Field Crop 2025, Vol.8, No.1, 1-10
http://cropscipublisher.com/index.php/fc

Feature Review Open Access

Innovation and Application of Hybrid Breeding Techniques in Sorghum

Shiying Yu
Biotechnology Research Center, Cuixi Academy of Biotechnology, Zhuji, 311800, China
Corresponding email: shiying.yu@cuixi.org

Field Crop, 2025, Vol.8, No.1 doi: 10.5376/fc.2025.08.0001
Received: 01 Nov., 2024
Accepted: 10 Dec., 2024
Published: 01 Jan., 2025

Preferred citation for this article:
Yu S.Y., 2025, Innovation and application of hybrid breeding techniques in sorghum, Field Crop, 8(1): 1-10 (doi: 10.5376/fc.2025.08.0001)

Abstract Sorghum is an important staple crop, especially in arid and semi-arid regions, where its adaptability to harsh conditions makes it critical for food security and bioenergy. Hybrid breeding has emerged as a key strategy to improve sorghum production performance, overcoming the limitations of traditional breeding techniques. In this study, we explored the integration of molecular markers, genomic selection, and genetic engineering in sorghum hybrid development. A case study was conducted in a region where advanced hybrid breeding methods were used to achieve significant improvements in yield, drought tolerance, and insect resistance. This review highlights the advantages of hybrid breeding, such as enhanced genetic diversity and nutritional quality, while acknowledging the remaining technical, economic, and sustainability challenges. Looking ahead, this study highlights the potential of emerging technologies, including precision breeding and artificial intelligence, to further advance sorghum hybrids. Continued investment and research are recommended to optimize the long-term sustainability and agricultural impact of hybrid breeding.

Keywords Sorghum; Hybrid breeding; Molecular markers; Genetic engineering; Crop improvement

1 Introduction

When you think of sorghum (*Sorghum bicolor* L.), you might first think of the bright red ears of corn in rural areas of the north. In fact, this crop is the real star in arid regions such as sub-Saharan Africa and South Asia (Prasad et al., 2021; Ruperao et al., 2021). Although it looks inconspicuous, sorghum can grow particularly well in places where even corn cannot survive-this is thanks to its natural drought resistance. But then again, people now grow sorghum not just to fill their stomachs (Adebo, 2020), although it is indeed a staple food for millions of people. In recent years, more and more sorghum has been processed into feed and biofuel (Tao et al., 2021), especially today when climate change is becoming more and more obvious, the value of this crop has become more prominent.

When it comes to sorghum breeding, hybridization technology has helped a lot now (Guo, 2024). But what's interesting is that although traditional breeding methods have been used for many years, it is these hybrid varieties that have really greatly improved yield and resistance (Perazzo et al., 2017; Kumar et al., 2022). Look at those new varieties that are drought-tolerant and insect-resistant. In fact, they are all good traits "scoured" from the huge gene pool of sorghum (Yahaya et al., 2023). Of course, luck alone is not enough. Now with the help of genomic technology, breeding efficiency is much higher. Especially today when climate change is becoming more and more troublesome, these new varieties not only have higher yields, but are also more stable to grow. In the final analysis, hybrid breeding has become an indispensable means of improving sorghum, and it is still improving.

This time, we mainly want to find out what breakthroughs sorghum hybrid breeding can bring. To be honest, it is becoming more and more difficult to farm now-either drought or flood, and there are more and more pests and diseases. So we focused on two directions: one is to see how rich the genes of sorghum itself are (after all, the more diverse the genes, the greater the breeding potential), and the other is to actually test whether these hybrid varieties can withstand the harsh environment and whether the yield can be increased. In terms of methods, we have looked through a lot of the latest research materials and sorted out all the tricks of hybrid breeding-from how to choose parents to how to combine good genes together.

Of course, it is not enough to just look at the theory, we also have to see how these hybrid sorghums actually perform in the field, such as whether they can stabilize the yield in drought areas, or whether they can survive in

saline-alkali land. Finally, I want to say that this research is not only to summarize the existing results, but also to point the way for future breeding work. After all, climate change is there, we have to prepare more resistant and higher-yielding varieties in advance.

2 Traditional Breeding Techniques in Sorghum

2.1 Conventional breeding methods

Sorghum is quite interesting. Although it is mainly self-pollinated (usually 85%-95%), it occasionally "crosses over"-the cross-pollination rate is about 5% to 15% (Rakshit and Bellundagi, 2019; Tu et al., 2023). When it comes to breeding goals, everyone is most concerned about increasing the yield and maintaining stability, but now more and more people are also thinking about how to make sorghum more resistant to diseases and pests. Interestingly, abiotic stresses such as drought and salinity have become a research hotspot in recent years. Of course, breeders are also thinking about reducing anti-nutritional factors and improving protein quality-although this is quite difficult. The choice of method actually depends on the purpose. If you want to make conventional varieties, you can use the old method of self-pollination. But if you want to cultivate hybrids, you have to see if there is a suitable male sterile source at hand. After all, hybrid vigor is not something that can be achieved casually.

