Computational Molecular Biology 2026, Vol.16, No.3, 205-217
http://bioscipublisher.com/index.php/cmb

Feature Review **Open Access**

Modeling Yield Formation in Sorghum Based on Temperature and Rainfall

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Computational Molecular Biology, 2026, Vol.16, No.3 doi: 10.5376/cmb.2026.16.0015
Received: 05 May, 2026
Accepted: 07 Jun., 2026
Published: 22 Jun., 2026

Preferred citation for this article:
Zhou M.L., 2026, Modeling yield formation in sorghum based on temperature and rainfall, Computational Molecular Biology, 16(3): 205-217 (doi: 10.5376/cmb.2026.16.0015)

Abstract Sorghum (*Sorghum bicolor* L.) is one of the most important cereal crops in semi-arid and drought-prone regions due to its remarkable tolerance to heat and water limitation. However, sorghum productivity remains highly dependent on climatic conditions, particularly temperature and rainfall variability. This review synthesizes current knowledge on the biological and physiological mechanisms underlying sorghum yield formation and examines how temperature, rainfall, heat stress, drought stress, and their interactions influence grain number, grain weight, and overall yield stability. The review further evaluates major approaches used in sorghum yield prediction, including empirical statistical models, process-based crop simulation models, remote sensing technologies, and machine learning methods. Case studies from semi-arid regions demonstrate that reproductive-stage heat stress, post-flowering drought, and irregular rainfall distribution are among the most critical factors limiting yield. Future climate change is expected to intensify these challenges, highlighting the need for climate-resilient cultivars, adaptive agronomic management, and integrated decision-support systems. The review concludes that combining biological understanding with advanced modeling techniques can substantially improve yield prediction accuracy and support sustainable sorghum production under changing climatic conditions.

Keywords Sorghum; Temperature; Rainfall; Yield prediction; Climate change

1 Introduction

Sorghum remains one of the most important cereals for dryland farming systems because it combines food, feed, fodder, and industrial value with a comparatively strong ability to function under water limitation and high temperature. That practical resilience explains why it is deeply embedded in semi-arid production systems across Africa and Asia, and why recent reviews increasingly frame sorghum as a strategic crop for climate adaptation rather than only a “fallback” crop for marginal lands. At the same time, this reputation should not hide the fact that sorghum productivity in many regions remains low and unstable, especially where smallholders depend on rainfed systems, shallow soils, and short, erratic wet seasons. In those environments, modest shifts in seasonal onset, dry-spell frequency, or reproductive-stage heat can have outsized effects on grain set and final harvest. The literature therefore increasingly treats sorghum not simply as a hardy crop, but as a crop whose performance is highly conditional on stage-specific weather patterns and local management. That is exactly why climate-based yield modeling has become central to sorghum research and planning (Hossain et al., 2022; Liaqat et al., 2024; Mwamahonje et al., 2024).

Temperature and rainfall influence sorghum yield through different but tightly linked pathways. Temperature controls developmental pace, especially through accumulated thermal time, and therefore shapes the timing of leaf appearance, panicle initiation, anthesis, and maturity. Rainfall, by contrast, determines whether the crop can maintain canopy expansion, transpiration, reproduction, and grain filling at those stages. In practice, yield formation depends less on either variable in isolation than on their interaction with plant development. A warm season can shorten the crop cycle, reduce the duration of grain filling, and increase atmospheric demand for water; if rainfall is poorly distributed at the same time, the combined effect can sharply reduce grain number or grain weight. Conversely, moderately warm conditions paired with timely rainfall can improve stand establishment and biomass production, especially where cold stress or delayed phenology is otherwise limiting. This stage-specific interaction is the reason recent sorghum studies rarely analyze temperature and rainfall as simple seasonal averages; they focus instead on monthly, event-based, or growth-stage-specific conditions (Kumar et al., 2009; Prasad et al., 2021; Tolosa et al., 2023).

Climate-based yield modeling in sorghum has moved through several phases. Early work relied mainly on correlation and regression, asking which combinations of rainfall totals, rainy days, or seasonal temperatures tracked annual yield variation. That approach remains useful where data are sparse and decisions must be made quickly. More recent work has added process-based models such as APSIM, DSSAT-CERES-Sorghum, and AquaCrop, which represent phenology, biomass accumulation, water balance, and grain formation mechanistically. In parallel, remote sensing and machine learning have expanded the modeling toolbox by making it possible to estimate yield from canopy signals, spatial heterogeneity, and multi-source environmental data. The result is not a single dominant method, but an increasingly layered modeling landscape in which empirical, mechanistic, and data-driven approaches are used for different purposes. For a review aimed at a computationally oriented journal, that diversity is especially important: the field is moving toward hybrid systems that use biology to structure models and data science to improve scale, speed, and prediction accuracy (Tirfessa et al., 2023; Jabed and Murad, 2024; Gardi et al., 2025).

This study has four linked objectives. First, it summarizes the biological and physiological basis of sorghum yield formation in a form that is clear enough to support modeling decisions. Second, it examines how temperature and rainfall affect yield formation directly and through heat stress, drought stress, and their interaction. Third, it compares the main modeling approaches now used for sorghum yield prediction, not to declare a single winner, but to clarify what each method captures well and where each remains limited. Fourth, it uses published case evidence from semi-arid regions to show how climate-yield relationships work in practice and what that means for adaptation and management. The review is deliberately written as a synthesis rather than a report of new experimental data, so its contribution lies in organizing established evidence into a coherent framework that can support both research design and practical decision-making.

2 Biological and Physiological Basis of Sorghum Yield Formation

2.1 Growth and development characteristics of sorghum

Sorghum is a C4 cereal with strong adaptation to hot, high-radiation environments, and its development is usually described through discrete vegetative and reproductive stages linked to thermal time. That developmental structure matters because the crop does not respond to weather uniformly across the whole season. The timing of panicle initiation, flowering, and maturity depends on genotype, temperature, and in many materials photoperiod sensitivity; together, those factors determine whether the crop escapes or encounters stress at key points. Modeling work on diverse sorghum genotypes has shown that accurate prediction of phenology and canopy development requires explicit representation of temperature and photoperiod responses rather than broad maturity labels alone. This has two practical implications. First, cultivars that appear similar in duration can behave differently under shifting sowing dates or altered season length. Second, any serious attempt to model yield formation from climate must begin with phenology, because an error in stage timing usually propagates into errors in stress exposure, biomass partitioning, and grain yield (Tirfessa et al., 2023).

