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A Review of Breeding Strategies for New Hybrid Sorghum Varieties

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Abstract This study reviewed recent advances in the development of hybrid sorghum varieties in recent years, evaluated their yield performance under different environmental conditions, and explored how conventional and molecular breeding methods can improve sorghum productivity, adaptability, and stress resistance. The results showed that modern crossbreeding programs significantly improved the yield and stability of sorghum under optimal and stress conditions, and molecular breeding, especially marker-assisted selection techniques, accelerated the development of hybrids with excellent traits. The introduction of these hybrids has improved the productivity of crop systems, the efficiency of resource use, and brought economic benefits to farmers. This study highlights the importance of continuous innovative hybrid breeding strategies to meet the needs of global food security, and aims to provide a scientific basis for the development of future sorghum varieties that can meet environmental challenges and have sustainable production capacity.

Keywords Hybrid sorghum varieties; Yield performance; Drought tolerance; Molecular breeding; Sustainable agriculture

1 Introduction

Sorghum (*Sorghum bicolor* L. Moench) is a vital cereal crop, particularly in arid and semi-arid regions, due to its resilience to harsh environmental conditions. The primary objective of sorghum hybrid breeding is to develop new varieties that exhibit superior yield performance, adaptability to diverse environments, and resistance to biotic and abiotic stresses. Hybrid breeding leverages the genetic diversity within sorghum to combine desirable traits from different parent lines, resulting in hybrids that outperform traditional varieties in terms of yield and stability (Kante et al., 2019; Maulana et al., 2023; Otwani et al., 2023).

Research on sorghum yield improvement has focused on several key areas, including the development of hybrids with enhanced heterosis, the use of genomic selection to predict hybrid performance, and the evaluation of genotype by environment (G×E) interactions. Studies have shown that sorghum hybrids can achieve significant yield advantages over local varieties, with heterosis levels ranging from 20% to 80% under various environmental conditions (Rattunde et al., 2013; Kante et al., 2019; Otwani et al., 2023). Genomic prediction models have been developed to improve the efficiency of hybrid selection, demonstrating that incorporating both additive and dominance effects can enhance prediction accuracy (Hunt et al., 2020; Kent et al., 2023; Maulana et al., 2023). Additionally, research has highlighted the importance of understanding G×E interactions to select hybrids that perform well across different environments (Ndiaye et al., 2019; Kumar et al., 2021; Otwani et al., 2023).

This study will evaluate the yield potential of sorghum hybrids under different environmental conditions, analyze genetic and environmental factors affecting yield, identify hybrids with better yield stability and adaptability, and use multi-environmental experiments to capture variability in yield performance across locations and seasons. By integrating quantitative genetic analysis and genomic prediction, this study aims to provide comprehensive insights into breeding strategies to improve sorghum yield and sustainability.

2 Genetic Basis and Breeding Strategies for Hybrid Sorghum

2.1 Sorghum genetic diversity and heterosis

Sorghum (*Sorghum bicolor* (L.) Moench) exhibits significant genetic diversity, which is crucial for hybrid breeding programs (Eniola et al., 2019). This diversity is often assessed using phenotypic traits and molecular markers such as simple sequence repeats (SSR). Studies have shown that genetic distance estimates based on phenotypic and SSR markers can range widely, indicating substantial genetic variation among sorghum genotypes (Amelework et al., 2016; Chauhan and Pandey, 2021). This genetic variation is essential for identifying unique genotypes with desirable traits and for maximizing heterosis, or hybrid vigor, which is the phenomenon where hybrid offspring exhibit superior qualities compared to their parents (Mengistu et al., 2020; Chen et al., 2024a; Chen, 2024b).

Heterosis in sorghum has been extensively studied, with findings indicating that hybrids can exhibit significant positive heterosis for traits such as grain yield, plant height, and micronutrient content. For instance, hybrids developed for grain Fe and Zn concentrations showed significant positive mid-parent heterosis, suggesting the potential for improving these nutritional traits through hybrid breeding (Gaddameedi et al., 2020). Additionally, studies have demonstrated that hybrids can outperform local varieties by 20% to 80% in yield under various environmental conditions, highlighting the potential of hybrid breeding to enhance sorghum productivity (Kante et al., 2019).