2.2 Limitations of traditional breeding approaches

Traditional breeding has indeed helped us solve many problems, but to be honest, it is not a panacea. One of the biggest troubles is that with each generation of selection, the gene pool of good varieties has become narrower and narrower (Jordan et al., 2011). Some people have suggested that we find some wild or unimproved germplasm to enrich genetic diversity? But the problem is that the offspring of these "outsiders" and cultivated varieties often perform poorly. Besides, traditional breeding is already very tiring. It takes seven or eight generations to stabilize a trait (Figure 1). Especially for complex traits like yield, there are too many influencing factors-genes and environment are both messing around (Sukumaran et al., 2016), and sometimes breeders are really powerless.

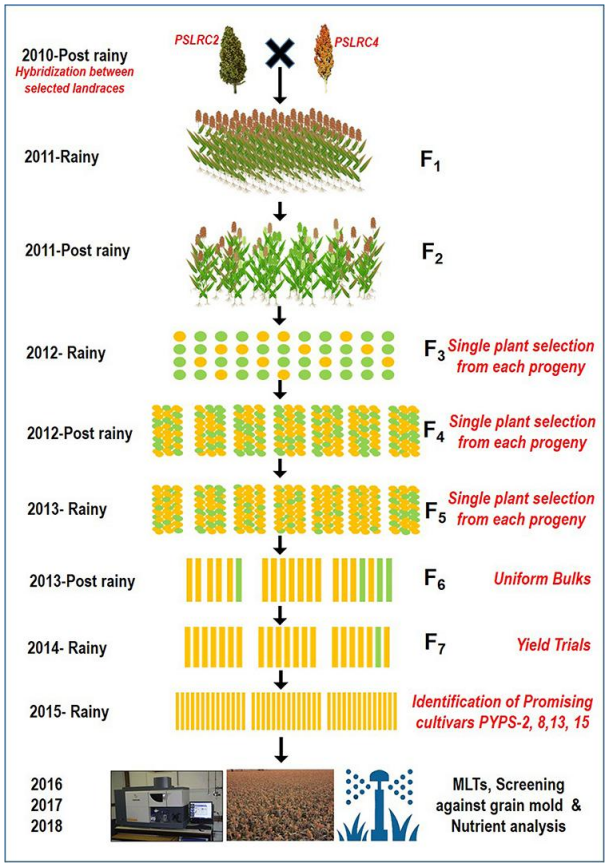

Figure 1 A flow diagram showing the development of sorghum varieties utilizing landraces through a pedigree selection (2010-2015) followed by multi-environment trials (2016-2018) (Adopted from Kumar et al., 2021)

2.3 Historical impact on sorghum yield and quality

When it comes to increasing sorghum yields, we really have to give credit to traditional breeding. Especially after the advent of hybrid sorghum in the 1950s, the changes were particularly obvious-in those dry lands that depend on the weather for food, the yield has been rising (Assefa and Staggenborg, 2010). Interestingly, the average annual yield has increased by 50 kilograms in 52 years, and hybrid technology and nitrogen fertilizer application have contributed to this. However, the yield in irrigated areas has not changed much, and it seems that breeding is still a matter of "looking at the food and eating it". The Guinea hybrids recently developed in West Africa are quite interesting. They perform particularly well on barren land and can yield 20% to 80% more than local varieties (Kante et al., 2019). This is good news for local small farmers. After all, food security is more important than anything else (Rattunde et al., 2013).

3 Innovation in Hybrid Breeding Techniques

3.1 Molecular markers and genomic selection

Sorghum breeding is very different now, thanks to new technologies such as molecular markers and genomic selection. It used to take many years to breed a new variety, but now with marker-assisted selection (MAS), the time can be shortened (Baloch et al., 2023). As you can see from Figure 2, these genetic markers are like GPS for breeding, making the whole process much more accurate. In particular, genomic selection is a great trick-you don't have to wait for the crop to grow up, just looking at its DNA can predict whether it will grow well in the future (Wang and Zhang, 2024). For example, some people use this method to predict the biomass of sorghum, and the results are quite accurate, so that they can decide which seedlings are worth focusing on earlier (Oliveira et al., 2018). What's more amazing is that now even the performance of hybrid offspring can be predicted in advance, which makes breeding hybrids much easier (Maulana et al., 2023). But then again, these high-tech technologies are not omnipotent, and the key lies in how to use them well.

