

## Genetic Diversity and Breeding Potential of Global Sorghum Germplasm Resources

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**Abstract** This study delves into the genetic diversity of sorghum (*Sorghum bicolor*) worldwide, with a focus on analyzing its significance in crop improvement and addressing climate change. Sorghum exhibits rich genetic variation in different regions. Studies from countries such as Ethiopia, Niger, and Senegal have shown that local varieties carry unique genes that are of great value for cultivating new sorghum varieties that can adapt to harsh climates. Scientists have utilized tools such as genotyping sequencing (GBS), microsatellite markers, and single nucleotide polymorphisms (SNPs) to identify multiple important gene regions associated with traits such as plant height, flowering time, and drought resistance. Case studies from Africa show that Ethiopian sorghum has a rich gene pool, while West African sorghum exhibits strong adaptability to high temperatures and drought. The research results provide important ideas for sorghum breeding.

**Keywords** Sorghum (*Sorghum bicolor*); Genetic diversity; Climate change; Molecular breeding; Breeding strategies

### 1 Introduction

In some of the most water scarce and barren areas, sorghum (*Sorghum bicolor*) actually shows the strongest resilience. The arid regions of Africa and Asia are where it takes root the deepest. People choose it as their staple food not only because it can be eaten, but also because it is drought tolerant, does not pick land, uses less water, and can survive in environments where many crops are powerless (Tao et al., 2021). In addition to satisfying hunger, sorghum can also be fed to livestock and even used to produce biofuels. For many developing countries, this is not only a food issue, but also a matter of survival bottom line (Maina et al., 2018). Moreover, sometimes people overlook its nutritional value. Sorghum contains beneficial components such as polyphenols, which can also help resist free radical damage and alleviate inflammation in the body (Rhodes et al., 2014; Mawouma et al., 2022).

Its adaptability is not small, from the dry and hot plateaus of Africa to the great plains of Asia and even the Americas, sorghum can be seen almost everywhere. Different environments have led to an increase in species - not only artificially cultivated but also wild ones (Motthaodi et al., 2016). The diversity resulting from the combination of natural and artificial factors has left scientists with a valuable genetic resource pool. It is precisely these differences that give people the opportunity to cultivate new varieties that are more drought resistant, nutritious, and disease resistant in the future. In addition to being used as food, sorghum is also used as a traditional fermented food in Africa. It not only nourishes the body, but also carries a part of culture (Adebo, 2020).

This study is not just an empty concept. We selected sorghum samples from multiple different climate zones, screened key regions related to drought tolerance, nutrition, and disease resistance in their genes one by one, and further explored how these genetic information can be truly applied to breeding work. Our starting point is very practical: we hope to use diversity wisely while protecting it. If food security is to be more stable in the future, crops like sorghum may have to take on more roles, especially in today's increasingly unstable climate.

## 2 Sorghum as a Model Crop for Genetic Diversity Studies

### 2.1 Sorghum's botanical characteristics

Sorghum is a C4 grass that uses sunlight very efficiently. It grows well in dry and semi-dry places. One reason it survives in tough conditions is its strong structure. It has deep roots, thick stems, and wide leaves, which all help it handle drought (Boyles et al., 2018). Sorghum can look quite different depending on the type. Some plants are short, while others grow very tall. Their flower heads also come in different shapes-some are tight and compact, while others are more open and loose (Figure 1) (Morris et al., 2012; Enyew et al., 2021). Scientists have studied these traits a lot. They've found many gene locations, or loci, that affect how tall the plant grows, how its flowers are arranged, and other important features for farming.

