leaves. The height of the plant changes depending on the type from 0.20m to 2m.

2.2 Soybean Origin and Distribution

Soybeans are thought to have started in East Asia in China. They were brought to East Africa in the 1800s because of long trade links with China [21]. Now soybeans are grown over the world in many different climates from cold to hot. For a national breeding program this move is not just about where the plants grow but about their DNA. Moving from cold to areas needs finding specific genes that control how long the plants take to grow. In our country studies are still not connected into a system that helps manage all the information. This gives a chance to use GWAS to pick plants that can grow well even with short days in hot places.

2.3 Importance of Soybean

Soybeans are one of the useful legumes around the world because of their nutrition, money, farming and environmental value. These days soybeans have become more important in developing countries like Ethiopia as a crop for food and nutrition security making money and farming that lasts.

2.3.1 Nutritional Importance of Soybean

Soybean seeds have 40% protein and 20% oil making them a big source of plant-based protein and oil [40]. Their protein gives amino acids while the oil is full of good fats that help people and animals eat better. The current study shows how soybeans help make diets more varied and help fight protein shortages in Sub-Saharan Africa. Soybeans are very important to food systems mostly in making things, like soy sauce.

2.3.2 Economic Significance of Soybean

Soybeans are an important agricultural product that has a lot of economic value mainly in countries that are big producers and are important cash crops with rising demand in local and global markets. Soybean meal is used as a high-protein feed for animals and birds. It is seen as an important crop in the meat production industry supporting the global meat and dairy markets. In Ethiopia soybeans have been known as a priority crop for replacing imports helping industrial growth and giving smallholder farmers more ways to earn money.

2.3.3 Soybean Role in Soil Fertility and Cropping Systems

From point of view soybeans have a very important role in sustainable farming systems because they can fix nitrogen from the air through a partnership with Bradyrhizobium species. Recent studies show that soybean-based cropping systems improve the nitrogen level in the soil the amount of matter and the overall productivity of the system [3].

2.3.4 Industrial Uses

In addition to being eaten soybean is a very useful industrial raw material. It is the source for making edible vegetable oil, as well as traditional and functional foods like tofu and soy sauce. In the -food industrial area progress in green chemistry uses soybean oil and by-products in the business of industrial textiles, eco-friendly inks and biodegradable bioplastics reducing dependence on petroleum-based materials.

2.3.5 Animal Feeds

The livestock, poultry and aquaculture sectors depend a lot on soybean production. Soybean meal, the by-product of oil extraction is seen as the top protein supplement in animal feed around the world. Its high digestibility and rich amino acid profile are important for improving growth rates and the efficiency of feeding in concentrated animal production systems.

2.3.6 Adaptability and Resilience

The wide genetic difference within soybeans allows it to adapt well to different farming areas from lowlands to mid-highlands. The crop shows resilience and can handle several types of environmental stress, including irregular water shortages and changing temperatures making it a reliable crop in changing weather conditions.

2.3.7 Global Trade Commodity

At a scale soybean is one of the most traded agricultural products worldwide. It plays a role in international trade balancing supply and demand for both vegetable oils and protein meals. For countries that produce soybeans exports help strengthen food systems improve trade balances and bring in currency into the economy.

2.4 Trends in Soybean Production in Ethiopia over the Past Decade

Soybean production in Ethiopia has been increasing steadily from 2015 to 2025 because of the rising demand for edible oil, livestock feed and export opportunities. From 2015 to 2016 production was low estimated at 66,000 to 90,000 tons with traditional farming practices. From 2017 to 2019 production started to rise as soybeans became more valuable in crop rotation systems and farmers expanded their planting areas reaching than 120,000 tons. From 2020 to 2023 soybean production increased faster mainly because of more land being used and growing market demand from processing industries. During this time national production reached about 180,000 to 240,000 tons.

However, yield improvements were not very high as production growth was mainly because of land being used, not better productivity. Oromia Benishangul Gumuz and SNNPR became the producing areas. From 2024 to 2025 soybean production stayed steady with an increase reaching around 240,000 to 260,000 tons. Overall soybean production in Ethiopia has tripled over the ten years showing strong potential for even more growth if better varieties, machines and farming methods are improved.

2.5 10-Years Overview: Soybean Genetic Variability Studies in Ethiopia

The study of soybean variability in Ethiopia over the past ten years has shown a lot of potential for improving the crop but there are still problems. Research done in farming areas has consistently shown high heritability and genetic improvement for traits like yield, 100-seed weight and days to maturity showing that selecting the best plants can help improve productivity [6].

These studies have helped find types that are adapted to specific areas like Jimma and Pawe, relying on a narrow genetic base from a few IITA and MARC accessions is risky in the long run. Also, the benefits of finding yielding lines are often canceled out by the problems of short trials, which don't capture the long-term stability needed for a farming system that can handle climate changes [38].