2.2 Major yield components

Sorghum grain yield is built from a small set of components, but the timing of their determination is staggered across the season. Grain number and grain weight are the dominant immediate components, while panicle size, floret fertility, seed set, and tiller contribution help explain how those two primary components are assembled. The number of kernels is largely determined during the earlier reproductive period, especially from panicle initiation through flowering and early fertilization, whereas kernel weight depends more strongly on post-flowering assimilate supply and the duration and quality of grain filling. That distinction matters for climate analysis because temperature and rainfall do not affect all components in the same way. Heat or water deficit around flowering tends to depress grain number, while post-flowering stress more often reduces individual grain weight. Genetic studies also reach the same broader conclusion from a different angle: grain size, grain number per panicle, and grain weight are central yield-related traits, but they are interconnected and subject to trade-offs.

A useful sorghum model must therefore represent not just total biomass, but how climate shapes the component pathway to yield (Baye et al., 2022; Otwani et al., 2025).

2.3 Physiological processes related to yield formation

Behind those yield components lie a set of physiological processes that climate directly modifies. Photosynthesis supplies assimilates for canopy growth, reproduction, and grain filling. Stomatal conductance and plant hydraulics regulate the trade-off between carbon uptake and water loss. Assimilate partitioning determines whether biomass supports stems, leaves, roots, or grain at a given stage. Under water stress, sorghum often maintains function better than many cereals through deep rooting, osmotic adjustment, partial stomatal control, and a capacity in some genotypes to conserve photosynthetic performance even when water becomes limiting. Recent physiological work has shown meaningful genotypic variation in intrinsic water-use efficiency and associated hydraulic traits, with improved water-use efficiency in some genotypes arising not only from stronger stomatal restriction but from better maintenance of photosynthetic capacity under stress. That is especially important for modeling because it means drought tolerance cannot be treated as a single trait or a single reduction factor. It emerges from interacting physiological controls that differ by genotype and stage (Ndlovu et al., 2021; Prasad et al., 2021; Al-Salman et al., 2024).

2.4 Environmental sensitivity across growth stages

Not all growth stages are equally vulnerable (Figure 1). The literature repeatedly shows that reproductive stages are more sensitive than vegetative stages, although early establishment can also be critical where emergence stress is severe. In sorghum, the period from panicle emergence through anthesis is especially important because it governs floret fertility, pollen development, fertilization, and embryo formation. Later, grain filling becomes the decisive stage for grain size and final grain mass. Water stress or heat stress during these windows can lower yield even when earlier biomass production looked satisfactory. The stage-specific nature of stress is one reason the same seasonal rainfall or seasonal mean temperature can produce very different outcomes in different years: what matters is where stress lands in relation to developmental timing. For modelers, that means stage-based sensitivity functions are not optional details. They are the bridge between weather time series and harvest outcomes (Prasad et al., 2015; Prasad et al., 2021; Smith et al., 2023).

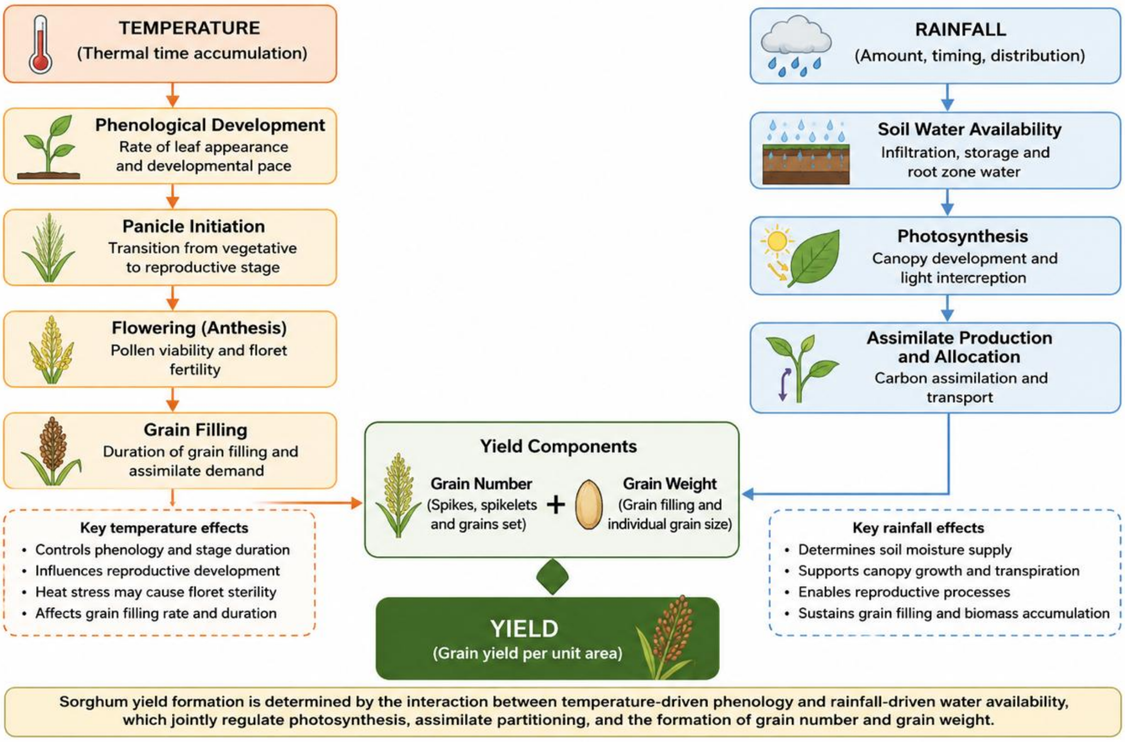


Figure 1 Biological and physiological framework of sorghum yield formation

3 Effects of Temperature and Rainfall on Sorghum Yield Formation

3.1 Temperature effects on growth and productivity

Temperature has a double role in sorghum. Within an appropriate range it accelerates development and supports rapid canopy formation, but above that range it can shorten critical phases and damage reproductive function. Growth-stage studies show that the most sensitive windows for high-temperature effects on floret fertility lie roughly from 10 to 5 days before anthesis and from 5 days before to 5 days after anthesis. In controlled and field experiments, mean daily temperatures above 25°C during panicle emergence and reproductive development reduced floret fertility sharply, with fertility reaching zero at about 37°C under one experimental setup. When heat occurs later, during grain filling, the main effect shifts from grain number to grain weight because high temperature shortens the effective filling period and limits final kernel mass. Even where sorghum is “heat adapted,” these results make clear that adaptation does not equal immunity. It means the crop can perform better than alternatives under heat, not that it can ignore reproductive heat stress (Prasad et al., 2015; Smith et al., 2023).