2.2 Breeding techniques for hybrid sorghum varieties

Several breeding techniques are employed to develop hybrid sorghum varieties. One common method is the line × tester mating design, which involves crossing multiple lines with testers to evaluate the combining ability and heterosis of the resulting hybrids. This approach helps in identifying the best parental combinations for producing high-yielding hybrids (Chauhan and Pandey, 2021; Rachman et al., 2022). Another technique involves the use of backcross populations to introduce genetic diversity from unadapted germplasm into elite breeding lines. This method has been effective in retaining genetic variation for key traits while improving the performance of the progeny (Jordan et al., 2011). Genomic selection is another advanced technique used in sorghum breeding. This method involves using genomic information from parental genotypes to predict the performance of hybrids (Sapkota et al., 2022). Studies have shown that genomic prediction can significantly improve the efficiency of hybrid breeding programs by accurately forecasting hybrid performance based on parental genotypes (Maulana et al., 2023).

2.3 Key traits targeted in hybrid sorghum breeding

Hybrid sorghum breeding programs target several key traits to develop superior varieties. These traits include grain yield, plant height, days to flowering, and micronutrient content. High grain yield is a primary target, as it directly impacts the economic viability of sorghum cultivation. Studies have shown that hybrids can achieve substantial yield improvements over local varieties, making yield a critical focus in breeding programs (Amelework et al., 2016; Kante et al., 2019). Plant height and days to flowering are also important traits, as they influence the adaptability and harvestability of sorghum. Breeding programs aim to develop hybrids with optimal plant height and early flowering to ensure better adaptation to different growing conditions and to facilitate mechanical harvesting (Ribeiro et al., 2021). Additionally, improving the nutritional quality of sorghum, particularly grain Fe and Zn concentrations, is a key objective. Hybrids with higher micronutrient content can address malnutrition issues in regions where sorghum is a staple food (Gaddameedi et al., 2020).

3 Development of New Hybrid Sorghum Varieties

3.1 Parent line selection and hybrid combination

The selection of parent lines and the combination of hybrids are critical steps in the development of new sorghum varieties. Studies have shown that combining ability and heterosis play significant roles in determining the success of hybrid breeding programs. For instance, research conducted on sorghum hybrids in West Africa demonstrated that hybrids developed from Guinea-race parents exhibited substantial yield advantages over local varieties, with heterosis levels ranging from 20% to 80% under different phosphorus conditions (Kante et al., 2017; Kante et al., 2019). Additionally, combining ability studies in tropical sorghum revealed that both general combining ability (GCA) and specific combining ability (SCA) are essential for traits such as grain yield, plant height, and seed mass, indicating the importance of both additive and non-additive gene actions (Kenga et al., 2004). These findings underscore the necessity of selecting parent lines with strong GCA and SCA effects to maximize hybrid performance.

3.2 Field trials and evaluation of new varieties

Field trials are indispensable for evaluating the performance of new sorghum hybrids under various environmental conditions. For example, a study on sorghum hybrids for silage production in semiarid conditions utilized a randomized block design to assess fresh matter yield (FMY) and dry matter yield (DMY) across multiple treatments (Perazzo et al., 2017). Similarly, the performance of photoperiod-sensitive sorghum hybrids was evaluated in farmer-managed and on-station trials in Mali, revealing significant genotypic differences and limited genotype × environment interactions (Rattunde et al., 2013). These trials are crucial for identifying hybrids with superior agronomic traits and adaptability to different growing conditions (Fonseca et al., 2021).

3.3 Analysis of agronomic performance

The analysis of agronomic performance involves assessing various traits such as yield, plant height, and resistance to diseases. For instance, a study on the genomic prediction of hybrid performance in sorghum demonstrated that including both additive and dominance effects in prediction models significantly improved the accuracy of yield predictions (Hunt et al., 2020). Another study focused on the combining ability and heterosis for grain Fe and Zn concentration, highlighting the potential for developing biofortified sorghum hybrids with enhanced nutritional value (Gaddameedi et al., 2020). These analyses provide valuable insights into the genetic and environmental factors influencing hybrid performance, guiding the selection and breeding of high-yielding, resilient sorghum varieties.