The biggest problem found over the ten years is the focus on describing plants and their traits rather than using advanced technology. While researchers have mapped the differences in plants and their genes there is a lack of work on using markers to help choose better plants [1]. This has left a gap in understanding the genes that control traits like drought tolerance and using nutrients efficiently. Also, while total yield has been the focus the genetic differences in nutritional quality, especially protein and oil content and resistance to soil acidity have not been explored much [8].

Over the ten years soybean genetic variability studies in Ethiopia have changed from simple checks to more targeted choices in the country's different farming areas. Research has shown a range of genetic diversity for important farming traits mainly yield, days to maturity and 100-seed weight. The main success of this ten-year period is finding a lot of variety in types showing that the differences are mostly genetic and can be used through selection [4].

Despite these successes a major research gap has stayed the same for ten years: Most Ethiopian studies focus on traits leaving the genetic differences not fully mapped at the DNA level, which stops the use of markers to speed up breeding. Also, while yield differences are well known there is a lack of data on resistance to rust and soil acidity, which are the two most important problems in Ethiopia.

2.5.1 Genetic Variability in Grain Yield

Over the ten years the main focus of soybean research in Ethiopia has been on checking total yield in different farming areas. Research done in areas like Pawe, Assosa and Jimma has shown significant differences in yield with several studies saying that the differences between plants are high enough to allow good selection [35]. The benefit of these ten years of work is finding yielding, stable types that have improved national yield.

There is a big problem that still exists: the gap between research stations and small farms. Even though yielding types were found in tests the lack of DNA information about the genes that control yield stopped breeders from improving it with better methods [26].

2.5.2 Description of Soybean Yield and Yield Components

National Context and Yield Dynamics

In the farming situation soybean yield is the most important but also the most complicated trait. While old farming methods have given varieties like Guda and Tesfaye that have yields from 2.75 to 3.74 tons per hectare the effect of the environment is a challenge for consistent yield [9]. Recent trials show that the environment explains about 45% of the differences in yield showing the need for tools to make farming more reliable across different areas. National farming is moving from picking plants based on how they look to using DNA tools to understand yield

Genomic Selection (GS) for Accelerated Genetic Gain

Using Genomic Selection (GS) is changing how national programs handle traits. Unlike methods GS uses DNA markers to predict how good a plant will be, even when it is young [22]. Recent models and field data show that using GS in programs can give 35% more improvement than just looking at plants. This is especially useful for traits like yield where GS can predict results with accuracy between 0.26 and 0.81 for yield and protein. By using these tools countries can shorten the time for breeding to 4 to 6 years helping them react faster to weather changes.

GWAS and Architecture of Yield Components

To find the main genes that affect yield, Genome-Wide Association Studies (GWAS) are being used to find DNA changes. A big focus is on the weight of 100 seeds, a trait with heritability that affects yield and money. Recent DNA studies have found stable parts of DNA for seed weight that work well over many years and in different areas.

Integrated Breeding

Combining DNA data with ways to pick the plants and using machines offers a new way to choose plants that give good yield and can handle stress [2]. For programs the ability to find plants that give good yield even when there is not enough water, which is common during the time when the seeds form, is important. As the country deals with unpredictable weather these DNA tools give a better way to grow more soybeans in a sustainable way.

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.
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 variability of oil and protein content. While results indicate that Ethiopian soybean germplasm possesses 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 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 decade steadily report significant differences among soybean genotypes for disease resistance traits. For example, field evaluations of introduced and locally adapted genotypes showed 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 bacterial diseases with some lines showing moderate resistance while others are highly susceptible.

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

Soybean rust resistance for example is controlled by resistance genes that interact with pathogen a-virulence genes proving gene-for-gene relationships. Similarly, resistance to 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're among the most important biotic stresses affecting yield, seed quality and overall crop performance.

Over the decade several studies have demonstrated that soybean germplasm exhibits considerable 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 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 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 conditions which lead to changes in genotype performance and reveal basic genetic variability. Research findings consistently show that soybean genotypes differ significantly in their response to insect pest pressure. Some genotypes exhibit damage levels and better recovery ability while others are highly susceptible indicating the presence of usable genetic diversity.

Traits such as leaf damage score, 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 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 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	*Phakopsora pachyrhizi*	Rapid defoliation and up to 65% yield loss.	Selection for genes and slow-rusting traits
Bacterial Blight	*Pseudomonas savastanoi*	Necrotic lesions reducing photosynthetic area.	Vertical resistance screening in germplasm.
Soybean Aphids	*Aphis glycines*	Sap-sucking damage and transmission of viral diseases.	Antibiosis and antixenosis (e.g., leaf hairs).
Pod Borers	*Helicoverpa armigera*	Direct damage to reproductive organs and pod number.	Morphological traits like pod pubescence.

