

Resilience of *sorghum* hybrids to planting date under rainfed conditions in Southern Dobrogea (Romania): implications for climate-resilient agriculture

Traian Ciprian Stroe^{1,2*} , Lonie Andres Balaban² and Liliana Panaitescu^{1,2} 

¹ University of Agronomic Sciences and Veterinary Medicine of Bucharest, 59 Marasti Blvd, District 1, Bucharest, Romania

² Ovidius University of Constanța, University Alley, Campus building B, 900470, Constanța, Romania

*Correspondence: str_ciprian@yahoo.com; Tel.: 0040745225661 (S.T.C.)

Keywords: *sorghum*; planting date; drought resilience; rainfed agriculture; agroecosystem resilience; climate change; sustainable agriculture.

Abstract: Climate change and increasing drought frequency represent major challenges for agricultural systems in semi-arid regions of Southeastern Europe. In this context, identifying resilient crops capable of maintaining productivity under water-limited conditions is essential for sustainable agriculture. The present study evaluates the agronomic performance and resilience of three grain sorghum hybrids (Willy, Legend and Anggy) cultivated under rainfed conditions in southern Dobrogea (Romania) on cambic chernozem soil during the 2021–2024 period. The experiment investigated the influence of planting date on phenological development, thousand-kernel weight (TKW), plant density and grain yield. Two planting dates were tested (April 4 and May 2), and the results represent multiannual averages over three agricultural years. Early planting ensured balanced vegetative growth, optimal grain moisture at harvest and the highest yields, reaching 5319 kg/ha for the Legend hybrid. Delaying planting by 28 days resulted in an average yield reduction of about 30%, associated with decreases in TKW and final plant density. ANOVA analysis revealed a highly significant effect of planting date ($p \leq 0.001$) and a significant effect of hybrid ($p \leq 0.01$) on yield. A strong correlation between TKW and yield ($r = 0.920$; $R^2 = 0.847$) and between precipitation and yield ($r = 0.872$; $R^2 = 0.760$) highlights the influence of climatic factors on crop performance. The results confirm that sorghum is a climate-resilient crop suitable for sustainable agriculture in arid and semi-arid agroecosystems.

1. Introduction

In the context of global climate change, characterized by increasing temperatures and more frequent drought events, modern agriculture must identify resilient crops capable of efficiently utilizing water resources and maintaining productivity under restrictive pedoclimatic conditions. In arid and semi-arid regions, the adaptation of agricultural systems to climate variability represents a major priority for maintaining food security and the sustainability of agroecosystems. One crop with high adaptive potential is sorghum (*Sorghum bicolor* L. Moench), a cereal species originating from Africa, recognized for its ecological plasticity and high tolerance to drought (Blum, 2004; Tari et al., 2013). Recent research further confirms the importance of this crop for agricultural systems exposed to climate change and highlights its relevance for arid and semi-arid regions worldwide (Gherasim et al., 2024; Mwamahonje et al., 2024).

Sorghum is one of the oldest crops cultivated by humans, having been domesticated approximately 5000 years ago in northeastern regions of Africa (Taylor, 2003; Léder,

2004). Over time, it spread across all continents and became a staple crop in Asia, America, and Europe. Globally, sorghum ranks fifth among cereals of economic importance, after wheat, rice, maize, and barley (Monk et al., 2014; Borrell et al., 2021). Its uses are diverse and include human food, animal feed, bioethanol production, and fiber sources for biodegradable materials (Anglani, 1998; Ramatoulaye et al., 2016). In recent years, interest in sorghum has also increased due to its high nutritional value and the presence of bioactive compounds with antioxidant properties (Angelov et al., 2025). Furthermore, recent studies highlight the potential of sorghum grain in the development of functional foods and gluten-free dietary products (Andronoiu and Nistor, 2025).

Due to its biological and physiological characteristics, sorghum is considered one of the most resilient agricultural crops worldwide. Its capacity to tolerate prolonged drought, high temperatures, and low soil fertility makes it a strategic species for adapting agriculture to climate change (Borrell et al., 2021; Manole et al., 2020). Recent studies also emphasize the role of sorghum in enhancing the resilience of agricultural systems located in climate-vulnerable regions (Gurgu-Lazăr et al., 2024). Owing to its deep root system and high water-use efficiency, sorghum can survive in conditions where other field crops, such as maize, suffer significant yield losses (Oprea et al., 2015; Panaitescu et al., 2016). Experimental studies also reveal genotypic differences in the ability of sorghum to adapt and recover after periods of water stress (Ssebulime et al., 2025).