3.2 Rainfall effects on crop development and yield

Rainfall affects sorghum yield not simply through total water supply, but through its timing, frequency, and match with soil type and plant stage. In semi-arid regions, rainfall can support germination, early canopy expansion, and reproductive development even when seasonal totals are modest, provided dry spells are short and well-positioned. Conversely, rainfall that arrives too early, too late, or in a few concentrated events can leave the crop exposed to long soil-water deficits during flowering or grain filling. Published case evidence from eastern Ethiopia illustrates this clearly: monthly rainfall amount and rainy-day number during the growing period were positively associated with sorghum yield, while temperature variables were negative. Similar conclusions also appear in dryland studies that emphasize rainfall distribution as more informative than seasonal totals. Rainfall excess can also become damaging. Waterlogging studies show that sorghum yield can decline markedly when excessive moisture occurs, particularly at early stages, because photosynthesis, enzyme activity, and panicle development are impaired. So the rainfall question is not “more or less,” but “when, how often, and under what soil and stage conditions.” (Tolosa et al., 2023; Zhang et al., 2023).

3.3 Heat stress, drought stress, and yield loss mechanisms

Heat stress and drought stress reduce yield through partially distinct but overlapping mechanisms (Figure 2). Heat stress during the pre-anthesis and anthesis period can disrupt tapetum development, pollen viability, pollen germination, and floret fertility, which directly lowers grain number. In one recent study, exposure to 42/32°C day/night heat at the pollen mother cell and booting stages severely disrupted male reproductive development, and 12 days of stress at the PMC stage caused almost complete loss of grain yield. Drought stress, meanwhile, acts through reduced leaf expansion, lower stomatal conductance, reduced assimilate supply, impaired reproductive success, and sometimes premature senescence. Water-deficit experiments further show that drought can alter intra-panicle grain number and depress individual grain weight, depending on timing. Under field conditions, both stresses converge on the same final logic: less successful grain set before flowering and weaker filling after flowering. The stress pathway changes, but the endpoint is the same (Adotey et al., 2021; Prasad et al., 2021; Smith et al., 2023).

3.4 Interactive effects of temperature and rainfall

The most serious yield losses often arise when high temperature and rainfall shortage occur together. Warm conditions increase vapor pressure deficit and evapotranspiration demand; if rainfall is simultaneously low or irregular, the plant faces a compounded water-energy imbalance. That interaction helps explain why a year with only moderate rainfall reduction can still perform poorly if accompanied by strong warming, especially around flowering. Reviews of combined stress in sorghum describe morphological injury, disrupted cell metabolism, lower membrane stability, reduced photosynthesis, and stronger oxidative stress under joint drought-heat exposure than under either stress alone. Modeling studies reinforce the same point. In the U.S. Great Plains, APSIM-based environment characterization identified water- and heat-stress clusters that aligned with observed yield reductions, and in the drier western sorghum belt grain-filling water stress was especially common. This is a reminder that climate variables should not be interpreted independently in yield models when they co-determine plant demand and stress timing (Ndlovu et al., 2021; Carcedo et al., 2022).