4 Yield Performance Analysis

4.1 Yield trials under different environmental conditions

Yield trials for the newly developed hybrid sorghum varieties were conducted across various environmental conditions to assess their performance and stability. Multi-environment trials (MET) were fundamental in evaluating genotype-by-environment interactions (G×E), which significantly influence yield outcomes. For instance, trials conducted in China using the AMMI and GGE biplot models revealed that significant G×E effects ($p < 0.001$) impacted yield performance, with broad-sense heritability estimates ranging from 0.40 to 0.94 (Wang et al., 2023). Similarly, in Australia, the inclusion of both additive and dominance effects in multi-environment models improved the prediction accuracy of hybrid performance, highlighting the importance of considering environmental variability (Hunt et al., 2020). In Senegal, trials demonstrated that specific genotypes showed particular adaptations to local conditions, with significant G×E interactions affecting both grain and biomass yields (Ndiaye et al., 2019). These findings underscore the necessity of conducting yield trials under diverse environmental conditions to identify high-yielding and stable sorghum hybrids.

4.2 Comparison with existing sorghum varieties

The performance of the new hybrid sorghum varieties was compared with existing varieties to determine their relative advantages. In a study conducted in West Africa, new Guinea-race hybrids exhibited 20 to 80% higher yields compared to local varieties under both low and high phosphorus conditions (Kante et al., 2019). Another study in China identified two superior genotypes, G3 (Liaoza No.52) and G10 (Jinza 110), which outperformed other varieties in terms of yield and stability across multiple environments (Wang et al., 2023). In the United States, the evaluation of sorghum hybrids under different water and heat stress patterns revealed that new hybrids could maintain higher yields under stress conditions compared to traditional varieties (Carcedo et al., 2022). These comparisons indicate that the newly developed hybrids have the potential to significantly enhance sorghum production, particularly in challenging environmental conditions.

4.3 Statistical analysis of yield data

Statistical analyses were employed to rigorously evaluate the yield data from the trials. The use of AMMI and GGE biplot models in China captured more than 66.3% of the total variance, demonstrating their effectiveness in analyzing G×E interactions and identifying stable, high-yielding genotypes (Wang et al., 2023). In Australia, linear mixed models incorporating both additive and dominance effects provided a more accurate prediction of hybrid performance, with the inclusion of dominance effects increasing prediction accuracies by up to 60% (Hunt et al., 2020). In Senegal, the joint analysis of variance revealed highly significant effects of genotypes, environments, and their interactions ($p < 0.000\ 1$), further emphasizing the complexity of G×E interactions (Ndiaye et al., 2019). These statistical approaches are crucial for understanding the factors influencing yield performance and for making informed breeding decisions.

5 Hybrid Sorghum Varieties: Case Studies

5.1 Case study: high-yielding hybrid sorghum varieties in Africa

In Africa, the development of high-yielding hybrid sorghum varieties has been a significant focus to enhance food security and improve the livelihoods of smallholder farmers. One notable study evaluated the performance of sorghum hybrids in West Africa, revealing that these hybrids exhibited substantial yield advantages over traditional varieties. For instance, hybrids developed from Guinea-race parents showed yield increases ranging from 20% to 80% under both low and high phosphorus conditions, demonstrating their potential to thrive in low-input farming systems (Figure 1) (Kante et al., 2019). Additionally, another study in Mali confirmed that photoperiod-sensitive sorghum hybrids derived from West African Guinea-race parents provided yield advantages of 17% to 37% over local landrace varieties, with significant yield improvements observed across various productivity levels (Rattunde et al., 2013).