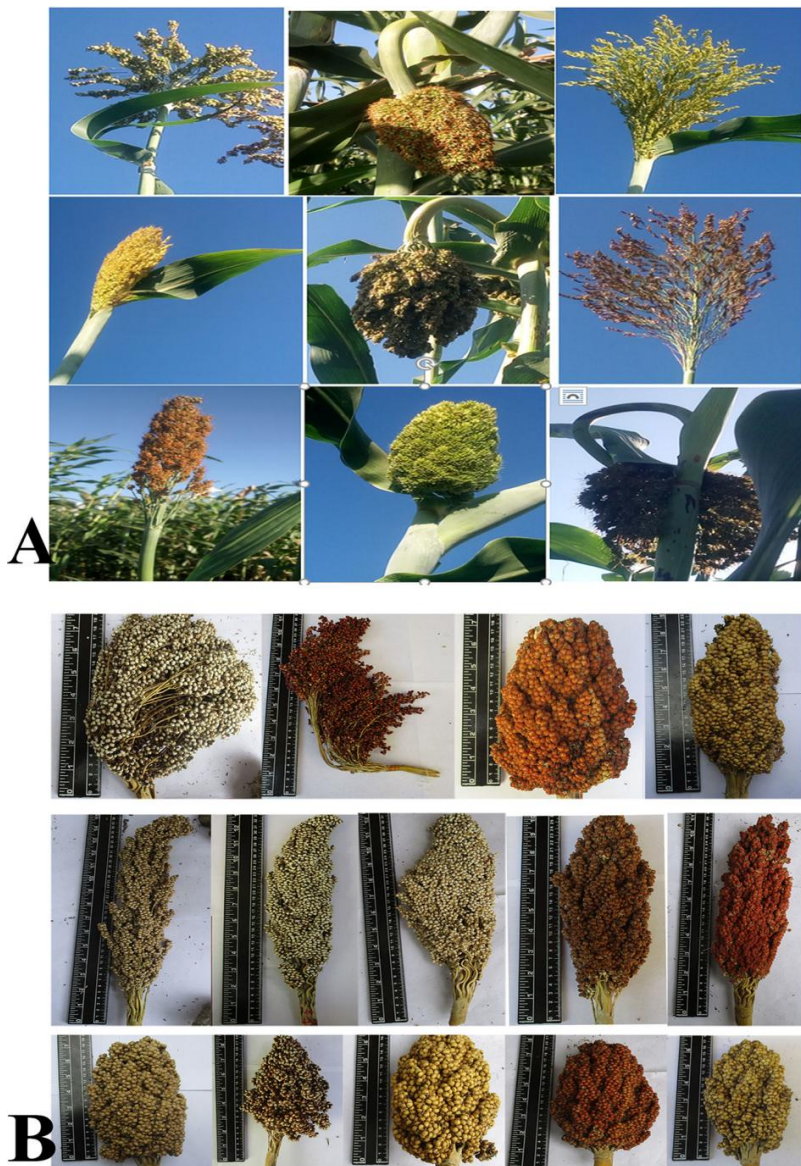


Figure 1 Diverse sorghum panicles (Adopted from Enyew et al., 2021)

Image caption: (A) at early grain filling and (B) at maturity (Adopted from Enyew et al., 2021)

Sorghum can grow a large amount of plant material, or biomass. This makes it useful for both food and fuel. Its grains are rich in starch, protein, and polyphenols, which are good for health (Rhodes et al., 2014). The makeup of the grain, especially the level of polyphenols, can be very different between types. These differences come from genetics. Scientists have used genome-wide association studies (GWAS) to find which parts of the genome affect these traits. Because of its many useful features and high genetic variety, sorghum is often used to study how genes control complex traits.

## 2.2 Sorghum's ecological adaptability and importance

Not all grains can survive in high temperatures, drought, or poor soil, but sorghum is an exception. This adaptability is not just summarized by the "drought tolerance". What truly supports its growth in various extreme environments is the vast genetic diversity behind it. The presence of some key genes enables it to complete its growth cycle even under unfavorable conditions such as water shortage and high heat (Girma et al., 2020).

In order to understand where this ability comes from, scientists have conducted extensive comparisons. They conducted genetic analysis on sorghum samples from different environments and ultimately identified the core genes that are truly related to climate adaptation. These findings make us see more clearly that the survival of sorghum is not accidental, but the result of long-term natural selection and genetic accumulation.

In contrast, many common cereal crops have already withered under similar conditions, while sorghum can still produce ears normally. This stability makes it particularly promising in crop breeding to cope with future climate change - not only can it survive, but it may also live better. It is precisely because of its strong adaptability that sorghum is regarded as a "seed player" in the breeding field to cope with climate pressure.

Sorghum also plays a big role in feeding people. In parts of Africa and Asia, it is a major food source. Even when the weather is bad, it can still produce stable harvests. That's especially important now that climate change is making farming harder. Sorghum is also used to make clean fuel. So it's not just important for food, but also for energy. All of these things show why sorghum matters so much.

