

UNDERSTANDING SORGHUM WATER USE TO CONTRASTED IRRIGATION REGIMES UNDER CONTROLLED FIELD CONDITIONS

COMPRENDRE L'UTILISATION DE L'EAU PAR LE SORGHO SOUMIS À DES RÉGIMES D'IRRIGATION CONTRASTÉS EN CONDITIONS CONTRÔLÉES AU CHAMP

Larsonneau Pierre¹, Gendre Sophie and Moynier Jean-Louis²

ABSTRACT

In the context of climate change characterized by increasing water stress, this study investigates the response of grain sorghum to different water regimes under controlled conditions. A two-year field experiment (2024–2025) conducted under mobile rain shelters compared four irrigation treatments (ETM, 50% of ETM, late-season stress, and rainfed conditions applied to two varieties differing in earliness (Arsky and ES Shamal). Water stress was quantified using the ETa/ETc ratio simulated by the Irrelis model and subsequently related to grain yield, its components, and water use efficiency.

The results show that yield is strongly influenced by water availability, with reductions of up to 45% under rainfed conditions. However, late-season water stress did not result in a significant yield decrease compared to optimal irrigation, unlike early water stress. Yield reductions were mainly associated with a decrease in thousand-kernel weight, while the number of grains remained relatively stable. Water use efficiency values confirm the good adaptation of sorghum, with a decrease in the marginal productivity of water as water inputs increase.

Keywords: Contrasted irrigation regimes; Controlled field conditions; Context of climate change; Water stress; Water availability.

RÉSUMÉ

Dans un contexte de changement climatique caractérisé par une aggravation du stress hydrique, cette étude examine la réponse du sorgho grain à différents régimes hydriques en conditions contrôlées. Une expérimentation au champ menée pendant deux ans (2024-2025) sous des abris mobiles contre la pluie a comparé quatre traitements d'irrigation (ETM, 50 % de l'ETM, stress de fin de cycle et conditions pluviales), appliqués à deux variétés de précocité différente (Arsky et ES Shamal). Le stress hydrique a été quantifié au moyen du rapport ETa/ETc simulé par le modèle Irrelis, puis mis en relation avec le rendement en grains, ses composantes et l'efficacité d'utilisation de l'eau.

Les résultats montrent que le rendement est fortement influencé par la disponibilité en eau, avec des baisses pouvant atteindre 45 % en conditions pluviales. Toutefois, contrairement à un stress hydrique précoce, un stress de fin de cycle n'a pas entraîné de diminution significative du rendement par rapport à une irrigation optimale. Les baisses de rendement étaient principalement liées à une diminution du poids de mille grains, tandis que le nombre de grains restait relativement stable. Les valeurs de l'efficacité d'utilisation de l'eau confirment la bonne adaptation du sorgho, la productivité marginale de l'eau diminuant à mesure que les apports augmentent.

¹ Arvalis, 6 Chemin de la Côté Vieille, 31450 Baziège, France, Email: p.larsonneau@arvalis.fr Arvalis, 6 Chemin de la Côté Vieille, 1450 Baziège, France, email : s.gendre@arvalis.fr

² Arvalis, Domaine expérimental du Magneraud, 17700 Saint-Pierre-d'Amilly, Email : jl.moynier@arvalis.fr

Mots clés : Régimes d'irrigation contrastés; Conditions contrôlées au champ; Contexte de changement climatique; Stress hydrique; Disponibilité en eau.

INTRODUCTION

Climate change in Europe is characterized by an increase in mean temperatures and a shift in the seasonal distribution of precipitation, with a marked decline in summer rainfall. These changes intensify the frequency and severity of water stress during the growing cycle of spring and summer crops, particularly during key yield formation stages. In this context, water management has become a central issue for the sustainability and resilience of cropping systems (European Commission, 2025; Moore & Lobell, 2015).