In Romania, interest in sorghum cultivation has increased over the last two decades due to the intensification of drought events and the need to diversify cropping systems. Research conducted in several regions of the country has confirmed the superior performance of sorghum under water stress conditions (Samuil, 2007; Drăghici, 2007). Additional studies carried out in Moldova and other agricultural areas of Romania have highlighted the stability of sorghum yields and its adaptability to contrasting climatic conditions (Isticioaia et al., 2020). In particular, studies conducted in the Dobrogea region indicate that sorghum may represent a sustainable alternative to maize under current climatic conditions (Panaitescu et al., 2016; Manole et al., 2018). Other research carried out in the same region also confirms the potential of this crop for drought-adapted agriculture (Jinga et al., 2018; Manole et al., 2020).

Climate change projections for Southeastern Europe indicate an increasing frequency of drought events and a growing deficit of soil moisture during the vegetation period. These conditions particularly affect agricultural regions such as Dobrogea and southern Romania, where irrigation infrastructure is limited and crop production relies largely on rainfall. Under such circumstances, traditional crops such as maize often suffer significant yield reductions during dry years. Consequently, sorghum is increasingly considered a viable alternative crop due to its high drought tolerance, efficient water use, and ability to maintain productivity under rainfed conditions (Oprea et al., 2015; Panaitescu et al., 2016). Recent research also highlights the role of sorghum in climate-resilient cropping systems designed for arid and semi-arid environments (Mwamahonje et al., 2024; Gurgu-Lazăr et al., 2024).

At the European level, sorghum cultivation is increasingly regarded as a strategic agricultural solution due to its potential contribution to the bioeconomy and its efficient use of water resources (Berenji and Dahlberg, 2004; Popescu et al., 2018). Recent research also highlights the role of sorghum in the sustainable management of natural resources and in reducing emissions associated with agricultural production (Gurgu-Lazăr et al., 2024). At the same time, the integration of digital technologies in farm management, such as digital twin models, is becoming increasingly important for optimizing crop management and improving the resilience of agricultural systems in climate-vulnerable regions, including Dobrogea (Mihai-Florea et al., 2025).

Climate change projections indicate a continuous increase in temperature and a higher frequency of drought episodes in Southeastern Europe, particularly in regions characterized by limited water availability. In Romania, the southern and southeastern agricultural areas, including Dobrogea and the southern plains, are increasingly affected by prolonged dry periods, reduced precipitation, and higher evapotranspiration rates.

These climatic trends are expected to significantly affect the productivity and stability of traditional crops, especially maize, which requires sufficient soil moisture during critical growth stages. As a consequence, the structure of cropping systems in drought-prone regions is gradually shifting toward more resilient species capable of maintaining productivity under rainfed conditions. Sorghum has emerged as one of the most promising alternatives due to its superior water-use efficiency, deep root system, and physiological mechanisms that allow the plant to tolerate prolonged water deficits (Oprea et al., 2015; Panaitescu et al., 2016). Several recent studies also highlight the growing importance of sorghum in climate-resilient agricultural systems and its potential to replace or complement maize cultivation in semi-arid regions (Mwamahonje et al., 2024; Gurgu-Lazăr et al., 2024). While maize productivity and grain quality are strongly affected by climatic variability and crop management, sorghum may provide a more resilient alternative under water-limited conditions (Stroe et al., 2026; Panaitescu et al., 2026).

The present study aims to evaluate the agronomic performance of three sorghum hybrids (Willy, Legend, and Anggy) cultivated under rainfed conditions with different planting dates in southern Dobrogea (Amzacea locality). Although several studies have investigated the adaptation of sorghum to drought conditions in Romania, limited information is available regarding the interaction between hybrid performance and planting date under the specific climatic conditions of the Dobrogea region. Understanding these relationships is essential for optimizing crop management strategies in areas increasingly affected by climate variability. The main objective of this research is to analyze the influence of planting time on the phenological development, adaptability, and productivity of the tested hybrids under conditions of climatic variability. The obtained results highlight the importance of planting date for maintaining yield stability and confirm the potential of sorghum as a strategic crop for climate-resilient and sustainable agriculture in arid regions of Romania.