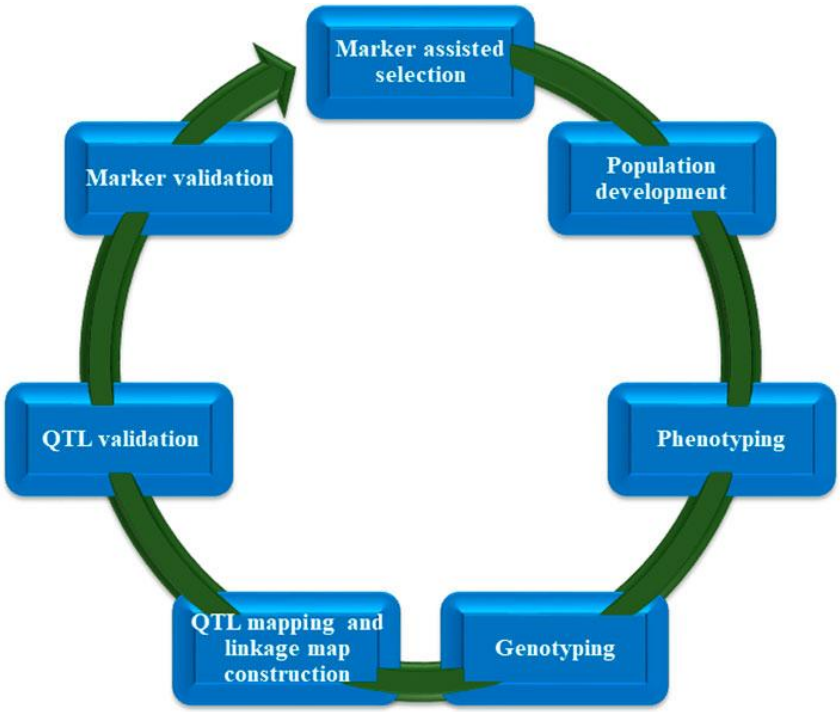

Figure 2 Important stages of marker-assisted selection (MAS) (Adopted from Baloch et al., 2023)

3.2 Genetic engineering for trait improvement

The application of genetic engineering in sorghum breeding is actually quite interesting. Although it started a little slower than other crops, there have been many breakthroughs in recent years. For example, scientists can now directly "tamper" with the genome of sorghum, and it is not a problem to enhance stress resistance or increase yield. However, the most practical progress is in gene positioning. Through QTL analysis (Ordonio et al., 2016), researchers have locked the location of many key genes, such as those that control yield, determine flowering time,

and the particularly practical "stay green" trait (Sukumaran et al., 2016). These discoveries are like drawing a treasure map for breeding work. Although only a few treasures may be dug up now, it at least proves that this path is feasible. Of course, it may take a few more years to really use these discoveries in the fields.

3.3 Role of biotechnology in hybrid development

Biotechnology has been a great help in sorghum hybrid breeding. In the past, breeders mainly relied on experience, but now with tools such as molecular markers, it is like suddenly having a pair of perspective glasses-you can directly see the doorway in the crop genes. For example, by analyzing the compatibility of hybrids, we can not only breed higher-yielding varieties, but also increase the content of trace elements such as iron and zinc in the grains (Gaddameedi et al., 2020). Interestingly, some people have recently combined genomic data with environmental factors for analysis, which makes it more accurate to predict the performance of hybrids, especially suitable for tailoring varieties for different regions (Fonseca et al., 2021). But to be honest, the most practical aspect of these technologies is that they can quickly breed varieties that are both high-yielding and disaster-resistant. After all, climate change is so severe now, and farmers can't wait for the slow work of traditional breeding.

4 Case Study: Hybrid Breeding in Practice

4.1 Background of the selected region or program

The research team of Embrapa Milho e Sorgo in Brazil has recently been working on a very interesting project-breeding hybrid sorghum for silage in semi-arid areas. You know, in those areas of Brazil where there is a perennial water shortage and high temperatures, cattle farmers are very worried, and ordinary crops can't stand it at all (Perazzo et al., 2017). The smartest thing about their project is that they don't just pursue high yields, but first figure out what local herders really need. For example, in some places where the annual rainfall is less than 800 mm, ordinary sorghum has already wilted, but these hybrids they selected can survive well. More importantly, the silage yield of these new varieties is really good and can fully meet the needs of local animal husbandry. To be honest, this breeding idea that adapts to local conditions is much more practical than those who only pursue data in the laboratory.

4.2 Techniques implemented and results

Their experiment was well designed, using a randomized block method to test the performance of different sorghum hybrids. A total of 24 treatment groups were set up, each with three replicates-focusing on two key indicators: fresh weight yield and dry weight yield. The results were particularly interesting, with quite a large difference between the different hybrids (fresh weight yield ranged from 22 tons to 44 tons, and dry weight yield fluctuated between 9.5 tons and 14.5 tons). The researchers lined up the hybrids according to their yield and found that the best performing groups were very good in both fresh weight and dry weight. What's even more surprising is that these top students also have a very good regeneration ability, which is very important in semi-arid areas-after all, whether the forage can continue to grow is directly related to the livelihood of farmers. To be honest, it is not easy to achieve such a yield in such a harsh environment.

I recently saw a very interesting study, in which they used genomic prediction to "open a plug-in" for sorghum breeding. The research team found 102 publicly available sorghum inbred lines as parents and came up with 204 hybrid combinations (Maulana et al., 2023). The best thing is their prediction model-not only taking into account the conventional additive effect, but also taking into account the dominant effect, so that the predicted results are obviously more reliable. Although the prediction accuracy of different traits varies, overall, this method can indeed save a lot of effort in breeding. Think about it, in the past, you had to wait until the hybrids grew up to know whether they were good or not, but now you can predict in advance through genetic data, which will save you a lot of detours. But then again, this high-tech method is currently mainly auxiliary. If you really want to breed good varieties, you still have to combine field trials.