In response to these constraints, identifying crops capable of maintaining satisfactory production under limited water availability represents an important adaptation strategy. Sorghum (*Sorghum bicolor* L. Moench) is recognized for its relative tolerance to water stress, largely due to physiological traits such as conservative stomatal regulation, deep root exploration, and high water use efficiency (FAO, n.d.; van Oosterom et al., 2021). These characteristics explain the growing interest in this crop in European regions exposed to summer water deficits.

At the global scale, a recent meta-analysis by Mbava et al. (2020), based on more than 500 studies, highlights the high variability of water use efficiency (WUE) depending on climatic and agronomic conditions. Nevertheless, this synthesis shows that sorghum ranks among the crops with the highest average WUE values ($25.2 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{mm}^{-1}$) and emphasizes that its efficiency tends to be particularly high under water-limited conditions. However, this approach relies on data derived from independent experiments and does not allow for a detailed analysis of the effects of stress intensity and timing during the crop cycle. In Europe, experimental studies on grain sorghum remain relatively scarce. Available research, particularly under Mediterranean conditions, indicates that sorghum is able to better maintain its yield and water use efficiency than other summer crops as water availability decreases (Farré & Faci, 2006). However, these studies are often dated, conducted under climatic conditions that differ from current European environments, and only partially characterize the intra-seasonal dynamics of water stress and their relationship with integrated indicators such as the ratio between actual and maximum evapotranspiration (E_t/E_{Tc}).

In this context, the impacts of water stress on grain sorghum, and particularly the combined effects of its intensity and timing, remain insufficiently documented under European conditions. A better understanding of these relationships is essential for optimizing sorghum irrigation management and improving its integration into cropping systems facing increasing water scarcity.

The objective of this study is therefore to characterize the response of grain sorghum to different levels and dynamics of water stress under controlled experimental conditions, over two years and for two varieties differing in maturity. More specifically, the study aims to analyze the impact of water stress on yield and its main components, to establish the relationship between yield and integrated water stress (E_t/E_{Tc}), and to evaluate water use efficiency and irrigation water use efficiency across the different irrigation treatments. The results are intended to provide scientific insights to support the adaptation of irrigation strategies and cropping systems under climate change conditions.

MATERIALS AND METHODS

To address these questions, an experiment was conducted at the Magneraud experimental station (Charente Maritime-France), using a mobile rain shelter system. This system consists of movable shelters that can be deployed over the crop during rainfall events, allowing precipitation to be excluded and simulating controlled low-rainfall conditions, thereby inducing water stress when desired.

The experiment was carried out over two consecutive years (2024–2025). Two varieties representative of those cultivated in the study region, differing in maturity, were sown: Arsky (very

early) and ES Shamal (early). Each variety was grown under a separate mobile shelter; therefore, comparisons among irrigation treatments were performed independently for each variety.

Four irrigation treatments were implemented to assess the impact of water stress on sorghum:

- **T1 ETM (Full irrigation):** irrigation aimed at meeting 100% of crop water requirements. ETM refers to maximum evapotranspiration, corresponding to evapotranspiration under optimal water conditions.
- **T2 ETM50:** irrigation was applied at the same timing as T1, but with volumes reduced by approximately 50% at each irrigation event.
- **T3 Late Stress:** irrigation was applied at the same frequency and volumes as T1 until the heading stage (BBCH 55–59), after which irrigation was reduced to match that of T4.
- **T4 Rainfed:** irrigation was limited to simulate a low rainfall year (second decile of precipitation over the past 20 years), corresponding to 15 mm per month from the deployment of the rain shelters.
- The experimental design consisted of three blocks per shelter, within which the irrigation treatments were randomized. All treatments received the same fertilization in order to avoid nutrient deficiencies, particularly nitrogen, as a limiting factor for yield.