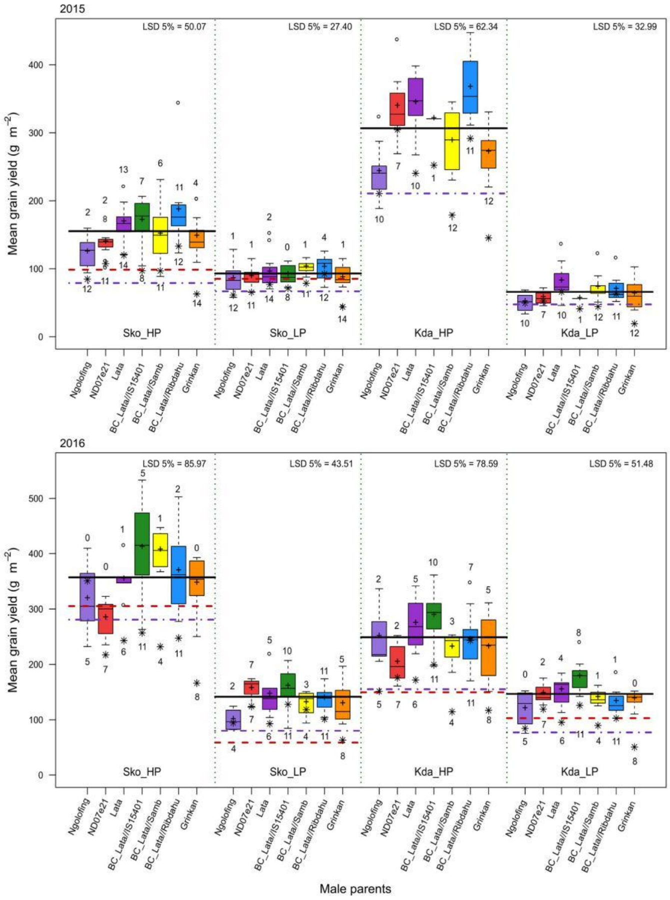

Figure 1 Grain yields (g m^{-2}) of Set 1 hybrids, grouped by male parents and presented as boxplots, from single environments in Samanko (Sko) and Kolombada (Kda) under low- and high-P (LP and HP, respectively) conditions in 2015 and 2016 (Adopted from Kante et al., 2019)

Image caption: each colored box corresponds to 25% above and 25% below the median for that group, midlines of each boxplot represent the median, whiskers indicate the total range, and circles denote outlier values. Plus signs indicate the mean of hybrids of a given male parent. Stars denote the yield of that male parent, and the numbers above and below each box indicate the count of hybrids significantly superior to Tieble and the total number of hybrids, respectively. The solid and the dashed horizontal lines represent the grain yield means of all hybrids and the landrace check Tieble, respectively, and the dot-dash horizontal lines represent the grain yield of the landrace check Ngolofing in 2015 or Woroponi in 2016. Distances (positive or negative) between the mean of each parent's hybrids and the overall hybrid mean yield indicate the general combining ability values of a given parent (Adopted from Kante et al., 2019)

5.2 Case study: drought-resistant hybrid sorghum

Drought resistance is a critical trait for sorghum varieties cultivated in arid and semi-arid regions. Research has identified several genotypes with superior drought tolerance and high yield performance under drought conditions (Prasad et al., 2021). For example, a study on African sorghum genotypes found that genotypes G114 and G56 were well-suited for both non-stressed and drought-stressed conditions, while G72 and G75 performed best under pre-anthesis drought stress (Yahaya et al., 2023). Another study highlighted the development of drought-tolerant sorghum varieties with high protein content and grain mold tolerance, such as the yellow pericarp sorghum variety PYPS 2, which demonstrated stable performance and adaptability across multiple environments (Figure 2) (Kumar et al., 2021). Furthermore, research in West Africa identified elite sorghum varieties that exhibited promising behavior under early drought stress, with varieties V1, V2, V8, and V9 showing potential for further application in breeding programs (Gano et al., 2021).