4.3 Lessons learned and broader implications

Indeed, the Brazilian case has taught us a vivid lesson. The most worthy lesson from their hybrid breeding project is the idea of "tailoring to the needs"-not to do a large-scale and comprehensive project, but to design it

specifically for the special needs of semi-arid areas (Perazzo et al., 2017). You see, the randomized block design they adopted is not a new method, but it is practical and reliable. Focusing on monitoring the two hard indicators of fresh matter yield and dry matter yield, a lot of good seedlings were screened out, and the fresh weight yield of some hybrids can even double. This shows that the key to breeding is to find the right direction. Just like this project, it is obvious that it is to solve the practical difficulties of local herders, so the varieties cultivated are particularly suitable. But then again, this kind of regional breeding project may not work well in other places, after all, the environmental conditions in each region are different. But at least it proves one thing: as long as the problem is studied thoroughly, breeding work can be targeted.

The most eye-catching thing about this Brazilian project is that they are very good at using genomic prediction technology. Think about it, traditional breeding is like buying a lottery ticket. You have to wait until the crops grow to know whether you have won the prize. Now, it is good that you can predict the performance of hybrids by directly scanning the genes (Kent et al., 2023). Their method is wonderful in three aspects: first, it saves time, and you don't have to wait for the crops to mature; second, it is very accurate, and even the environmental differences of different plots can be taken into account; third, it is the most practical-the herders finally don't have to rely on the weather every year for their food. But to be honest, this set of technology has a high threshold. It requires both experts who understand molecular breeding and are familiar with local planting conditions. But the effect is really nothing to say. I heard that the prediction accuracy can now reach 70% to 80%, which is a qualitative leap for breeding work.

When it comes to breeding, it is not enough to rely on old methods or new technologies alone. Think about it, farmers have been growing crops in the fields for so many years. Although those traditional methods look "rustic", they are indeed effective, right? However, times have changed. It is not enough to just rely on your eyes and measure with a ruler (Kent et al., 2023). A breeding expert I know said that they put the data observed in the field and the results of genetic testing together for analysis, and the varieties selected are different-they can withstand drought and have a very stable yield. Of course, the situation in different places is different. Some places are short of water, and some places have many pests and diseases. They have to be adjusted according to actual needs. But in any case, this "combination of traditional and foreign" approach is indeed reliable. It can not only allow farmers to produce more food, but also make sustainable use of land. Isn't this the best of both worlds?

5 Advantages of Hybrid Breeding in Sorghum

5.1 Improved yield and nutritional quality

Speaking of the progress in agriculture in recent years, sorghum hybrid breeding is definitely a highlight. I remember reading the report of the Indian Ministry of Agriculture last time. From the 1990s to now, the sorghum yield per mu there has jumped from more than 2 000 kilograms to more than 4 000 kilograms (Kumar et al., 2022). This increase is indeed quite good. However, the benefits of hybrids are not only high yields, but the most surprising thing is that the nutrition has also kept up-the content of trace elements such as protein, iron, and zinc has increased (Otwani et al., 2023), which is a life-saving straw for those areas with perennial drought and food shortages. Of course, the breeding process is not that simple. Agronomists have to conduct repeated experiments in order to find those "excellent students" who can produce stable yields under different climatic conditions (Kumar et al., 2021). To be honest, I always thought that breeding was to make crops produce more food, but now it seems more and more like a nutritional engineering.

5.2 Drought and pest resistance

When it comes to the benefits of sorghum hybrids, drought and insect resistance are definitely at the top of the list. I remember seeing in the field that ordinary sorghum wilts in the dry season, but those hybrids with "stay green" survived until the harvest season (Jordan et al., 2012). However, drought resistance alone is not enough. The biggest headache for farmers is insect pests-especially those nasty moths and mildew. Now, the newly cultivated hybrids are resistant to these pests (Prasad et al., 2021). Interestingly, the researchers also started with the root system, adjusting transpiration and root structure to allow these varieties to grow tenaciously in the dry season. Of course, the breeding process is not simple, but seeing the performance of these "all-round players" in the end, the hard work is worth it.

5.3 Enhancing genetic diversity

In recent years of sorghum breeding, experts have found that genetic diversity is particularly important. In the past, we always focused on those high-yield parents and repeatedly bred them, but the gene pool became narrower and narrower. Later, someone came up with a solution-to bring those inconspicuous local varieties and even wild germplasm to "match" (Jordan et al., 2011). You know what, this tossing has a really good effect. It not only preserves genetic diversity, but also unexpectedly harvests a lot of excellent traits that adapt to special environments (Figure 3). Take climate change for example. Now pests and diseases are becoming more and more difficult to deal with, but relying on this "wide-ranging" hybridization strategy, the new varieties bred are obviously more resistant (Otwani et al., 2023). Although the process is a bit troublesome, for long-term considerations, this "not putting all eggs in one basket" approach is indeed wise.