The nitrogen nutrition index (NNI) was calculated for the 2025 season only (due to lack of data in 2024) to verify the absence of nitrogen limitation. In the absence of a validated reference for sorghum, the critical nitrogen dilution curve developed for maize (Plénet & Lemaire, 2000) was used:

$$INN = \frac{\%N}{\%N_c} \quad (1)$$

$$\%N_c = 3.4 \times DM^{-0.37} \quad (2)$$

where DM is the aboveground dry matter (t·ha⁻¹). Grain yield and its main components (thousand-kernel weight -TKW-, number of grains per panicle, panicle density, and grain moisture at harvest) were measured for each treatment and block. Each microplot was equipped with an access tube to measure soil water content using a neutron probe (Evelt et al., 2008). Measurements were performed at sowing, around heading, and at harvest. Crop water consumption between two dates was calculated using a soil water balance approach:

$$Water\ consumption = Rainfall + Irrigation - Drainage - Runoff - \Delta(Soil\ Water) \quad (3)$$

Based on these measurements, water use efficiency (WUE) was calculated for each treatment:

$$WUE = \frac{Yield}{Water\ consumption} \quad (4)$$

(kg·ha⁻¹·mm⁻¹) This was compared with irrigation water use efficiency (iWUE), defined as:

$$iWUE = \frac{Yield_{irrigated} - Yield_{rainfed}}{Irrigation} \quad (5)$$

A daily soil water balance was also simulated using the Irrelis model (Gendré, 2020), integrating climatic data, soil water storage dynamics, and phenological development. This model provided daily estimates of actual evapotranspiration (ETa) and crop evapotranspiration under non-limiting conditions (ETc). The ETa/ETc ratio was calculated over different BBCH-defined growth periods, allowing quantification of water stress dynamics. These indicators were used to analyze the relationships between cumulative water stress and yield.

Statistical analyses were performed using R (version 4.4.2.). ANOVA tests ($\alpha = 0.05$) were conducted to assess the effect of irrigation treatments on yield, its components, and WUE. Tukey's HSD test was used for pairwise comparisons.

RESULTS

Table 1. ETa/ETc ratios simulated by the Irrelis model for each irrigation treatment, variety, year, and phenological period.

Variety Year	Modality	ETa/ETc 10-leaf stage – Booting	ETa/ETc Booting – Heading	ETa/ETc Heading – Maturity	ETa/ETc 10-leaf stage – Maturity
Arsky 2024	T1-ETM	1	1	0.52	0.67
	T2-ETM 50	0.94	0.71	0.37	0.53
	T3-Late stress	1	0.97	0.38	0.58
	T4-Rainfed	0.77	0.64	0.29	0.43
Es Shamal 2024	T1-ETM	0.99	0.85	0.56	0.70
	T2-ETM 50	0.84	0.52	0.41	0.53
	T3-Late stress	0.97	0.83	0.33	0.54
	T4-Rainfed	0.66	0.49	0.28	0.40
Arsky 2025	T1-ETM	0.87	0.99	0.81	0.84
	T2-ETM 50	0.83	0.72	0.52	0.61
	T3-Late stress	0.87	0.99	0.68	0.68
	T4-Rainfed	0.67	0.38	0.28	0.37
Es Shamal 2025	T1-ETM	0.83	0.98	0.79	0.82
	T2-ETM 50	0.74	0.68	0.52	0.59
	T3-Late stress	0.83	0.98	0.54	0.66
	T4-Rainfed	0.57	0.33	0.29	0.35

Table 1 presents the ETa/ETc ratios simulated by the Irrelis model for each irrigation treatment, variety, year, and phenological period.

Across all situations, ETa/ETc values were below 1 during at least one part of the crop cycle, indicating that all treatments—including T1—were subjected to some degree of water stress. Therefore, no strictly non-stressed condition could be used as a reference, and comparisons are based on differences in stress intensity and dynamics.