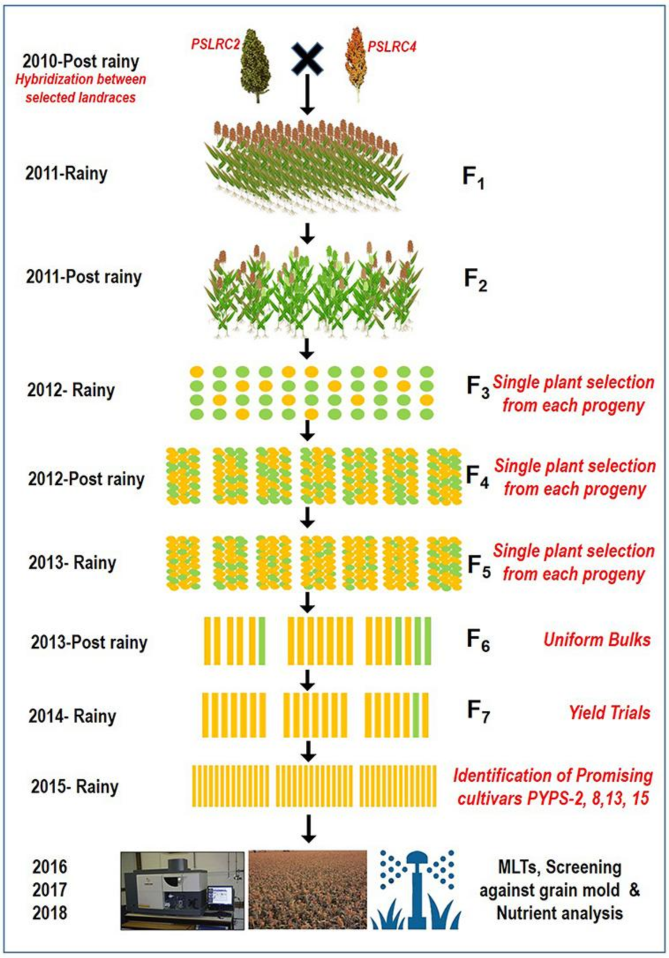

Figure 2 A flow diagram showing the development of sorghum varieties utilizing landraces through a pedigree selection (2010~2015) followed by multi-environment trials (2016~2018) (Adopted from Kumar et al., 2021)

5.3 Insights from case studies

The case studies on high-yielding and drought-resistant hybrid sorghum varieties provide valuable insights into the potential of these hybrids to enhance sorghum production in Africa. The development of hybrids with Guinea-race parents has shown significant yield advantages, making them suitable for low-input farming systems in West Africa (Rattunde et al., 2013; Kante et al., 2019). Additionally, the identification of drought-tolerant genotypes and the incorporation of traits such as high protein content and grain mold tolerance have further strengthened the resilience of sorghum varieties to environmental stresses (Gano et al., 2021; Kumar et al., 2021; Yahaya et al., 2023). These findings underscore the importance of targeted breeding programs that focus on both yield performance and stress tolerance to ensure sustainable sorghum production in diverse agro-ecological zones.

6 Challenges and Limitations in Hybrid Sorghum Breeding

6.1 Environmental and biotic stress factors

Hybrid sorghum breeding faces significant challenges due to environmental and biotic stress factors. Variability in weather patterns, such as those observed in Australia, can lead to substantial differences in yield between locations, complicating the prediction of hybrid performance (Hunt et al., 2020). Additionally, genotype-by-environment (G×E) interactions significantly affect yield stability, as seen in biomass sorghum hybrids, where factors like precipitation, temperature, and wind speed play crucial roles (Oliveira et al., 2020). Drought and grain mold are also major constraints, impacting both production and productivity (Kumar et al., 2021). In the Great Plains region of the United States, water-deficit and heat stress patterns further complicate breeding efforts, necessitating a better definition of target environments to improve predictability and genetic gains (Carcedo et al., 2022).

6.2 Genetic constraints and breeding efficiency

Genetic constraints and breeding efficiency are critical limitations in hybrid sorghum breeding. The lack of quantitative genetic information about the genetic value of new hybrids and their parents, especially under low-input conditions, hampers the development of high-yielding varieties (Kante et al., 2019). Genomic prediction models have shown promise in improving selection efficiency, but the accuracy of these models varies significantly depending on the traits and the size of the training population (Maulana et al., 2023). Moreover, the interplay between local adaptation and G×E interactions can lead to maladaptive phenotypic plasticity, affecting heterosis estimates and breeding outcomes (Otwani et al., 2023). The complexity of genetic mechanisms underlying specific traits, such as semolina recovery, also poses challenges for breeding genotypes with desired end-use qualities (Suguna et al., 2021).

6.3 Market acceptance and commercialization barriers

Market acceptance and commercialization barriers are significant hurdles in the adoption of new hybrid sorghum varieties. Despite the potential benefits of hybrid sorghum, such as higher yields and improved stress tolerance, the uptake of hybrid seeds remains low in many developing countries (Otwani et al., 2023). This low adoption rate can be attributed to several factors, including the lack of awareness among farmers, limited access to high-quality seeds, and the absence of robust market infrastructure to support the commercialization of new varieties. Additionally, the trade-offs between agronomic performance and yield stability, as observed in dual-purpose sorghum genotypes in Senegal, can affect market acceptance, as farmers may prefer stable yields over high but variable performance (Ndiaye et al., 2019).