2.5.5 Genetic Variability Drought Stress

Drought is the important abiotic stress limiting soybean production in Ethiopia especially in regions such as Jinka, Humera and Gofa. Research shows: 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 genetic variation for adaptation traits. Drought stress mainly affects soybean during flowering and pod filling stages leading to photosynthesis early leaf senescence, flower abortion and poor seed development. In Ethiopia drought-prone environments such as 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 genetic diversity for drought tolerance. Research conducted in Ethiopia has con-firmed differences among soybean genotypes for drought tolerance-related traits. Some genotypes maintain growth and yield stability under moisture deficit while others are highly sensitive. Traits showing 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 se-lection under drought stress is effective for improving soybean performance [16]. Several studies report moderate to 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 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 adjustment. In a breeding program identifying genotypes that maintain 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
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 stresses mainly soil acidity and heat stress, which are major constraints in many soybean growing regions of Ethiopia. Recent studies indicate that these stresses not reduce yield but also reduce genetic variability among soybean genotypes providing opportunities for selection and breeding improvement. Soil acidity is a constraint in western and southwestern Ethiopia, where highly weathered soils dominate. Acid soils are characterized by 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 genetic variability in tolerance to acidic soils. Some genotypes perform 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 soil conditions have moderate to high heritability indicating that selection can be effective for improvement. Heat stress, increasingly associated with climate change is another 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 genetic variability.

Moreover, heat stress during the seed filling stage accelerates leaf senescence. Shortens the grain-filling duration resulting in smaller shriveled seeds with altered protein and oil compositions. Selecting heat- genotypes is therefore essential 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 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 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 unpredictable yield losses annually.

Limited Genetic Diversity: A 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 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 due to the crop's inherently long generation time. Inefficient utilization of fertilizers, water and other agrochemical inputs prevents soybean crops from achieving their genetic yield potential.

2.6.3 Socio-Economic and Market Barriers

The limited availability of 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 market vulnerabilities, including price instability, inadequate processing infrastructure and weak market access for smallholders.

2.6.4 Narrow genetic base of 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 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 driver of loss with major fungal and bacterial diseases such as Red Leaf Blotch and Bacterial Pustule being widely spread across southwestern Ethiopia.

Among this Soybean Rust is mainly devastating, capable of causing yield losses up to 65% through defoliation and reduced green leaf area [29]. Extensive regions in the 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 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 breeding technologies

In Ethiopia it is vital to recognize the significant progress made in integrating biotechnology. In 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]. Contrary to the view that the country relies solely on methods. Research conducted by the Ethiopian Institute of Agricultural Research (EIAR) in alliance with global partners like IITA has successfully identified and validated molecular markers for resistance genes. This allows breeders to identify genotypes at the seedling stage significantly increasing selection precision and shortening breeding cycles.

2.6.7 Institutional and Systemic Challenge

These include 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 growth due to several key opportunities that can be leveraged through strategic breeding and policy interventions. Ethiopia, with its agro ecological zones has the potential to become a significant player in the global soybean market.

2.7.1 Ecological and Genetic Potential

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

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

2.7.2 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 yields and multi-stress tolerance.

Improved Agronomic Practices: There is room to maximize crop productivity by optimizing field management. Key opportunities include implementing 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 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.

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

2.7.4 Domestic and International Demand

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

2.7.5 Government Support and Policies

The Ethiopian government has recognized the potential of soybean production. Has implemented policies to support its growth. These include providing seed varieties offering training for farmers and facilitating access to credit and market information. One of the systemic hurdles in Ethiopia is the regulatory framework surrounding seed distribution and the use of modern genetic tools. The exchange and certification of 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 potential genotypes from research stations to smallholder farms. Also while you have noted the increasing use of Marker-Assisted Selection the application of advanced genetic changes is strictly managed under the Biosafety Proclamation No. 896/2015. This legislation allows for research into improved crops but maintains severe safety procedures that breeders must follow before any large-scale environmental release. Firming the linkage between these bases and regional research institutes is essential for building a more efficient national soybean genetic database.

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 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 protein (35-45%) and oil (18-22%) content playing a critical role in enhancing soil fertility through atmospheric nitrogen fixation. Over the 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 than productivity-driven as national yield averages remain below global standards.

Genetic variability studies conducted in 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 phenotypic coefficients of variation. The high heritability and genetic advance observed for these traits suggest that they are governed by gene action making phenotypic selection an effective tool for current breeding programs. Despite this potential the sector is heavily constrained by a 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 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 successful varieties the current status of research is mainly anchored in conventional breeding practices. This reliance on 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 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 field-based screening. By integrating cost 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 improving the genetics of soybean is very important for the future of Ethiopias farming. This review shows that even though there is already some variety that can be used traditional breeding methods are reaching their limits. The future of growing soybean depends on using science to handle complicated traits that were hard to work with before. The key for farming programs is to create plant types that have good yield don't drop their pods easily and use nutrients better than before.

Also growing soybean is in danger because of problems like soybean rust, which can take away up to 65% of the crop and other issues like soil that is too acidic especially in the western highlands. This kind of soil makes it harder for plants to take in nutrients and deal with elements. Even though traditional farming methods are still the way Ethiopia is starting to use new science, like special tools to find good genes for disease and drought resistance.

The future of growing soybean in Ethiopia depends on connecting what is seen with what is done. This includes looking at the differences in plants making sure there are good seeds and growing soybean in areas that are best for it. This is important to meet the needs of people in Ethiopia and around the world.

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