The lowest ETa/ETc values were consistently observed for the Rainfed treatment (T4), reflecting sustained and severe water stress throughout the growing season. In contrast, T1 generally showed the highest ETa/ETc values, although stress occurred during the late stages in some cases, particularly in 2024. The ETM50 (T2) and Late Stress (T3) treatments exhibited similar integrated ETa/ETc values over the entire cycle (10-leaf stage to maturity). However, their temporal distribution differed markedly: T2 experienced earlier and more continuous stress, whereas T3 maintained ETa/ETc values close to 1 before heading, followed by significant stress during the grain-filling period (BBCH 71–89). These patterns were consistent across both years and varieties, although overall stress intensity was lower in 2025.

Table 2. Grain yield and main yield components according to treatment, year, and variety. Different letters indicate statistically significant differences within the same variety and year.

Variety Year	Modality	Yield (q·ha ⁻¹)	TKW (g)	Number of grains per panicle	Grain moisture at harvest
Arsky 2024	T1-ETM	80.2 (a)	26.1 (a)	1220.9 (a)	18.9 (a)
	T2-ETM 50	70.1 (ab)	23.8 (ab)	1198.1 (a)	18.4 (a)
	T3-Late stress	73.6 (a)	24.4 (ab)	1233.9 (a)	18.8 (a)
	T4-Rainfed	58.9 (b)	22.9 (b)	1122.7 (a)	18.4 (a)
Es Shamal 2024	T1-ETM	85.0 (a)	24.1 (a)	1341.4 (a)	20.3 (a)
	T2-ETM 50	68.1 (bc)	22.0 (bc)	1248.2 (ab)	19.2 (bc)
	T3-Late stress	72.6 (ab)	23.0 (ab)	1203.4 (ab)	19.5 (b)
	T4-Rainfed	57.2 (c)	20.9 (c)	1127.1 (b)	18.8 (c)
Arsky 2025	T1-ETM	84.0 (a)	27.7 (a)	1218.8 (ab)	17.8 (a)
	T2-ETM 50	71.5 (b)	26.0 (a)	1213.8 (ab)	16.7 (a)
	T3-Late stress	77.8 (ab)	25.9 (a)	1287.5 (a)	17.7 (a)
	T4-Rainfed	48.0 (c)	22.7 (b)	978.6 (b)	15.3 (a)
Es Shamal 2025	T1-ETM	96.1 (a)	27.9 (a)	1277.2 (a)	20.5 (a)
	T2-ETM 50	82.8 (a)	25.6 (b)	1319.7 (a)	18.8 (a)
	T3-Late stress	86.8 (a)	26.0 (ab)	1306.6 (a)	19.1 (a)
	T4-Rainfed	56.2 (b)	21.5 (c)	1165.4 (a)	16.6 (b)

Table 2 presents grain yield and its main components for each irrigation treatment, year, and variety. Yield was significantly affected by irrigation treatment in all cases.

The highest yields were observed for T1 and T3, with no significant differences between these two treatments regardless of year or variety. T2 showed intermediate yields, often significantly lower than T1 but generally not different from T3. In contrast, the Rainfed treatment (T4) consistently exhibited the lowest yields, with reductions ranging from approximately 25% to 45% compared to T1. These trends were consistent for both varieties, although ES Shamal generally showed higher absolute yields than Arsky, particularly in 2025.

Thousand-kernel weight (TKW) was moderately affected by water stress. No significant differences were observed among T1, T2, and T3 in most cases, whereas T4 showed significantly lower values, except for Arsky in 2024.

The number of grains per panicle was only weakly affected by irrigation treatments. Significant differences were observed in only two situations: between T1 and T4 for ES Shamal in 2024, and between T3 and T4 for Arsky in 2025. Overall, this component appeared less sensitive to water stress than yield or TKW.

Grain moisture at harvest was not significantly affected by irrigation treatments for Arsky. However, for ES Shamal, significantly lower moisture contents were observed under more severe water stress (T2 and especially T4), with variation depending on the year.