7 Concluding Remarks

The breeding of new hybrid sorghum varieties has shown significant promise in enhancing yield performance across various environments and conditions. Sorghum hybrids, particularly those developed from Guinea-race parents, demonstrated substantial yield advantages over local varieties. For instance, hybrids showed 20% to 80% higher yields under both low-phosphorus (LP) and high-phosphorus (HP) conditions in West Africa. Similarly, hybrids based on Guinea-race germplasm exhibited 17% to 37% yield superiority over traditional landrace cultivars in Mali. The use of diverse unadapted germplasm in breeding programs has been effective in introducing new alleles and retaining genetic variation, which is crucial for future genetic gains. This approach has led to the identification of progeny that outperform recurrent parent hybrids for grain yield.

Combining ability analysis has also identified promising parent lines that can be used to develop hybrids with high yield, earliness, and ideal plant height. The stability and adaptability of new sorghum varieties have been evaluated using AMMI and GGE biplot analyses. These methods have identified high-yielding, stable varieties that perform well across multiple environments, despite genotype × environment interactions. Genomic selection has been shown to improve the efficiency of predicting hybrid performance based on parental genotypes. This method has demonstrated high prediction accuracies for grain yield, suggesting its potential as a valuable tool in sorghum breeding programs.

The findings from these studies have several important implications for future sorghum breeding programs. The substantial yield advantages of sorghum hybrids over local varieties underscore the importance of continuing to develop and promote hybrid breeding strategies. This approach can significantly enhance the livelihoods of smallholder farmers by increasing productivity. Incorporating diverse unadapted germplasm into breeding programs is essential for maintaining genetic diversity and achieving long-term genetic gains. Breeding methods that effectively utilize such germplasm should be prioritized.

Future breeding efforts should focus on identifying and combining favorable alleles for key traits such as yield, earliness, and plant height. This can be achieved through complex crosses and gene pyramiding strategies. The integration of genomic selection into breeding programs can enhance the accuracy and efficiency of selecting high-performing hybrids. This approach should be further developed and applied to optimize breeding outcomes. Breeding programs should continue to evaluate the adaptation and stability of new varieties across diverse environments. This will ensure the development of sorghum varieties that are resilient to local conditions and climate variability.

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Conflict of Interest Disclosure

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

References

Amelework B., Shimelis H., and Laing M., 2016, Genetic variation in sorghum as revealed by phenotypic and SSR markers: implications for combining ability and heterosis for grain yield, Plant Genetic Resources, 15: 335-347.
https://doi.org/10.1017/S1479262115000696

Carcedo A., Mayor L., Demarco P., Morris G., Lingenfelser J., Messina C., and Ciampitti I., 2022, Environment characterization in sorghum (*Sorghum bicolor* L.) by modeling water-deficit and heat patterns in the great plains region, United States, Frontiers in Plant Science, 13: 768610.
https://doi.org/10.3389/fpls.2022.768610
PMid:35310654 PMCid:PMC8929132

Chauhan P., and Pandey P., 2021, Parental selections in sorghum (*Sorghum bicolor* L.) on the basis of heterosis and combining ability in association with SSR diversity in sub-tropical plains of Uttarakhand, India, Plant Archives, 21(1): 540-549.
https://doi.org/10.51470/PLANTARCHIVES.2021.v21.no1.076

Chen B., Hou J.F., Cai Y.F., Wang G.Y., Cai R.X., and Zhao F.C., 2024a, Utilizing genetic diversity for maize improvement: strategies and success stories, Maize Genomics and Genetics, 15(3): 136-146.
https://doi.org/10.5376/mgg.2024.15.0014

Chen F.P., 2024b, Genetic diversity and adaptability analysis of wild rice germplasm resources, Rice Genomics and Genetics, 15(2): 58-68.
https://doi.org/10.5376/rgg.2024.15.0007

Eniola A., Odiyi A., Fayeun L., and Obilana A., 2019, Evaluation of hybrids sorghum (*Sorghum bicolor* L. Moench.) for growth and yield in a rainforest agro-ecological zone, Town Planning Review, 6: 497-505.
https://doi.org/10.22271/tpr.2019.v6.i3.062

Fonseca J., Perumal R., Klein P., Klein R., and Rooney W., 2021, Mega-environment analysis to assess adaptability, stability, and genomic predictions in grain sorghum hybrids, Euphytica, 218: 128.
https://doi.org/10.21203/rs.3.rs-1157295/v1