## 2.3 Sorghum in farming and food security

In water scarce and barren land, many crops find it difficult to grow, but sorghum can take root and sprout, ensuring a stable harvest. It is not an emerging crop, but a staple crop that has long been relied upon in arid regions. It can not only be eaten, but also fed to livestock, and even used to produce biofuels. It relies not on luck, but on its own strong genetic foundation, which can support continuous improvement in yield, nutrition, and stress resistance (Salih et al., 2016).

These advantages are not obtained out of thin air. Scientists have used techniques such as genome-wide association analysis (GWAS) to identify gene loci associated with high yield and other important traits (Enyew et al., 2022). These achievements provide people with a clearer direction in breeding and offer the possibility of growing high-quality sorghum in harsher environments in the future.

Sorghum is also good for the environment. It can grow in poor soils without extensive irrigation or fertilizer, making it more sustainable than some other crops. Researchers have long collected a variety of sorghum types and established a variety of research tools. These resources help breed better sorghum varieties to meet the growing global demand for food and energy (Cuevas et al., 2016). By continuing to leverage its genetic diversity, sorghum is expected to continue to play an important role in agriculture and food systems.

## 3 Global Collection and Conservation of Sorghum Germplasm

### 3.1 Major seed resource banks and their work

In many parts of the world, sorghum seeds have been systematically collected and preserved. These germplasm resource banks are silently guarding the genetic diversity of sorghum. Their existence may not be noticed in ordinary times, but once it comes to crop improvement, they are the foundation of the foundation.

The largest collection system currently exists, established by the National Plant Germplasm System (USDA NPGS) of the United States Department of Agriculture. Among them, there are over 7 000 samples from Ethiopia alone - which happens to be one of the origins of sorghum. These samples are not "dormant" in the library. Scientists have conducted in-depth research on them and the results show that they contain extremely rich genetic variations, which have high development value in the future, whether for improving yield or enhancing environmental adaptability (Cuevas et al., 2016).

Another major genebank is ICRISAT. It has nearly 38 000 samples, mostly made up of traditional types from dry tropical areas. ICRISAT has also created smaller “core” collections to make it easier for researchers to use these seeds in breeding programs (Upadhyaya et al., 2014).

In South Africa, the national seed bank has saved 312 traditional sorghum types collected from 1996 to 2008. These seeds help us learn how sorghum has changed in different places. In Nigeria and Mali, scientists used DNA markers to look at how different their sorghum seeds are. These findings can help improve crops in the future (Afolayan et al., 2019).

### 3.2 Strategies for germplasm conservation

There are generally two paths to protect the genetic diversity of sorghum. One way is to collect seeds and store them in a seed bank (this is called 'remote protection'); Another approach is to allow them to continue growing naturally in the fields (i.e. 'in situ conservation'). At present, the former method is used more frequently. Germplasm banks such as the National Plant Germplasm System (NPGS) in the United States and the International Crop Research Institute for Arid Tropics (ICRISAT) not only store seeds, but also analyze them using modern DNA technology to ensure good sample condition (Allan et al., 2020). In addition, in order to improve utilization efficiency, they also established a "core germplasm bank" and a "mini core germplasm bank" - these are sample sets that are small in number but can represent a wide range of traits and can play a significant role in breeding work (Upadhyaya et al., 2009).

Protecting sorghum genetic resources is not just about storing seeds in warehouses. In fact, there are still many places, especially in countries like Ethiopia with complex terrain and variable climate, where farmers are still planting traditional sorghum varieties in their fields. These seemingly ordinary planting behaviors are actually a means of protection in themselves.

The differences in natural environments in different regions are already "screening" and "preserving" genes. For example, in eastern Ethiopia, there are some sorghum types with special genes that cannot be found elsewhere. This local genetic characteristic precisely illustrates the importance of in situ conservation - it can continue unique genetic resources that may be overlooked in the laboratory in the real environment (Enyew et al., 2022).

Of course, either way, modern tools can come in handy. Scientists now use molecular markers and other methods to not only identify specific genes, but also track population trends. This type of technology can assist in in-situ conservation and optimize the research and practice path for off-site preservation (Girma et al., 2019; Girma et al., 2020).

### 3.3 Problems in saving sorghum germplasm

Even with all these efforts, there are still problems. One big issue is that some seed collections have too many samples that are genetically the same. This wastes time and money. For example, researchers found many similar samples in the U.S. sorghum collection and said they could cut down the number without losing genetic variety.