Overall, yield reductions under water stress were primarily associated with decreases in yield and, to a lesser extent, thousand-kernel weight, while the number of grains per panicle remained relatively stable. Treatments T2 and T3, despite similar integrated stress levels, resulted in comparable agronomic responses, in contrast with the Rainfed treatment.

DISCUSSION

To ensure that the differences observed among treatments were primarily attributable to water stress, the nitrogen nutrition index (NNI) was measured at flowering for the 2025 season (Figure 1). NNI values were generally close to 1 for all treatments and both varieties, indicating a satisfactory and non-limiting nitrogen status.

Slightly lower values were observed for treatments T3 and T4 in the Arsky variety. However, treatment T3 showed no significant differences in yield or yield components compared to T1. These results suggest that the observed differences among treatments cannot be attributed to nitrogen limitation, and that water stress was the main factor explaining the agronomic responses.

The combined analysis of ETa/ETc ratios (Table 1) and agronomic performance (Table 2) highlights clear differences in sorghum response depending on the timing of water stress, despite comparable levels of integrated stress. Although yield differences between treatments T1 and T3 ranged from 7 to 13 $q \cdot ha^{-1}$ depending on the situation, these differences were never statistically significant. This stability suggests that late-season water stress, occurring mainly after heading (BBCH 59), has only a limited impact on final sorghum yield.

In contrast, yield differences between treatments T1 and T2 were significant in approximately half of the situations studied, whereas no significant differences were observed between T2 and T3. These results indicate that early but moderate water stress, occurring during vegetative and early reproductive stages, is more detrimental to yield than stress of similar intensity occurring later in the crop cycle.

The analysis of yield components provides further insight into the mechanisms underlying these responses. Thousand-kernel weight (TKW) showed a pattern similar to that of yield, with a progressive decrease as water stress intensity increased. This component therefore appears to be a major driver of yield reductions under water stress conditions.

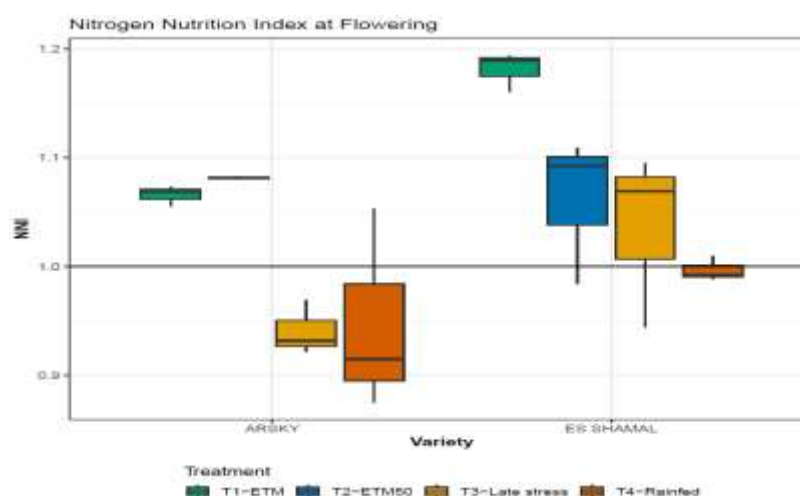


Figure 1. Nitrogen nutrition index calculated at flowering, 2025

In contrast, the number of grains per panicle was only weakly affected by irrigation treatments, except under severe stress (T4). This relative stability suggests that, under the conditions of this study, sorghum does not exhibit substantial grain abortion in response to moderate water stress, unlike what is commonly observed in maize.

These results confirm the ability of sorghum to maintain its grain set potential under water-limited conditions, with yield reductions primarily linked to reduced grain filling efficiency.