2. Materials and Methods

2.1. Study design and experimental conditions

The study was conducted to evaluate the resilience of grain sorghum hybrids (*Sorghum bicolor* L. Moench) in relation to planting date under rainfed conditions in southern Dobrogea, Romania. The experiment was carried out during three consecutive agricultural years (2021–2022, 2022–2023, and 2023–2024). The research focused on assessing the biological adaptability of sorghum to water and thermal stress, the influence of environmental conditions on phenological development and productivity, and the agronomic potential of sorghum as a resilient crop in an agroecosystem increasingly affected by climate variability.

The experimental field is located in Amzacea locality (Constanța County, Romania), at approximately 44°07' N latitude and 28°24' E longitude, at an altitude of about 90 m above sea level. The area belongs to the southern Dobrogea agricultural region, characterized by continental climatic influences and increasing aridity associated with recent climate change trends. The soil type of the experimental field is cambic chernozem, characterized by medium texture, good structure, high permeability, and balanced humus and macronutrient content. The cambic chernozem soil of the experimental site presents a slightly alkaline reaction (pH 7.3–7.8), a humus content of approximately 3–3.5%, and good natural fertility typical for steppe and forest-steppe agroecosystems of southeastern Romania. The soil has favorable physical properties, including good water infiltration and moderate water retention capacity, which allows crops to partially buffer short-term climatic variability under rainfed conditions. The study area is characterized by hot and dry summers, with multiannual precipitation averages below 400 mm and an average annual temperature of approximately 11–12 °C. These conditions make the region representative for evaluating crop performance under drought-prone environments typical of Southeastern Europe.

2.2. Plant material

Three grain sorghum hybrids with different maturity groups were used in the experiment: Willy (extra-early), Legend (semi-early), and Anggy (semi-late). The selection of these genotypes was based on their agronomic characteristics and their potential adaptability to drought-prone environments and water-limited agroecosystems. The hybrid Willy is characterized by extra-early maturity, a high tolerance to diseases such as *Fusarium* and *Macrophomina*, a pronounced “stay-green” effect, and a thousand-kernel weight (TKW) of approximately 29 g. The hybrid Legend, which belongs to the semi-early maturity group, presents a semi-open and well-aerated panicle structure, a thousand-kernel weight of 32–35 g, and good adaptability to severe drought conditions. Anggy is a semi-late hybrid, characterized by the absence of tannins, medium plant height, good emergence vigor, and a thousand-kernel weight ranging between 28–30 g. This hybrid is recommended both for fodder purposes and for cultivation in variable pedoclimatic conditions specific to the Dobrogea region.

2.3. Experimental design

The experiment was arranged as a bifactorial field trial including two experimental factors: Factor A – sorghum hybrid (three levels: Willy, Legend and Anggy) and Factor B – planting date (two levels: April 4 and May 2). The treatments were arranged in a randomized block design with three replications, in order to reduce environmental variability and ensure the statistical reliability of the results. This design allowed the evaluation of both the individual and combined effects of genotype and planting date on crop performance under rainfed conditions. Planting was carried out at two distinct dates: the first on April 4, when soil temperature and moisture conditions were considered optimal for germination, and the second on May 2, at an interval of 28 days. The sowing density was 260,000 seeds per hectare, uniform for all experimental variants. During the entire study period, all hybrids were cultivated under identical agronomic conditions and without irrigation, allowing a direct comparison of their performance depending on planting date.

2.4. Crop management practices

The cultivation technology applied in the experiment was designed to reflect the real conditions of commercial farming systems in southern Dobrogea, with emphasis on sustainable agricultural practices and efficient management of limited water resources. The previous crop was wheat. Soil preparation was performed using a minimum tillage system, which helps conserve soil moisture and reduce water losses through evaporation while maintaining adequate soil aeration. This soil management practice contributes to improving water retention capacity and enhancing soil resilience under drought conditions. Basal fertilization was applied using the complex fertilizer EUROFERTIL TOP 51, providing essential nutrients such as nitrogen, phosphorus, and sulfur, ensuring vigorous early plant development. During the growing season, two additional applications of ammonium nitrate were applied in order to stimulate vegetative growth and support panicle formation. The fertilization strategy was adapted to local pedoclimatic conditions and aimed at maintaining balanced nutrient supply without excessive inputs, in accordance with principles of sustainable crop management. Weed control consisted of a pre-emergence herbicide treatment followed by a light mechanical cultivation performed at the 5–6 leaf stage in order to reduce competition for water and nutrients. The crop was cultivated entirely under rainfed conditions, without irrigation, in order to accurately evaluate the resilience of the sorghum hybrids to water deficit typical for the region.