Another issue is keeping the seeds genetically “pure” during regrowth. Sometimes, cross-pollination or outside factors can change the genetic makeup. This is a bigger concern for traditional types stored in genebanks, where differences between and within types can vary a lot (Allan et al., 2020).

The issue of funding is also a major challenge currently faced. The preservation and research of seed resources are ultimately not a one-time deal, they require sustained and stable investment of funds. However, the reality is that budgets are often stretched thin. While funding is tight, agricultural technology updates and climate change are quietly changing the planting pattern of sorghum-where and how to plant it are all changing, which undoubtedly makes the protection of genetic diversity even more difficult.

## 4 Geographic distribution pattern and genetic variation of sorghum germplasm

### 4.1 Overview of genetic diversity across continents

The staple food of millions of people does not necessarily mean that its genetic background is singular. The genetic diversity of sorghum varies significantly between different continents. These differences do not only exist in modern times, but have gradually formed since the initial domestication stage, after long-term adaptation to different climatic conditions.

In Africa, the birthplace of sorghum, this diversity is most prominent. For example, Ethiopia has diverse ecological types, and various types of sorghum have evolved here, forming significant regional differences (Enyew et al., 2022). In Niger, research has also found that sorghum in the west of the country has more abundant genetic variations than in the east. Not only that, there are multiple sorghum "races" coexisting on the African continent, such as the Guinea type, Caudium type, and Durra type, and the hybridization and interweaving between these types also make the genetic lineage more complex.

The situation in Asia is different. During the process of sorghum being introduced from Africa to Asia, although it carried some primitive genes, over time and with the intervention of human selection, some gene diversity decreased, while others evolved into new alleles under new ecological pressures (Figueiredo et al., 2008). This also indicates that migration itself is a form of genetic remodeling (Tao et al., 2021).

### 4.2 Influence of domestication on genetic diversity

When humans began to grow sorghum, its genetic composition changed. This process exists in the domestication of most crops and is often accompanied by a decrease in genetic diversity. Studies have found that cultivated sorghum has fewer DNA variants than wild types. For example, DNA polymorphism decreased by about 30% and gene activity levels decreased by about 18%. These data suggest that sorghum experienced a "genetic bottleneck" effect when it was domesticated into a cultivated crop (Casa et al., 2005).

Still, traditional types-called landraces-kept about 86% of the diversity seen in wild sorghum. So not everything was lost. Although sorghum lost some of its genetic diversity during domestication, agricultural cultivation has also led to the selection of some useful traits. Traits such as plant shape, seed size, seed dormancy, and the ease with which seeds fall off have been gradually optimized to meet the needs of agricultural production. The domestication process also changed the expression pattern of genes, causing some genes to be activated or silenced. Today, cultivated sorghum and wild sorghum show significant differences in gene expression levels (Burgarella et al., 2021).

### 4.3 Genetic drift and gene flow in sorghum populations

Sorghum's genetic makeup is also shaped by drift and gene flow. Gene flow happens when wild and farmed sorghum grow near each other and cross. This happens a lot in places like sub-Saharan Africa. Wild, weedy, and farmed sorghum there often mix genes. In West Africa, for example, wild and weedy types often have genes from farmed sorghum. This creates a mixed genetic picture (Sagnard et al., 2011).

Genetic drift is different. It's a random change in genes, more common in small groups. Drift can make some genes disappear over time. In places like Ethiopia and Niger, drift-along with limited seed sharing between farmers—helps explain the differences between local sorghum types (Deu et al., 2008). Knowing how both drift and gene flow work is important. It helps us protect and use sorghum's genetic resources better.

## 5 Case Study: Genetic Diversity of African Sorghum

### 5.1 Background and importance of African sorghum

Sorghum (*Sorghum bicolor* L. Moench) is a major grain in Africa. It feeds millions of people in dry areas. It is especially important in West, East, and Southern Africa, where it grows well in many different climates and farming systems. Its genetic variety makes it a great resource for breeding. In West Africa, different local cultures and environments have helped create many types of sorghum (Faye et al., 2021). In Southern Africa, scientists also found big differences between samples. These can help create better plants in the future (Motilhaodi et al., 2016).