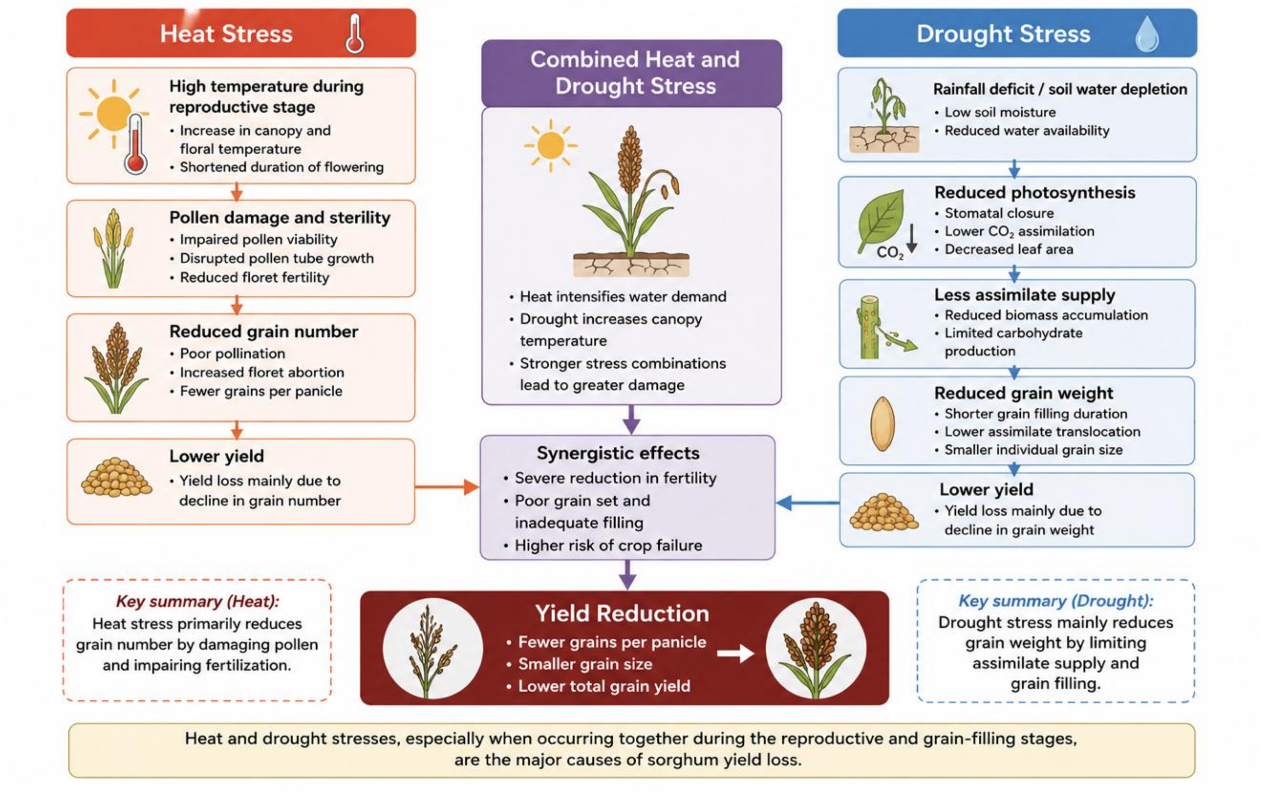


Figure 2 Mechanisms of yield loss under heat and drought stress

3.5 Climatic thresholds influencing yield stability

Thresholds in sorghum are real, but they are not universal constants. They depend on genotype, developmental stage, and stress duration. Even so, the literature gives useful working thresholds. For reproductive heat, mean daily temperatures above about 25°C during panicle emergence and early reproductive development begin to depress fertility, and sustained exposure to higher temperatures causes sharply larger losses. During grain filling, elevated temperatures mainly reduce kernel weight. For water-related thresholds, the message is less about a single rainfall total than about distribution. In Babile district, for example, August and September rainfall variability and the number of rainy days in September were among the strongest predictors of yield, whereas seasonal rainfall totals had weaker relationships. Dryland management studies likewise show that adaptation measures perform differently across rainfall bands, with some rainwater-harvesting practices helping under certain conditions but not across all semi-arid settings. In practical modeling, this means threshold thinking should focus on stage-specific heat episodes, rainfall sequence, and stress duration, not on a single whole-season cutoff (Prasad et al., 2015; Kubiku et al., 2022; Tolosa et al., 2023).

4 Modeling Approaches for Sorghum Yield Prediction

4.1 Statistical and empirical models

Statistical and empirical models remain the most straightforward entry point for sorghum yield prediction. Their usual strength is clarity: the analyst can directly test how yield covaries with rainfall totals, rainy-day frequency, monthly temperatures, or growing degree days. In data-scarce regions, that simplicity is a genuine advantage. The Babile study is a good example. Using 1995-2020 data, the authors found that a multiple regression based on monthly rainfall, rainy days, and temperature explained about 77% of the annual variation in sorghum yield, underscoring how much explanatory power can be obtained from carefully chosen climate predictors in a local rainfed system. At the same time, empirical models are only as stable as the relationships they learn from the past. They often struggle when management changes, cultivars change, or climate enters combinations outside the historical range. They also explain association better than mechanism. So they are useful for local forecasting and first-pass diagnosis, but they rarely suffice for scenario analysis on their own (Tolosa et al., 2023).

4.2 Process-based crop simulation models

Process-based crop models are the backbone of much sorghum climate-impact research because they translate weather into plant development through explicit biological rules. APSIM and DSSAT-CERES-Sorghum are the most widely used in the literature reviewed here, with AquaCrop often used for irrigation and water-productivity questions. Their main attraction is interpretability: they can represent thermal-time driven phenology, soil-water balance, biomass production, and yield formation in a way that makes adaptation experiments possible. That is why they are especially useful for testing cultivar maturity, sowing date, fertilizer response, supplemental irrigation, and trait ideotypes under future climates. APSIM-based studies in Ethiopia and Mali, for example, have been used to characterize drought patterns, explore genotype × environment × management interactions, and identify where trait changes or sowing shifts might reduce risk. DSSAT-based studies in Ethiopia have simulated both future yield decline and the performance of adaptation packages under SSP scenarios. The cost of this power is data demand and calibration effort. A crop model can formalize biology beautifully and still perform poorly if soils, varieties, or management are mis-specified (Tirfessa et al., 2023; Diancoumba et al., 2024; Gardi et al., 2025; Ali and Kothari, 2026).

A general process-based expression of sorghum yield prediction can be written as:

$$Y=f(T,R,S,G,M,\varepsilon)$$

where Y is yield, T is the temperature regime, R is rainfall and soil water supply, S is soil condition, G is genotype, M is management, and ε captures unobserved variation. In empirical models, f is usually a fitted statistical relation. In crop simulation models, f is decomposed into linked sub-processes such as phenology, transpiration, biomass accumulation, and partitioning.

4.3 Remote sensing applications

Remote sensing expands sorghum yield modeling by observing the crop directly across space rather than relying only on weather and field samples. The main value of remote sensing lies in its ability to capture canopy status, vegetation indices, spatial heterogeneity, and sometimes stage-specific crop responses that are difficult to measure manually at large scale. Recent sorghum studies show that multispectral imagery from satellites or UAVs can support reasonably strong yield prediction when aligned with key phenological stages. In tropical environments, artificial neural network models built from vegetation indices and soil elevation data reached strong performance in estimating sorghum grain yield, while arid-region UAV studies found that integrating multispectral and meteorological data can predict yield with high accuracy and reveal which growth stage contributes most to predictive skill. A recurring theme is that timing matters: the best observation date is not necessarily the latest one, because some stages carry more information about final yield formation than others. Remote sensing therefore works best when it is phenology-aware, not just image-rich (Ferraz et al., 2024; Deng et al., 2025).

4.4 Machine learning and artificial intelligence approaches

Machine learning has become increasingly attractive in sorghum yield prediction because sorghum systems are shaped by non-linear interactions among climate, soils, management, and canopy signals. Algorithms such as random forests, gradient boosting, support vector machines, artificial neural networks, and stacking ensembles can absorb high-dimensional predictor sets and model interactions that are difficult to specify mechanically. Recent sorghum applications illustrate both the promise and the limits of this approach. In South Sudan, machine-learning models combining yield, climate, remote sensing, and conflict-probability data produced useful end-of-season yield predictions, with XGBoost, decision tree, and random forest performing especially well. In tropical and arid experiments, neural networks and ensemble approaches also produced strong fits. But these models can become opaque, and their success depends greatly on training data coverage and quality. When extrapolation is required, or when the user needs biological explanation rather than prediction alone, machine learning is strongest when paired with domain knowledge rather than treated as a black box (Ferraz et al., 2024; Jabed and Murad, 2024; Deng et al., 2025; Karongo et al., 2025).

4.5 Comparison of existing modeling approaches

The various modeling traditions are best understood as complementary tools rather than competing ideologies. Empirical models are attractive when transparency and low input demand matter most. Process-based models are preferable when the user needs biological realism, trait testing, or future scenario analysis. Remote sensing improves spatial monitoring and in-season updating. Machine learning is especially useful when relationships are complex and observation streams are large. The real challenge is not to choose one method forever, but to align method with question. If the purpose is local seasonal diagnosis, regression may be enough. If the purpose is trait-by-environment adaptation research, APSIM or DSSAT is more suitable. If the purpose is spatial forecasting or operational monitoring, remote sensing and machine learning become more important. Increasingly, the strongest studies combine them (Jones et al., 2003; Holzworth et al., 2014; Mihret et al., 2024).