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: 2989-2994.
https://doi.org/10.1016/j.jksus.2020.08.003

Gano B., Dembele J., Tovignan T., Sine B., Vadez V., Diouf D., and Audebert A., 2021, Adaptation responses to early drought stress of west Africa sorghum varieties, Agronomy, 11(3): 443.
https://doi.org/10.3390/agronomy11030443

Hunt C., Hayes B., Eeuwijk F., Mace E., and Jordan D., 2020, Multi-environment analysis of sorghum breeding trials using additive and dominance genomic relationships, Theoretical and Applied Genetics, 133: 1009-1018.
https://doi.org/10.1007/s00122-019-03526-7
PMid:31907563

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: 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

Kante M., Rattunde H., Leiser W., Nebié B., Diallo B., Diallo A., Tourè A., Weltzien E., and Haussmann B., 2017, Can tall Guinea-race sorghum hybrids deliver yield advantage to smallholder farmers in west and central Africa, Crop Science, 57: 833-842.
https://doi.org/10.2135/cropsci2016.09.0765

Kenga R., Alabi S., and Gupta S., 2004, Combining ability studies in tropical sorghum (*Sorghum bicolor* (L.) Moench), Field Crops Research, 88(2-3): 251-260.
https://doi.org/10.1016/j.fcr.2004.01.002

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., 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
PMid:34276722 PMCid:PMC8279770

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
PMid:37180401 PMCid:PMC10167770

Mengistu G., Shimelis H., Laing M., Lule D., and Mashilo J., 2020, Combining ability and heterosis among sorghum (*Sorghum bicolor* [L.] Moench) lines for yield, yield-related traits, and anthracnose resistance in western Ethiopia, Euphytica, 216: 33.
https://doi.org/10.1007/s10681-020-2563-6

Ndiaye M., Adam M., Ganyo K., Guisse A., Cisse N., and Muller B., 2019, Genotype-environment interaction: trade-offs between the agronomic performance and stability of dual-purpose sorghum (*Sorghum bicolor* L. Moench) genotypes in Senegal, Agronomy, 9(12): 867.
https://doi.org/10.3390/agronomy9120867

Oliveira I., Guilhen J., Ribeiro P., Gezan S., Schaffert R., Simeone M., Damasceno C., Carneiro J., Carneiro P., Parrella R., and Pastina M., 2020, Genotype-by-environment interaction and yield stability analysis of biomass sorghum hybrids using factor analytic models and environmental covariates, Field Crops Research, 257: 107929.
https://doi.org/10.1016/j.fcr.2020.107929

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
PMid:28690626 PMCid:PMC5479915

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
PMid:34575989 PMCid:PMC8472353

Rachman F., Trikoesoemaningtyas T., Wirnas D., and Reflinur R., 2022, Estimation of genetic parameters and heterosis through line × tester crosses of national sorghum varieties and local Indonesian cultivars, Biodiversitas Journal of Biological Diversity, 23(3): 1588-1597.
https://doi.org/10.13057/biodiv/d230349

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

Ribeiro L., Tardin F., Menezes C., Baldoni A., Teodoro P., and Bhering L., 2021, Combining yield, earliness and plant height in a single genotype: a proposal for breeding in grain sorghum (*Sorghum bicolor* L.), Revista de la Facultad de Ciencias Agrarias UNCuyo, 53(1): 11-21.
https://doi.org/10.48162/rev.39.002

Sapkota S., Boatwright J., Kumar N., Myers M., Cox A., Ackerman A., Caughman W., Brenton Z., Boyles R., and Kresovich S., 2022, Genomic prediction of hybrid performance for agronomic traits in sorghum, G3: Genes, Genomes, Genetics, 13(4): jkac311.
https://doi.org/10.1093/g3journal/jkac311
PMid:36454599 PMCid:PMC10085789

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

Wang R., Wang H., Huang S., Zhao Y., Chen E., Li F., Qin L., Yang Y., Guan Y., Liu B., and Zhang H., 2023, Assessment of yield performances for grain sorghum varieties by AMMI and GGE biplot analyses, Frontiers in Plant Science, 14: 1261323.
https://doi.org/10.3389/fpls.2023.1261323
PMid:37965005 PMCid:PMC10642804

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