In Africa, sorghum is not only a crop that can satisfy hunger, but it is also deeply embedded in the local way of life and traditional agriculture. For example, in Ethiopia, a land believed to be the origin of sorghum, various types of sorghum emerge one after another - this is actually the result of evolution and the imprint of sorghum's long-term adaptation to different ecological environments (Enyew et al., 2022). It may seem like a local characteristic, but behind it lies important genetic information.

This local diversity is not only related to Africa's own food security, but also has practical significance for the whole world. Many useful traits, such as heat tolerance, drought tolerance, or flexible growth period, are hidden in these local varieties. Reasonably utilizing them may help us develop new sorghum varieties that are adaptable to climate change. Ultimately, the protection and development of African sorghum resources are no longer just regional affairs, but strategic issues related to the future direction of global agriculture (Tao et al., 2021).

## 5.2 Research methods and main findings

In order to uncover the secrets behind the genetic diversity of African sorghum, scientists have used many "hard tools". Technologies such as GBS (genotyping sequencing), microsatellite markers, and single nucleotide polymorphisms (SNPs) are currently the mainstream methods.

Taking West Africa as an example, the WASAP project collected 756 sorghum samples from multiple countries. Researchers have screened multiple genes related to key traits such as flowering time and plant height using GBS technology (Figure 2) (Faye et al., 2021). These achievements not only provide us with a clearer understanding of African sorghum, but also offer a practical genetic basis for precision breeding in the future.

In Southern Africa, scientists studied 22 sorghum types. They used both DNA tools and physical trait measurements. The study found big differences between the samples. This means those types could be helpful in breeding stronger and better sorghum (Motlhaodi et al., 2016).

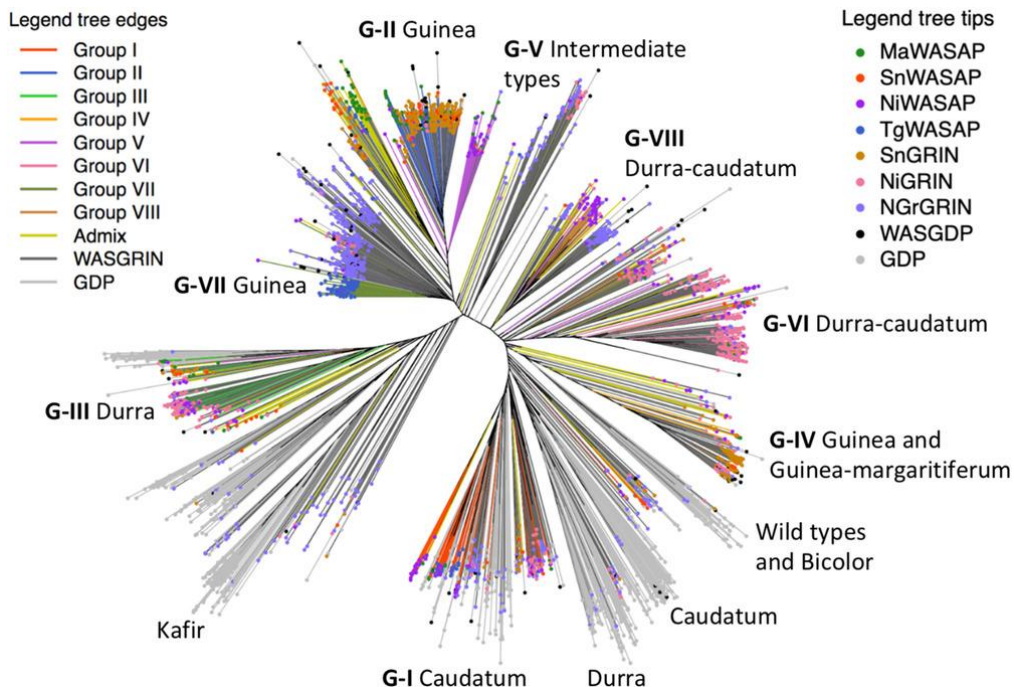


Figure 2 Neighbor-joining analysis of the West African sorghum association panel (WASAP) (Adopted from Faye et al., 2021)  
 Image caption: Clustering of the WASAP accessions (MaWASAP, Mali; NiWASAP, Niger; SnWASAP, Senegal, and TgWASAP, Togo) in relationship with other West African sorghums in GRIN (SnGRIN, Senegal, Gambia, and Mauritania; NiGRIN, Niger; NGrGRIN, Nigeria) and global sorghum diversity panel (GDP). The color coding of the tree edges is based on the ADMIXTURE ancestral populations (G-I to G-VIII, including admixed accessions) of the WASAP. The edges in yellow, dark gray, and light gray represent admixed WASAP accessions (<0.6 ancestry fraction), West African sorghum in USDA-GRIN (WASGRIN) accessions, and GDP accessions, respectively. The color coding of the tree tips indicate accessions origin, with black tips indicating West African sorghum accessions in the GDP (WASGDP) (Adopted from Faye et al., 2021)