5 Case Study: Modeling Sorghum Yield Responses to Temperature and Rainfall Variability in Semi-Arid Regions

5.1 Background and climatic characteristics

A useful published example comes from semi-arid Ethiopia, where sorghum is central to rainfed livelihoods and climate variability is already strongly visible in farm outcomes. In Babile district, eastern Ethiopia, the agro-climatic setting is semi-arid, the growing period is relatively short, rainfall is bimodal and highly erratic, and long-term average annual rainfall is about 731 mm. The area's rainfall pattern includes Belg rainfall from March to May and Kiremt rainfall from June to September, but what matters agronomically is not that there are two rainy windows; it is that their reliability is low and their intra-seasonal distribution is unstable. Published work from Kobo, Miesso, and Melkassa extends the same logic across semi-arid Ethiopia: these areas differ in rainfall response, baseline temperatures, and future vulnerability, but they share a dependence on rainfed sorghum under high interannual variability. This makes them ideal for examining how temperature and rainfall signals are translated into yield through empirical and simulation methods (Tolosa et al., 2023; Gardi et al., 2025; Ali and Kothari, 2026).

5.2 Effects of temperature variability on yield

In Babile, observed sorghum yield showed a negative relationship with both maximum and minimum temperatures during the crop-growing period, and specific monthly temperature variability explained part of the year-to-year yield fluctuation. The logic is biologically plausible: warmer conditions can accelerate development, intensify evapotranspiration, and raise the probability that reproductive processes occur under suboptimal moisture. The more recent Ethiopia modeling study reinforces this concern in forward-looking terms. Using DSSAT-CERES-Sorghum, Gardi (2025) et al. projected warming of up to about 4°C by the 2080s in semi-arid Ethiopian sites and identified Kobo as especially vulnerable where higher temperatures and reduced rainfall coincide. Taken together, the observational and simulation evidence suggests that temperature is not merely a background variable in semi-arid sorghum systems. It is an active driver of phenological compression and water-stress escalation (Tolosa et al., 2023; Gardi et al., 2025).

5.3 Effects of rainfall variability on yield

Rainfall variability in the same case-study region appears even more nuanced. In Babile, monthly rainfall and number of rainy days during the growing season were positively correlated with sorghum yield, and rainfall in August and September was more informative than crude seasonal totals. This suggests that late-season water availability supports reproductive success and grain development in that environment. Yet rainfall does not work as a simple "more is better" factor. The Zimbabwe meta-analysis on rainwater harvesting found that some adaptation practices produced neutral or even negative yield responses under specific rainfall bands and soil conditions, showing that poor alignment between technology and rainfall environment can undermine expected benefits. The lesson from these dryland case studies is that rainfall variability must be modeled at a finer temporal scale than annual or even seasonal totals. Temporal sequencing matters (Kubiku et al., 2022; Tolosa et al., 2023).

5.4 Application of yield prediction models

The case-study literature from semi-arid Ethiopia shows how different model families answer different questions. Multiple regression in Babile captured historical climate-yield relationships with useful explanatory power and highlighted specific months and rainy-day patterns. DSSAT-based regional modeling then extended the analysis into future climate scenarios, allowing more explicit testing of varietal differences and long-term adaptation options. Related APSIM work in Ethiopian drylands has gone further by examining genotype × environment × management interactions and sowing-risk trade-offs, while APSIM-based environment characterization in Mali identified drought-pattern frequencies rather than only mean conditions. This layered use of models is perhaps the most interesting lesson of the case study. Researchers did not move from a “simple bad model” to a “complex good model.” They used simpler models to identify local signal and more mechanistic models to ask why the signal occurs and how it may change (Tirfessa et al., 2023; Tolosa et al., 2023; Diancoumba et al., 2024; Gardi et al., 2025).

5.5 Implications for climate adaptation and crop management

For adaptation, the published case evidence points to a clear but unspectacular conclusion: stability comes from better matching crop duration, sowing time, and water availability. In practical terms, this means cultivar choice matters, planting-date adjustment matters, and in some settings supplemental irrigation or more targeted moisture conservation may matter. It also means region-wide recommendations are risky. Even within semi-arid Ethiopia, Miesso is projected to receive larger rainfall increases than Kobo, while Kobo remains more vulnerable to heat and rainfall decline. In other words, the case study argues against generic “dryland sorghum packages” and in favor of locally parameterized decision support. Climate adaptation for sorghum is more likely to succeed when it is built from climate windows, varietal maturity, and site-specific soil-water logic than when it relies on broad labels such as drought tolerant or early maturing alone (Gardi et al., 2025; Ali and Kothari, 2026).

6 Climate Change and Future Sorghum Production

6.1 Projected changes in temperature and rainfall

The climate projections discussed across recent sorghum studies are broadly consistent even when the size of change differs by region. Temperatures are expected to continue rising across major sorghum environments, while rainfall is projected to become more variable in amount, distribution, or both. In semi-arid Ethiopia, simulation studies project warming on the order of about 2.1°C by the 2050s and around 4°C by the 2080s in some locations, with rainfall changes that vary by site rather than moving uniformly upward or downward. Similar work in India suggests that future sorghum responses may depend on whether rainfall increases offset thermal penalties, which again emphasizes that precipitation change cannot be interpreted without temperature and season type. The future climate problem for sorghum is therefore not a single trend line. It is a moving combination of faster development, stronger atmospheric water demand, altered rainy-season reliability, and more frequent extreme events (Chadalavada et al., 2022; Tolosa et al., 2023; Gardi et al., 2025).

6.2 Potential impacts on sorghum yield formation

Future sorghum yield formation is likely to be affected most where warming shifts sensitive reproductive stages into hotter and drier windows. That can reduce grain set before flowering and shorten or weaken grain filling afterward. In North Wollo, Ethiopia, future simulations suggested that rainfed grain sorghum yield would likely decline by roughly 15%-16% in mid-century and 17%-22% in late century relative to the recent baseline. Other studies, however, show that yield declines are not inevitable everywhere. In post-rainy sorghum environments in India, rising rainfall and CO2 in some scenarios were sufficient to offset part of the temperature burden and even generate simulated yield gains. The important point is not that one study is optimistic and another pessimistic. It is that future yield formation depends on how multiple climate drivers alter stage-specific stress exposure, not on warming alone (Chadalavada et al., 2022; Ali and Kothari, 2026).