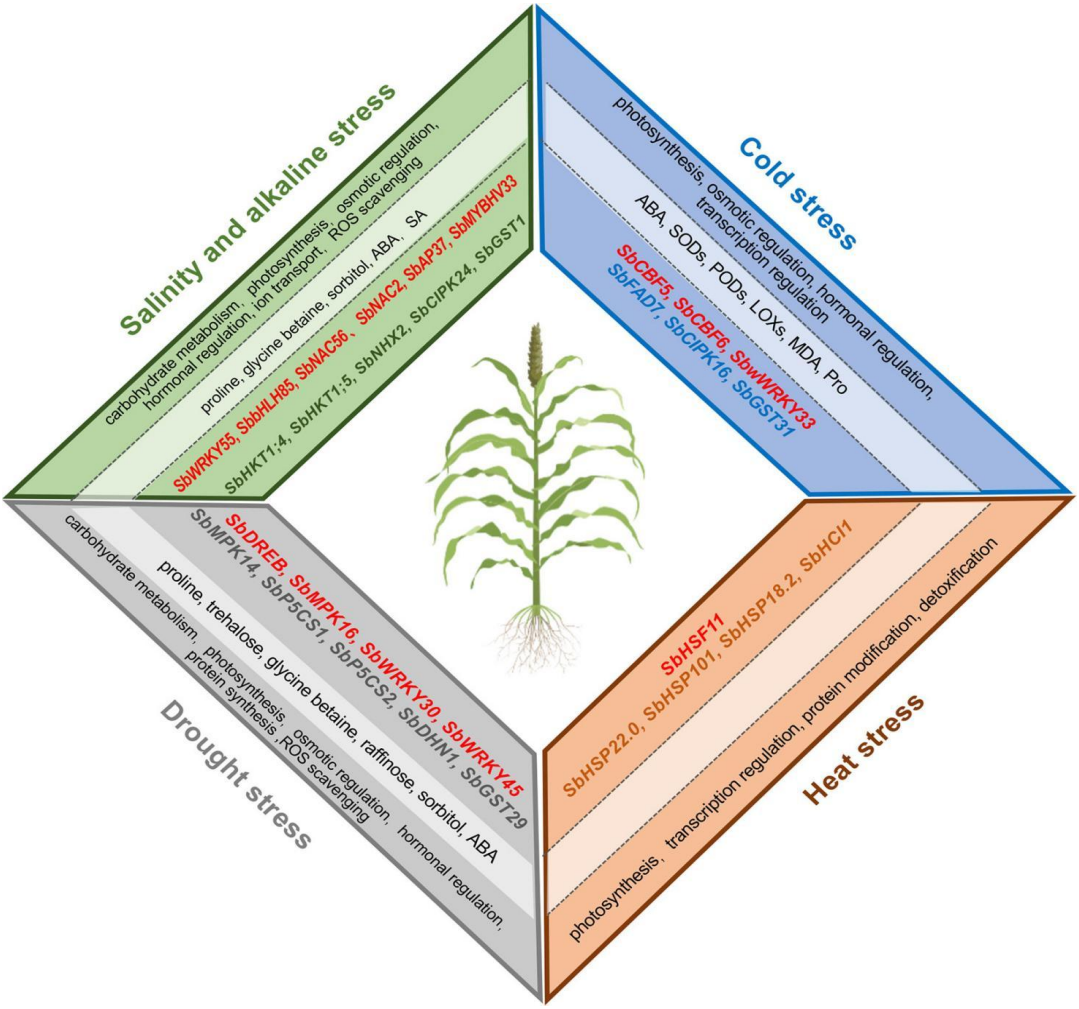

Figure 3 Molecular regulations involved in the response to and tolerance of abiotic stresses in sorghum. For each of the four abiotic stresses (drought, heat, cold, and salinity and alkaline), the candidate genes (transcription factors in red), metabolites, and physiological processes are depicted in three layers (from the innermost to outermost layer, respectively) (Adapted from Tu et al., 2023)

6 Challenges and Limitations of Hybrid Breeding

6.1 Technical and economic barriers

Sorghum hybrid breeding is easier said than done. Take the breeding of Guinea sorghum in West Africa as an example. It is not enough to know how to breed. The genetic characteristics of each parent must be understood clearly (Kante et al., 2019). However, the most troublesome thing is the wild germplasm. Although the genetic diversity is preserved, the hybrid offspring are often not up to standard, which makes breeders have to try every possible way to preserve the good traits (Jordan et al., 2011). When it comes to economic issues, it is even more

complicated. For example, in the Sudan savannah in West Africa, whether farmers can afford hybrid seeds depends on who is in charge of the family. This sounds outrageous, but this is the reality. So, no matter how advanced the breeding technology is, it must take into account the actual conditions of the local area.