In East and Central Africa, researchers have studied genetic differences in sorghum by analyzing its DNA. They used tools such as microsatellite markers to analyze sorghum samples from Sudan, Kenya, and Ethiopia. These studies found that sorghum in the region has a high degree of genetic diversity. Different regions and different sorghum races show unique genetic patterns (Salih et al., 2016).

In Ethiopia, scientists used SNP markers to study 359 samples. The results showed a clear genetic population structure and high heterozygosity was observed in some samples. This rich diversity is of great value for breeding work (Enyew et al., 2022). These results show that African sorghum contains rich genetic resources and has great potential for crop improvement.

### **5.3 Lessons from other regions**

Many important insights from the study of African sorghum are worth referencing for other regions. For example, the value of local germplasm and traditional varieties is often underestimated. In fact, it is these "old varieties" that often hide key genes that can resist adverse environments such as drought and high temperatures. Instead of chasing after repairs afterwards, it's better to protect these local resources first. The diversity of African sorghum illustrates one thing: local resources that will be available in the future.

Another point worth noting is the efficient application of modern genetic tools. Whether it's GBS or SNP markers, these technologies can help researchers find genetic signals related to important traits faster and more accurately. In the study of African sorghum, such tools have proven their practical value; And their applicability can also be fully extended to other crops and regions.

## **6 Utilizing the Genetic Diversity of Sorghum for Breeding Work**

### **6.1 Screening for suitable and excellent traits**

If you want to cultivate sorghum varieties with better performance and stronger adaptability, the first step is to identify valuable traits from their genes. Existing research has shown that there are significant differences in agricultural traits among different types of sorghum - this is actually a resource, not a problem.

Taking Ethiopia as an example, researchers have found that sorghum there exhibits significant differentiation in plant height, flowering time, and grain yield (Birhanu et al., 2020; Enyew et al., 2022). These differences are not just data, but also suggest that we can selectively select breeding materials suitable for different ecological environments, thereby improving the adaptability and stability of new varieties.

### **6.2 Combination of hybrid breeding and molecular-assisted tools**

Hybridization is a common method in breeding. Hybridization of different types of sorghum can introduce new genes. In one study, researchers used wild-type sorghum to construct a BC1F1 backcross population, screened out individuals with outstanding performance of important traits such as drought resistance, and introduced new genes into the breeding line (Jordan et al., 2011). This method not only increases genetic diversity, but also improves the performance of key traits such as yield.

In recent years, new technologies such as molecular-assisted selection (MAS) and genomic selection (GS) have further accelerated the breeding process. Through DNA markers such as SNPs and SSRs, breeders can directly identify genes associated with target traits. For example, using GBS technology, researchers have discovered multiple SNP loci associated with plant height and flowering time (Faye et al., 2021). These tools enable breeders to select suitable parents at an early stage, significantly improving the efficiency and success rate of sorghum breeding, especially in responding to climate stress.

### **6.3 Real success stories in sorghum breeding**

Some breeding projects have already used genetic diversity and modern tools with great success. In Ethiopia, scientists found sorghum types that produced more grain and had traits that farmers like, such as medium plant height. These types were used to make new varieties that grow better and yield more in different conditions.

In West Africa, the WASAP project gathered many local sorghum types and studied them using genotyping-by-sequencing (GBS). The results showed a high level of genetic diversity. Researchers also found key gene regions linked to traits like flowering time and plant height (Faye et al., 2021). These findings helped breeders create new sorghum varieties that grow well in West Africa's climate. Thanks to this work, farming in the region has become more stable, helping more people get enough food (Enyew et al., 2021).