6.3 Regional differences in climate vulnerability

Regional vulnerability is a recurring theme in the literature. Semi-arid production systems with high rainfall variability, shallow water storage, and low management buffering are typically more exposed than better-resourced systems, but even within dryland sorghum regions vulnerability differs sharply. In the Ethiopian studies reviewed here, Kobo emerged as more vulnerable than Miesso in part because future warming and rainfall deficits align there more strongly with yield loss. In the Great Plains of the United States, modeled stress environments differ between the northeast and southwest sorghum belt, with grain-filling water stress dominating much of the southwest. These differences matter because they also change which traits or practices are worthwhile. A trait that helps under grain-filling drought may add little benefit in a low-stress or pre-flowering-drought environment. Vulnerability, then, is not just regional climate severity. It is the frequency of the specific stress pattern that matches the crop's sensitive stages (Carcedo et al., 2022; Gardi et al., 2025).

6.4 Future yield trends under climate scenarios

The best-supported summary of future yield trends is cautious heterogeneity. Many semi-arid sorghum systems show projected yield declines under warming, especially in rainfed and already heat-prone sites, but some environments show stable or improving simulated yields when rainfall, CO2 fertilization, or adaptation measures offset part of the thermal stress. West African APSIM simulations earlier suggested that medium-maturing material could outperform early-maturing material under some climate scenarios, while more recent Ethiopia studies show strong site and genotype contingency. This variation should not be read as contradiction. It is evidence that future yield trends are conditional on environment, cultivar duration, and management. The practical inference is simple: climate scenarios should be used to identify likely stress profiles and adaptation niches, not to produce one global verdict on sorghum (Gardi et al., 2025; Ali and Kothari, 2026).

7 Strategies for Improving Yield Stability and Prediction Accuracy

7.1 Development of climate-resilient cultivars

The breeding literature makes clear that climate-resilient sorghum will not come from one "super trait." Useful improvement will likely require trait combinations that align with the dominant stress pattern of target environments. These include reproductive heat tolerance, stable grain filling under water limitation, appropriate maturity duration, root-system traits, and physiological behaviors such as stay-green or limited transpiration in certain environments. Recent reviews on sorghum improvement emphasize that breeding progress will depend not only on identifying tolerant germplasm, but on linking physiological insight, quantitative genetics, and realistic target environments. Modeling can help here by testing the expected value of candidate traits before they are expensive to phenotype or introgress widely. In that sense, crop models do not replace breeding; they improve trait prioritization (Mwamahonje et al., 2024; Raymundo et al., 2024; Fontanet-Manzaneque et al., 2025).

7.2 Agronomic management practices

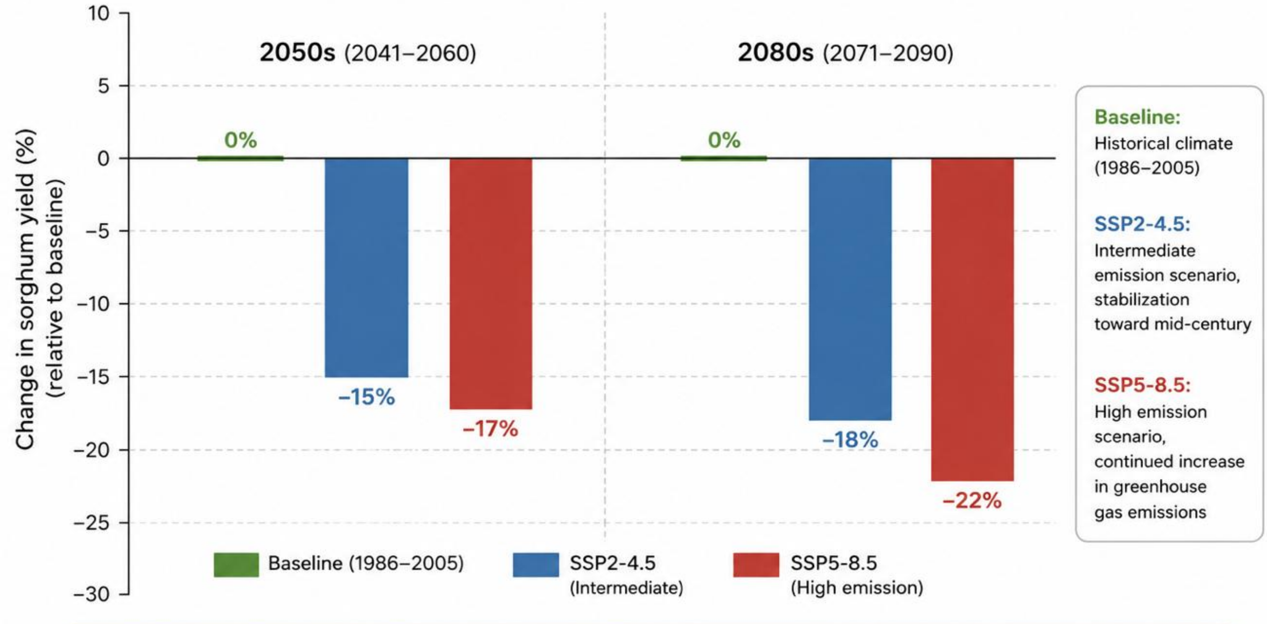
Agronomy remains the fastest route to stabilizing sorghum yield under climate variability because it can reposition the crop relative to stress without waiting for long breeding cycles. Sowing date is consistently important, especially in environments where early or delayed planting can help flowering avoid peak heat or terminal drought. Soil-water conservation, improved fertility, and context-appropriate irrigation also matter, but their value depends heavily on local rainfall regime and soil properties. The literature on rainwater-harvesting and deficit-irrigation modeling shows that management gains are not automatic: a practice that works in one rainfall band or soil class may fail in another. The most defensible management strategy is therefore adaptive rather than prescriptive. It should be based on dominant local stress patterns, cultivar duration, and short-term seasonal expectations (Kubiku et al., 2022; Fazel et al., 2023; Ali and Kothari, 2026).

7.3 Integration of climate information and decision support systems

A recurring gap in sorghum production is not the absence of climate data, but the weak translation of climate knowledge into field decisions. Decision-support systems can close that gap by combining weather history, seasonal outlooks, crop-model outputs, and local management rules. For sorghum, that might include sowing-window advisories, cultivar-duration matching, drought-risk maps, or irrigation scheduling. The strength of such systems is greatest when they integrate climate information with biologically meaningful crop thresholds rather than simply reporting rainfall probabilities. The broader crop-modeling literature also shows that operational systems become more valuable when they are iterative: they begin with pre-season planning, then absorb in-season observations from weather and remote sensing to update expected yield and risk. For dryland sorghum systems facing increasing climate variability, this kind of staged decision support may matter as much as any single new trait. (Jabed and Murad, 2024; Mihret et al., 2024).