6.2 Sustainability concerns and environmental impact

When it comes to sorghum hybrid breeding, people are increasingly concerned about sustainability. The "stay-green" trait is interesting and can help crops resist drought and lodging, but the effect depends on the location-some areas have obvious yield increases, but they may not work in other places (Jordan et al., 2012). The photoperiod-sensitive hybrids developed in Mali are a successful case. They use Guinea germplasm and perform particularly well under farmers' actual planting conditions (Rattunde et al., 2013). But then again, the most surprising thing about this hybrid is not only that the yield has increased, but more importantly, it is both environmentally friendly and allows farmers to earn more money, which is a win-win situation. Of course, breeding can never be a one-size-fits-all thing. The key is to adapt to local conditions.

6.3 Regulatory and ethical considerations

When it comes to hybrid breeding, it is not enough to just consider the technology. The regulatory and ethical issues are even more troublesome. Take genetically modified crops for example. The review standards of each country are different. If you are not careful, you may get stuck in the approval process. There is a successful case in West Africa. After using improved hybrid seeds, not only the yield has increased, but also the people's dining tables have become richer (Smale et al., 2018). However, this matter also has two sides-experts have to walk a tightrope between increasing yields and protecting local varieties (Suguna et al., 2021). The most troublesome thing is that when promoting new varieties, you have to consider fairness, so that only large farmers can afford it, and small farmers can only stare blankly. So, breeding not only requires understanding agriculture, but also balancing the interests of all parties.

7 Future Directions in Hybrid Breeding

7.1 Emerging technologies in hybrid breeding

When it comes to the future of sorghum breeding, those wild, undomesticated germplasm resources may come in handy. Although these "wild" varieties may not look impressive, they contain many good genes (Jordan et al., 2011). Recently, it has been found that after the excellent alleles of these wild species were introduced into cultivated varieties, the genetic variation of grain yield was actually maintained quite well. However, the most exciting thing is the breakthrough in marker-assisted breeding technology-now DNA markers can quickly lock in disease-resistant and high-yield gene loci (Baloch et al., 2023). Think about it, breeding used to be like looking for a needle in a haystack, but now with these new technologies, the efficiency has increased by many times. Of course, the specific effect depends on the field performance, but at least it gives breeding experts new hope.

7.2 Potential for precision breeding and ai applications

In recent years, breeding technology has become increasingly "smarter". Take genome editing, for example. Now it is much more accurate to breed new disease-resistant and drought-resistant sorghum varieties than before (Lassoued et al., 2018). Especially with climate change becoming more and more severe, these technologies come at the right time. But the most surprising thing is that even artificial intelligence has come to help with breeding-it can quickly analyze massive amounts of data and predict which hybrid combinations are the most reliable. Although it sounds a bit sci-fi, it does make breeding work a lot easier. Of course, these high-tech technologies are not omnipotent, and field trials are still necessary, but at least they allow breeders to avoid many detours. In my opinion, traditional experience combined with these new tools may really produce some amazing new varieties.

7.3 Policy and investment needs

To develop these new breeding technologies, scientific breakthroughs alone are not enough. Without adequate policy support and insufficient funding, even the best technology can only stay in the laboratory. There is an example in West Africa where hybrids made from Guinea germplasm are indeed much more productive than local varieties (Kante et al., 2019), but promotion is still difficult. In the final analysis, the regulatory framework must be straightened out first so that farmers can use them with confidence. And there are small farmers who need

technical support the most, but often invest the least in research and development. Environmental issues must also be considered, so as not to exhaust the soil fertility in order to increase production. In my opinion, breeding requires both "hard and soft"-the technology must be strong, and supporting policies and services must also keep up.

8 Concluding Remarks

In recent years, sorghum hybrid breeding has indeed made a lot of progress. In West Africa, the hybrids bred with Guinea germplasm are particularly impressive. Regardless of whether the soil is fertile or not, the yield is much higher than that of local varieties. However, the most surprising thing is that these new varieties not only produce more grain, but also have higher iron and zinc content in the grains. When it comes to drought resistance, it is even more amazing. Some new varieties can still maintain their yields in drought and are not even susceptible to mildew. Of course, breeding experts are not idle either. They invite wild species and local species to "help" and add a lot of new genes to cultivated varieties. Although the process is quite tiring, this effort is still necessary for long-term genetic gain. In my opinion, this breeding direction of increasing production and nutrition is the real timely rain to quench thirst.

In the research of sorghum hybrid breeding, we need to focus on several things. First of all, we need to continue to explore the genes that control yield and nutrition. However, knowing the genes is not enough. The key is how to match the parents most appropriately-this requires a lot of compatibility tests. Now QTL positioning and other molecular technologies are quite useful, and transgenic methods should not be left behind. After all, the demand for sorghum in different regions varies greatly (some people want feed, some want food). With such severe climate change, research on drought and heat resistance traits is even more urgent. But the most easily overlooked thing is that farmers should be more involved in the breeding process. Their experience in the fields is much more real than the data in the laboratory. In the final analysis, whether a new variety is good or not depends on whether farmers are willing to plant it.