## **7 Impact of Climate Change on Sorghum Genetic Diversity**

### **7.1 Climate-driven selection pressures on germplasm**

Climate change is putting more stress on sorghum. To survive, the plants need to cope with new problems like heat, drought, and pests. Sorghum's genetic diversity plays a key role in helping it adapt. For example, one study on Ethiopian sorghum showed that it contains many rare gene types. These genes help the plant grow in different climates (Girma et al., 2020). In Senegal, researchers found that local sorghum had special gene changes that help it survive in very hot and dry areas. These cases show how climate changes can shape the way sorghum evolves. They also highlight why genetic diversity is so important for future adaptation.

But not all regions have enough genetic variety. In the U.S., sorghum breeding uses a smaller range of genetic types. This makes it harder to develop new varieties that can deal with rising temperatures. To fix this, breeding programs need to include sorghum types from more places to bring in new traits and improve the crop's ability to handle climate change.

### **7.2 Identification of climate-resilient sorghum varieties**

To find sorghum types that can handle climate stress, scientists study sorghum collections from around the world. Some traditional types (landraces) have special gene versions, called alleles, that help them survive in tough conditions. In one study, researchers created a group of sorghum plants using wild and exotic types. These new plants had unique alleles that could be useful in breeding (Mace et al., 2020). In Ethiopia, genome studies also found genes that help sorghum survive problems like drought and cold (Menamo et al., 2020).

GWAS (genome-wide association studies) are helpful too. They have found gene regions linked to important traits like plant height and flower shape. These traits help sorghum adapt to different environments (Morris et al., 2012). In Senegal, SNP markers for drought resistance were found in the same parts of the genome as other known helpful genes. This shows that some parts of the sorghum genome are key to surviving in hot, dry climates (Faye et al., 2019).

### **7.3 Strategies for future adaptation**

To make sorghum ready for the future, we need to use more diverse types in breeding. This helps bring in new genes from wild or less-used sorghum and increases the plant's ability to cope with stress (Tack et al., 2017). We also need better tools to improve sorghum. New methods in genomics and phenomics can help link genes to traits in different environments. These tools make it easier and faster for breeders to find useful genes (Boyles et al., 2018). It's also important to study how sorghum reacts to the environment and how traits are connected. This helps breeders pick types that grow well in many different places (Enyew et al., 2021).

## **8 Challenges and Future Directions in Sorghum Genetic Diversity Studies**

### **8.1 Gaps in existing research and data**

Although significant progress has been made in sorghum research, some core issues remain unresolved. One of the biggest uncertainties actually comes from our insufficient understanding of gene function. Although a large amount of DNA data has been accumulated, it is still not easy to accurately match this information with specific traits, such as drought resistance.

In addition, the limitations of germplasm resources also pose practical challenges in certain regions. In countries like Nigeria and Mali, the genetic basis of sorghum is relatively narrow, which directly limits the space for exploring the potential of new varieties. Even in Ethiopia, which has abundant germplasm resources, it is still far from reaching the level of "understanding thoroughly". Many potential local resources have yet to be

systematically and thoroughly studied and utilized (Enyew et al., 2022). So, although resources are available, more focused and meticulous work is needed to continuously promote their transformation into breeding achievements.

Another issue is that breeders don't use unadapted sorghum types often. Even though new methods exist to add these types to breeding programs, the resulting plants often grow poorly. So, better ways are needed to use unadapted types without losing performance.

## 8.2 Technology and practical problems

Technology also limits progress. Tools like high-throughput phenotyping and advanced genetic methods are promising but not widely used yet in sorghum research (Boyles et al., 2018). These methods are still costly and need trained people.

Saving and testing sorghum seeds is also a big job. For example, the USDA's Ethiopian collection is one of the biggest in the world. But managing such a large group of seeds takes a lot of time, money, and technical effort (Cuevas et al., 2016). Genome-wide studies on these collections are useful but hard to do due to the huge amount of data involved.

## 8.3 Future research priorities

To move forward, researchers should develop faster and cheaper tools to study sorghum. New technologies can help show how genes affect traits more clearly. Future studies should also bring together genetic, trait, and environmental data to find key adaptive genes (Girma et al., 2020).

It's also important to improve breeding strategies. Better methods are needed to keep useful traits from unadapted sorghum while still making sure new varieties grow well. Adding sorghum types from less-studied regions can bring in new useful alleles for breeding (Afolayan et al., 2019).

Finally, countries and labs should work together and share data. By teaming up, they can handle big challenges like saving seeds and studying large data sets. This will help use sorghum's full genetic potential in future crop development.

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The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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