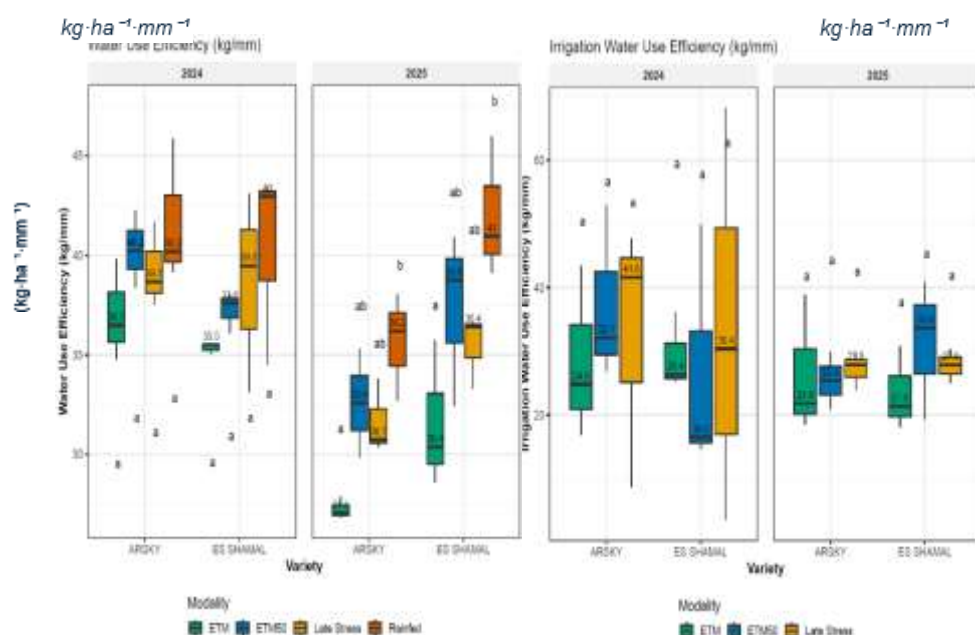


Figure 2. Water use efficiency and Irrigation water use efficiency for both years and both variety, in ($\text{kg} \cdot \text{ha}^{-1} \cdot \text{mm}^{-1}$)

Water use efficiency (WUE) and **irrigation water use efficiency (IWUE)** were calculated at the microplot scale. The absence of significant differences among treatments T1, T2, and T3 for both indicators suggests that moderate or late reductions in water supply do not strongly affect overall crop water use efficiency.

In 2025, the Rainfed treatment (T4) exhibited significantly higher WUE than T1 for both varieties. This result reflects a classical effect of yield concentration per unit of water consumed under strongly limiting conditions, without being associated with high absolute yield levels.

Observed WUE values ranged from 27 to 43 $\text{kg} \cdot \text{ha}^{-1} \cdot \text{mm}^{-1}$, while IWUE values ranged from 16 to 41 $\text{kg} \cdot \text{ha}^{-1} \cdot \text{mm}^{-1}$. These values are higher than the average reported by Mbava et al. (2020), indicating good water productivity under the studied climatic conditions. Irrigation water use efficiency was consistently lower than total WUE for a given treatment, indicating that the last millimeters of water applied or consumed are less efficiently used than the first ones. These results suggest that the marginal productivity of water decreases as water inputs increase, in agreement with previous findings for these species (Djaman & Irmak, 2012).

The relationship between yield and TKW with ETa/ETc ratios reveals a relatively strong linear relationship between integrated water stress and agronomic performance. The strongest relationship was observed when ETa/ETc was calculated over the entire crop cycle (10-leaf stage to maturity), with high coefficients of determination for yield ($R^2 = 0.84$ for Arsky and 0.81 for ES Shamal) and for TKW ($R^2 = 0.76$ for both varieties).

However, the range of observed ETa/ETc values remained limited, with a maximum of approximately 0.84. Therefore, it is not possible, based on the available data, to determine whether this linear relationship remains valid beyond this threshold. It is plausible that the response of yield to water stress may level off or become non-linear under conditions of very low stress, where physiological

processes are only weakly affected. Additional experiments including less water-limited conditions would be required to confirm or refute this hypothesis.