When it comes to improving sorghum, hybrid breeding is indeed effective. Look at those high-yield and nutritious hybrid varieties, which have now become the backbone of many regions-especially those where sorghum is a staple food. But the most surprising thing is that these hybrids are not only high-yielding, but also very resistant to drought. Of course, now that climate change is getting more and more serious, breeders have to work harder. In my opinion, combining new technology with old experience and letting breeding teams in various places communicate more will make this thing work. After all, what farmers want is varieties that can survive when planted and are enough to eat when harvested. Although the process is not easy, seeing the golden sorghum in the field is worth it.

Acknowledgments

Author would like to express our appreciation to the editor and reviewers for their time and efforts to improve the quality of our manuscript.

Conflict of Interest Disclosure

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

References

Adebo O., 2020, African sorghum-based fermented foods: past, current and future prospects, Nutrients, 12(4): 1111. https://doi.org/10.3390/nu12041111

Assefa Y., and Staggenborg S., 2010, Grain sorghum yield with hybrid advancement and changes in agronomic practices from 1957 through 2008, Agronomy Journal, 102(2): 703-706. https://doi.org/10.2134/AGRONJ2009.0314

Baloch F., Altaf M., Liaqat W., Bedir M., Nadeem M., Cömertpay G., Çoban N., Habyarimana E., Barutçular C., Cerit İ., Ludidi N., Karaköy T., Aasim M., Chung Y., Nawaz M., Hatipoğlu R., Kökten K., and Sun H., 2023, Recent advancements in the breeding of sorghum crop: current status and future strategies for marker-assisted breeding, Frontiers in Genetics, 14: 1150616. https://doi.org/10.3389/fgene.2023.1150616

Fonseca J., Klein P., Crossa J., Pacheco A., Pérez-Rodríguez P., Ramasamy P., Klein R., and Rooney W., 2021, Assessing combining abilities, genomic data, and genotype × environment interactions to predict hybrid grain sorghum performance, The Plant Genome, 14(3): e20127.
https://doi.org/10.1002/tpg2.20127

Gaddameedi A., Phuke R., Polavarapu K., Gorthy S., Subhasini V., Jagannathan J., and Are A., 2020, Heterosis and combining ability for grain Fe and Zn concentration and agronomic traits in sorghum [*Sorghum bicolor* (L.) Moench], Journal of King Saud University-Science, 32(7): 2989-2994.
https://doi.org/10.1016/j.jksus.2020.08.003

Guo T.X., 2024, Hybridization events in gossypium: impact on crop improvement, Cotton Genomics and Genetics, 15(1): 31-40.

Jordan D., Hunt C., Cruickshank A., Borrell A., and Henzell R., 2012, The relationship between the stay‐green trait and grain yield in elite sorghum hybrids grown in a range of environments, Crop Science, 52(3): 1153-1161.
https://doi.org/10.2135/CROPSCI2011.06.0326

Jordan D., Mace E., Cruickshank A., Hunt C., and Henzell R., 2011, Exploring and exploiting genetic variation from unadapted sorghum germplasm in a breeding program, Crop Science, 51(4): 1444-1457.
https://doi.org/10.2135/CROPSCI2010.06.0326

Kante M., Rattunde F., Nebié B., Sissoko I., Diallo B., Diallo A., Tourè A., Weltzien E., Haussmann B., and Leiser W., 2019, Sorghum hybrids for low-input farming systems in West Africa: quantitative genetic parameters to guide hybrid breeding, Crop Science, 59(6): 2544-2561.
https://doi.org/10.2135/cropsci2019.03.0172

Kent M., Fonseca J., Klein P., Klein R., Hayes C., and Rooney W., 2023, Assessing the agronomic potential of sorghum B‐lines using genomic prediction, Crop Science, 63(6): 3367-3381.
https://doi.org/10.1002/csc2.21107

Kumar M., Ramya V., Govindaraj M., Dandapani A., Maheshwaramma S., Ganapathy K., Kavitha K., Goverdhan M., and Jagadeeshwar R., 2022, India's rainfed sorghum improvement: three decades of genetic gain assessment for yield, grain quality, grain mold and shoot fly resistance, Frontiers in Plant Science, 13: 1056040.
https://doi.org/10.3389/fpls.2022.1056040

Kumar M., Ramya V., Govindaraj M., Kumar C., Maheshwaramma S., Gokenpally S., Prabhakar M., Krishna H., Sridhar M., Ramana M., Kumar K., and Jagadeeshwar R., 2021, Harnessing sorghum landraces to breed high-yielding, grain mold-tolerant cultivars with high protein for drought-prone environments, Frontiers in Plant Science, 12: 659874.
https://doi.org/10.3389/fpls.2021.659874

Lassoued R., Smyth S., Phillips P., and Hesseln H., 2018, Regulatory uncertainty around new breeding techniques, Frontiers in Plant Science, 9: 1291.
https://doi.org/10.3389/fpls.2018.01291

Maulana F., Perumal R., Serba D., and Tesso T., 2023, Genomic prediction of hybrid performance in grain sorghum (*Sorghum bicolor* L.), Frontiers in Plant Science, 14: 1139896.
https://doi.org/10.3389/fpls.2023.1139896