7.4 Improving Yield Modeling Through Emerging Technologies

The next step in sorghum yield modeling is not simply "more AI." It is better integration across scales. Emerging work already points in that direction: UAV and satellite remote sensing add frequent canopy observations, machine learning improves pattern detection, and process-based models provide biological structure. Phenotyping, explainable AI, and genotype-aware modeling can make this integration more useful rather than merely more complex. Particularly promising are hybrid frameworks in which a crop model provides stage structure and water-balance logic, while data-driven methods update parameters or correct prediction error using contemporary observations. This may be the most realistic way to improve sorghum yield prediction under rapidly changing climates, because it preserves interpretability while benefiting from rich data streams. The most valuable future systems will likely be those that can explain why a yield prediction changed, not only produce a more accurate number (Figure 3) (Jabed and Murad, 2024; Deng et al., 2025; Karongo et al., 2025).



- Sorghum yield is projected to decline under future warming scenarios.
- Yield reduction is greater under the high emission scenario (SSP5-8.5) than under the intermediate scenario (SSP2-4.5).
- By the 2080s, yield losses are projected to reach about 18% under SSP2-4.5 and 22% under SSP5-8.5.

Source: Adapted from Ali & Kothari (2026). *Impacts of climate change on sorghum production: A global meta-analysis. Agricultural Systems, 198, 103367.*

Figure 3 Integrated framework for next-generation sorghum yield prediction

8 Conclusions and Future Perspectives

This study argues that sorghum yield formation cannot be understood, or modeled well, by treating temperature and rainfall as broad background variables. Their impact depends on developmental timing, stress duration, and interaction. Temperature drives phenology and can damage reproduction directly, while rainfall determines whether the crop can sustain the physiological processes that support grain set and grain filling. Reproductive-stage heat, post-flowering drought, and poorly distributed rainfall are repeatedly identified as the most consequential threats to stable yield. At the modeling level, empirical, process-based, remote-sensing, and machine-learning approaches all contribute something important, but their real value is highest when they are combined rather than isolated.

Several gaps remain. First, many studies still rely on seasonal climate summaries that are too coarse to represent the biological reality of stage-specific stress. Second, genotype differences are often acknowledged but insufficiently parameterized in operational models. Third, interactions among heat, drought, soil constraints, and excess rainfall remain under-modeled in many sorghum systems. Fourth, strong local case studies exist, but transferability across regions is still limited. Finally, predictive accuracy is improving faster than interpretability in some data-driven studies, which risks producing models that are useful technically but harder to trust agronomically.

Future work should move toward integrated sorghum modeling systems that connect phenology, plant physiology, remote sensing, and climate analytics in the same framework. More attention is needed on stress timing around flowering and grain filling, on genotype-specific calibration of water-use and heat-response traits, and on decision tools that translate model output into locally actionable advice. For both researchers and practitioners, the most productive perspective may be to treat sorghum neither as a miracle crop nor as a victim crop, but as a biologically understandable crop whose yield can be better stabilized when climate signals are interpreted through the lens of development, physiology, and carefully chosen models.

Acknowledgments

I am deeply grateful to Professor R. Cai for his multiple reviews of this paper and for his constructive revision suggestions.

References

Adotey R.E., Patrignani A., Bergkamp B., Kluitenberg G., Prasad P.V.V., and Jagadish S.V.K., 2021, Water-deficit stress alters intra-panicle grain number in sorghum, Crop Science, 61(4): 2680-2695.
https://doi.org/10.1002/csc2.20532

Ali K.H., and Kothari K., 2026, Assessing future climate change impacts and adaptation strategies for sorghum yield in North Wollo, Ethiopia, Theoretical and Applied Climatology, 157(1): 36.
https://doi.org/10.1007/s00704-025-05986-y

Al-Salman Y., Cano F.J., Mace E., Jordan D., Groszmann M., and Ghannoum O., 2024, High water use efficiency due to maintenance of photosynthetic capacity in sorghum under water stress, Journal of Experimental Botany, 75(21): 6778-6795.
https://doi.org/10.1093/jxb/erae418

Baye W., Xie Q., and Xie P., 2022, Genetic architecture of grain yield-related traits in sorghum and maize, International Journal of Molecular Sciences, 23(5): 2405.
https://doi.org/10.3390/ijms23052405

Carcedo A.J.P., Mayor L., Demarco P., Morris G.P., Lingenfelser J., Messina C.D., and Ciampitti I.A., 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

Chadalavada K., Gummadi S., Kundeti R.K., Kadiyala D.M., Deevi K.C., Dakhore K.K., Diana R.K.B., and Thiruppathi S.K., 2022, Simulating potential impacts of future climate change on post-rainy season sorghum in India using CERES-Sorghum model, Sustainability, 14(1): 334.
https://doi.org/10.3390/su14010334

Deng L.Q., Li Y.Y., Liu X.F., Zhang Z.M., Mu J.J., Jia S.J., Yan Y.Q., and Zhang W.P., 2025, Sorghum yield prediction using UAV multispectral imaging and stacking ensemble learning in arid regions, Frontiers in Plant Science, 16: 1636015.
https://doi.org/10.3389/fpls.2025.1636015

Diancoumba M., Kholová J., Adam M., Famanta M., Clerget B., Traore P.C.S., Weltzien E., Vacksmann M., McLean G., Hammer G.L., van Oosterom E.J., and Vadez V., 2024, APSIM-based modeling approach to understand sorghum production environments in Mali, Agronomy for Sustainable Development, 44(3): 25.
https://doi.org/10.1007/s13593-023-00909-5

Fazel F., Ansari H., and Aguilar J., 2023, Determination of the most efficient forage sorghum irrigation scheduling strategies in the U.S. Central High Plains using the AquaCrop model and field experiments, Agronomy, 13(10): 2446.
https://doi.org/10.3390/agronomy13102446

Ferraz M.A.J., Barboza T.O.C., Piza M.R., Von Pinho R.G., and dos Santos A.F., 2024, Sorghum grain yield estimation based on multispectral images and neural network in tropical environments, Smart Agricultural Technology, 9: 100661.
https://doi.org/10.1016/j.atech.2024.100661

Fontanet-Manzaneque J.B., Hernández D.M., Giordano A., and Caño-Delgado A.I., 2025, Sorghum as a monocot model for drought research, Frontiers in Plant Science, 16: 1665967.
https://doi.org/10.3389/fpls.2025.1665967

Gardi M.W., Zewdu E., and Sida T.S., 2025, Modeling sorghum yield response to climate change in the semi-arid environment of Ethiopia, Journal of Agriculture and Food Research, 22: 102143.
https://doi.org/10.1016/j.jafr.2025.102143