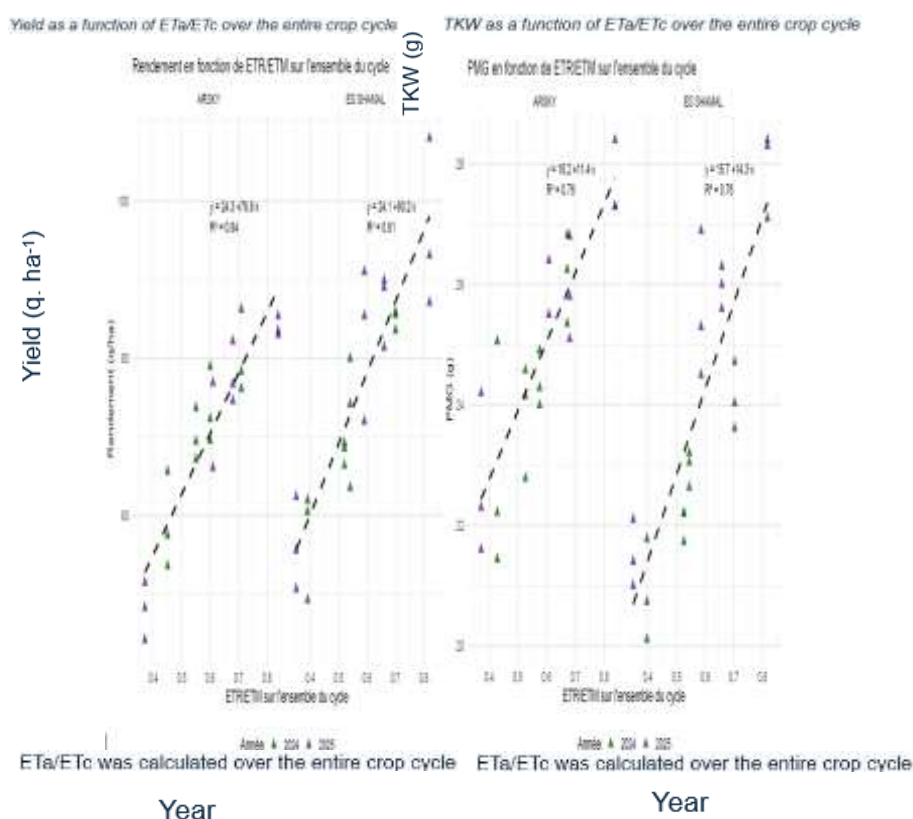


Figure 3. Relations between Yield and ETa/ETc ratios and between TKW and ETa/ETc ratios

CONCLUSION

This study highlights the capacity of sorghum to maintain its agronomic performance under different water stress dynamics, based on a two-year controlled experimental study. The results show that, under moderate to severe water stress conditions, yield response is primarily driven by a reduction in grain weight, while the number of grains per panicle remains relatively stable, except under very severe stress. This relative insensitivity of grain number to water deficit suggests that sorghum has a strong ability to preserve its grain set potential, with yield losses mainly associated with reduced grain filling efficiency.

In addition, the analysis of water use efficiency indicators reveals a decrease in the marginal productivity of water as water consumption increases. Irrigation water use efficiency is consistently lower than overall water use efficiency, indicating that the last millimeters of water applied or consumed contribute less to yield than the first ones. This finding highlights the relevance of irrigation strategies aimed at securing water supply during key growth stages, rather than systematically meeting maximum crop water requirements.

By combining the analysis of integrated water stress (ETa/ETc), yield, and its components, this study confirms that sorghum is particularly well adapted to environments with limited water availability. It also shows that a rational irrigation management, allowing for moderate or late-season water stress, can limit yield losses while optimizing water use. These results provide useful insights for guiding sorghum irrigation strategies under increasing water scarcity in agriculture.

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