Oliveira A., Pastina M., Souza V., Parrella R., Noda R., Simeone M., Schaffert R., Magalhães J., Damasceno C., and Margarido G., 2018, Genomic prediction applied to high-biomass sorghum for bioenergy production, Molecular Breeding, 38(4): 49.
https://doi.org/10.1007/s11032-018-0802-5

Ordonio R., Ito Y., Morinaka Y., Sazuka T., and Matsuoka M., 2016, Molecular breeding of *Sorghum bicolor*, a novel energy crop, International Review of Cell and Molecular Biology, 321: 221-257.
https://doi.org/10.1016/bs.ircmb.2015.09.001

Otwani D., Hunt C., Cruickshank A., Powell O., Koltunow A., Mace E., and Jordan D., 2023, Adaptation and plasticity of yield in hybrid and inbred sorghum, Crop Science, 64(2): 560-570.
https://doi.org/10.1002/csc2.21160

Perazzo A., Carvalho G., Santos E., Bezerra H., Silva T., Pereira G., Ramos R., and Rodrigues J., 2017, Agronomic evaluation of sorghum hybrids for silage production cultivated in semiarid conditions, Frontiers in Plant Science, 8: 1088.
https://doi.org/10.3389/fpls.2017.01088

Prasad V., Govindaraj M., Djanaguiraman M., Djalović I., Shailani A., Rawat N., Singla-Pareek S., Pareek A., and Prasad P., 2021, Drought and high temperature stress in sorghum: physiological, genetic, and molecular insights and breeding approaches, International Journal of Molecular Sciences, 22(18): 9826.
https://doi.org/10.3390/ijms22189826

Rakshit S., and Bellundagi A., 2019, Conventional breeding techniques in sorghum, In: Breeding sorghum for diverse end uses, Woodhead Publishing, PP.77-91.
https://doi.org/10.1016/B978-0-08-101879-8.00005-X

Rattunde H., Weltzien E., Diallo B., Diallo A., Sidibé M., Tourè A., Rathore A., Das R., Leiser W., and Tourè A., 2013, Yield of photoperiod-sensitive sorghum hybrids based on guinea-race germplasm under farmers' field conditions in Mali, Crop Science, 53(6): 2454-2461.
https://doi.org/10.2135/CROPSCI2013.03.0182

Ruperao P., Thirunavukkarasu N., Gandham P., Selvanayagam S., Govindaraj M., Nebié B., Manyasa E., Gupta R., Das R., Odeny D., Gandhi H., Edwards D., Deshpande S., and Rathore A., 2021, Sorghum pan-genome explores the functional utility for genomic-assisted breeding to accelerate the genetic gain, Frontiers in Plant Science, 12: 666342.
https://doi.org/10.3389/fpls.2021.666342

Smale M., Assima A., Kergna A., Thériault V., and Weltzien E., 2018, Farm family effects of adopting improved and hybrid sorghum seed in the Sudan Savanna of West Africa, Food Policy, 74: 162-171.
https://doi.org/10.1016/j.foodpol.2018.01.001

Suguna M., Aruna C., Deepika C., Ratnavathi C., and Tonapi V., 2021, Genetic analysis of semolina recovery and associated traits- A step towards breeding for specific end uses in sorghum (*Sorghum bicolor* (L.) Moench, Journal of Cereal Science, 100: 103226.
https://doi.org/10.1016/J.JCS.2021.103226

Sukumaran S., Li X., Li X., Zhu C., Bai G., Perumal R., Tuinstra M., Prasad P., Mitchell S., Tesso T., and Yu J., 2016, QTL mapping for grain yield, flowering time, and stay-green traits in sorghum with genotyping-by-sequencing markers, Crop Science, 56(4): 1429-1442.
https://doi.org/10.2135/CROPSCI2015.02.0097

Tao Y., Luo H., Xu J., Cruickshank A., Zhao X., Teng F., Hathorn A., Wu X., Liu Y., Shatte T., Jordan D., Jing H., and Mace E., 2021, Extensive variation within the pan-genome of cultivated and wild sorghum, Nature Plants, 7(6): 766-773.
https://doi.org/10.1038/s41477-021-00925-x

Tu M., Du C., Yu B., Wang G., Deng Y., Wang Y., Chen M., Chang J., Yang G., He G., Xiong Z., and Li Y., 2023, Current advances in the molecular regulation of abiotic stress tolerance in sorghum via transcriptomic, proteomic, and metabolomic approaches, Frontiers in Plant Science, 14: 1147328.
https://doi.org/10.3389/fpls.2023.1147328

Wang Y.F., and Zhang L.M., 2024, Gene-driven future: breakthroughs and applications of marker-assisted selection in tree breeding, Molecular Plant Breeding, 15(3): 132-143.
http://dx.doi.org/10.5376/mpb.2024.15.0014

Yahaya M., Shimelis H., Baloua N., Mashilo J., and Pop G., 2023, Response of African sorghum genotypes for drought tolerance under variable environments, Agronomy, 13(2): 557.
https://doi.org/10.3390/agronomy13020557