Holzworth D.P., Huth N.I., deVoil P.G., Zurcher E.J., Herrmann N.I., McLean G., Chenu K., van Oosterom E.J., Snow V., Murphy C., Moore A.D., Brown H., Whish J.P.M., Verrall S., Fainges J., Bell L.W., Peake A.S., Poulton P.L., Hochman Z., Thorburn P.J., Gaydon D.S., Dalgliesh N.P., Rodriguez D., Cox H., Chapman S., Doherty A., Teixeira E., Sharp J., Cichota R., Vogeler I., Li F.Y., Wang E., Hammer G.L., Robertson M.J., Dimes J.P., Whitbread A.M., Hunt J., van Rees H., McClelland T., Carberry P.S., Hargreaves J.N.G., MacLeod N., McDonald C., Harsdorf J., Wedgwood S., and Keating B.A., 2014, APSIM-Evolution towards a new generation of agricultural systems simulation, Environmental Modelling & Software, 62: 327-350.
https://doi.org/10.1016/j.envsoft.2014.07.009

Hossain M.S., Islam M.N., Rahman M.M., Mostofa M.G., and Rahman Khan M.A., 2022, Sorghum: A prospective crop for climatic vulnerability, food and nutritional security, Journal of Agriculture and Food Research, 8: 100300.
https://doi.org/10.1016/j.jafr.2022.100300

Jabed M.A., and Murad M.A.A., 2024, Crop yield prediction in agriculture: A comprehensive review of machine learning and deep learning approaches, with insights for future research and sustainability, Heliyon, 10(24): e40836.
https://doi.org/10.1016/j.heliyon.2024.e40836

Jones J.W., Hoogenboom G., Porter C.H., Boote K.J., Batchelor W.D., Hunt L.A., Wilkens P.W., Singh U., Gijsman A.J., and Ritchie J.T., 2003, The DSSAT cropping system model, European Journal of Agronomy, 18(3-4): 235-265.
https://doi.org/10.1016/S1161-0301(02)00107-7

Karongo J., Mwaniki J.I., Ndiritu J., and Mokaya V., 2025, Sorghum yield prediction based on remote sensing and machine learning in conflict affected South Sudan, Scientific Reports, 15(1): 4469.
https://doi.org/10.1038/s41598-025-89030-z

Kubiku F.N.M., Mandumbu R., Nyamangara J., and Nyamadzawo G., 2022, Sorghum (Sorghum bicolor L.) yield response to rainwater harvesting practices in the semi-arid farming environments of Zimbabwe: A meta-analysis, Heliyon, 8(3): e09164.
https://doi.org/10.1016/j.heliyon.2022.e09164

Kumar S.R., Hammer G.L., Broad I.J., Harland P., and McLean G., 2009, Modelling environmental effects on phenology and canopy development of diverse sorghum genotypes, Field Crops Research, 111(1-2): 157-165.
https://doi.org/10.1016/j.fcr.2008.11.010

Liaqat W., Altaf M.T., Barutçular C., Mohamed H.I., Ahmad H., Jan M.F., and Khan E.H., 2024, Sorghum: A star crop to combat abiotic stresses, food insecurity, and hunger under a changing climate: A review, Journal of Soil Science and Plant Nutrition, 24(1): 74-101.
https://doi.org/10.1007/s42729-023-01607-7

Mihret Y.C., Ketsela G.M., and Mintesinot S.M., 2024, Implementation and application of APSIM for crop modelling in Ethiopia: A comprehensive review, Heliyon, 10(10): e31612.
https://doi.org/10.1016/j.heliyon.2024.e31612

Mwamahonje A., Mdindikasi Z., Mchau D., Mwenda E., Sanga D., Garcia-Oliveira A.L., and Ojiewo C.O., 2024, Advances in sorghum improvement for climate resilience in the global arid and semi-arid tropics: A review, Agronomy, 14(12): 3025.
https://doi.org/10.3390/agronomy14123025

Ndlovu E., van Staden J., and Maphosa M., 2021, Morpho-physiological effects of moisture, heat and combined stresses on Sorghum bicolor [Moench (L.)] and its acclimation mechanisms, Plant Stress, 2: 100018.
https://doi.org/10.1016/j.stress.2021.100018

Otwani D., McLean G., Hammer G., Cruickshank A., Hunt C., Tao Y., Koltunow A., Mace E., and Jordan D., 2025, Extended grain filling has potential to improve yield in grain sorghum, Journal of Experimental Botany, 76(10): 2763-2774.
https://doi.org/10.1093/jxb/eraf117

Prasad P.V.V., Djanaguiraman M., Perumal R., and Ciampitti I.A., 2015, Impact of high temperature stress on floret fertility and individual grain weight of grain sorghum: Sensitive stages and thresholds for temperature and duration, Frontiers in Plant Science, 6: 820.
https://doi.org/10.3389/fpls.2015.00820

Prasad V.B.R., Govindaraj M., Djanaguiraman M., Djalovic I., Shailani A., Rawat N., Singla-Pareek S.L., Pareek A., and Prasad P.V.V., 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

Raymundo R., McLean G., Sexton-Bowser S., Lipka A.E., and Morris G.P., 2024, Crop modeling suggests limited transpiration would increase yield of sorghum across drought-prone regions of the United States, Frontiers in Plant Science, 14: 1283339.
https://doi.org/10.3389/fpls.2023.1283339

Smith A., Gentile B.R., Xin Z., and Zhao D., 2023, The effects of heat stress on male reproduction and tillering in Sorghum bicolor, Food and Energy Security, 12(6): e510.
https://doi.org/10.1002/fes3.510

Tirfessa A., Getachew F., McLean G., van Oosterom E., Jordan D., and Hammer G., 2023, Modeling adaptation of sorghum in Ethiopia with APSIM-opportunities with G×E×M, Agronomy for Sustainable Development, 43(1): 15.
https://doi.org/10.1007/s13593-023-00869-w

Tolosa A.A., Dadi D.K., Mirkena L.W., Erena Z.B., and Liban F.M., 2023, Impacts of climate variability and change on sorghum crop yield in the Babile district of eastern Ethiopia, Climate, 11(5): 99.
https://doi.org/10.3390/cli11050099

Zhang R.D., Yue Z.X., Chen X.F., Huang R.D., Zhou Y.F., and Cao X., 2023, Effects of waterlogging at different growth stages on the photosynthetic characteristics and grain yield of sorghum (Sorghum bicolor L.), Scientific Reports, 13(1): 7212.
https://doi.org/10.1038/s41598-023-32478-8