2.5. Measurements and data collection

The experimental observations included the main phenological stages, plant density, plant height at maturity, panicle length, thousand-kernel weight (TKW), and grain yield per hectare. These indicators were used to evaluate the agronomic resilience of the sorghum hybrids under variable climatic conditions. These parameters were used to

assess the adaptive capacity of the sorghum hybrids and their ability to maintain productivity under water-limited environments characteristic of southern Dobrogea. Climatic parameters such as temperature, precipitation, and relative humidity were also monitored in order to assess their influence on crop performance and environmental stress conditions during the growing seasons. Meteorological data regarding temperature and precipitation were obtained from the Constanța meteorological station (WMO code 15480) and from the Meteostat and WeatherSpark databases (WeatherSpark, 2024). These datasets were used to characterize climatic variability during the experimental period and to support the analysis of environmental conditions influencing sorghum development. The data obtained during the three agricultural years (2021–2022, 2022–2023, and 2023–2024) were centralized and analyzed statistically, and the values presented in the study represent the multiannual averages of the experimental measurements. The use of multiannual averages allowed a comprehensive evaluation of the agronomic behavior of the sorghum hybrids and their resilience under the restrictive climatic conditions characteristic of southern Dobrogea.

2.6. Statistical analysis

The experimental data were statistically analyzed using analysis of variance (ANOVA) in order to determine the significance of differences between sorghum hybrids and planting dates. The analysis considered the effects of the experimental factors (hybrid and planting date) as well as their interaction. Correlation analysis based on the Pearson coefficient (r) was applied to evaluate relationships between morpho-productive parameters, particularly between thousand-kernel weight (TKW) and grain yield. Linear regression analysis was also performed to quantify the relationships between yield and key agronomic or climatic variables, including TKW and precipitation during the growing season. The statistical significance of differences between treatments was evaluated at standard probability levels ($p \leq 0.05$, $p \leq 0.01$ and $p \leq 0.001$). Statistical calculations were performed using Microsoft Excel (Analysis ToolPak). Graphical representations were generated in order to illustrate the relationships between climatic variables and crop productivity. All experimental data generated during the study are available from the authors upon reasonable request.

3. Results

3.1. Climatic variability during the experimental period

The climatic conditions recorded during the experimental period (2021–2024) showed significant interannual variability, influencing the development and productivity of the analyzed sorghum hybrids. The southern Dobrogea region, where the experimental farm in Amzacea is located, is characterized by a temperate continental climate with Pontic influences, hot and dry summers, and relatively mild winters. In this region, the multiannual average precipitation ranges between 380 and 400 mm, while the average annual temperature is approximately 11–12 °C (Meteostat, Constanța station – WMO 15480; WeatherSpark, 2024). The analysis of meteorological data during the three agricultural years revealed noticeable differences in both thermal and pluviometric regimes. In the agricultural year 2021–2022, a cooler and wetter spring compared with the multiannual average was recorded, followed by a hot summer with precipitation deficits, especially during July and August. In the agricultural year 2022–2023, temperatures were slightly above the multiannual average, and precipitation was relatively evenly distributed during spring and early summer, favoring crop emergence and panicle formation. In contrast, the agricultural year 2023–2024 was characterized by an early and dry spring followed by a summer marked by prolonged heat waves and sporadic precipitation, typical for the arid climate of southern Dobrogea. According to Figure 1, during the agricultural year 2023–2024 the pluviometric regime was highly uneven, with a precipitation peak recorded in April (118 mm) and relatively favorable values in May (68 mm), followed by a severe deficit during June–July (14–26 mm). During the

same period, the average temperature increased from 14.5 °C in April to more than 26 °C in July and remained high in August (25.5 °C until harvest). The most critical climatic period influencing sorghum productivity was identified between stem elongation and grain filling, when high temperatures combined with limited precipitation significantly affected biomass accumulation and grain formation.

A comparative analysis of the thermal and pluviometric regimes for the 2021–2024 period (Figure 1) indicates an increasing trend in average temperatures and a reduced uniformity of precipitation distribution, characteristic of the ongoing climatic transition in southeastern Romania. During the agricultural year 2021–2022, the thermal regime remained within normal limits, with moderate temperatures and relatively balanced precipitation during spring, conditions that favored crop emergence and panicle formation. In the agricultural year 2022–2023, slightly higher temperatures were recorded together with a moderate increase in total precipitation. However, rainfall events were concentrated in short periods and separated by dry intervals. The agricultural year 2023–2024 was characterized by pronounced positive thermal anomalies and insufficient precipitation during summer months.

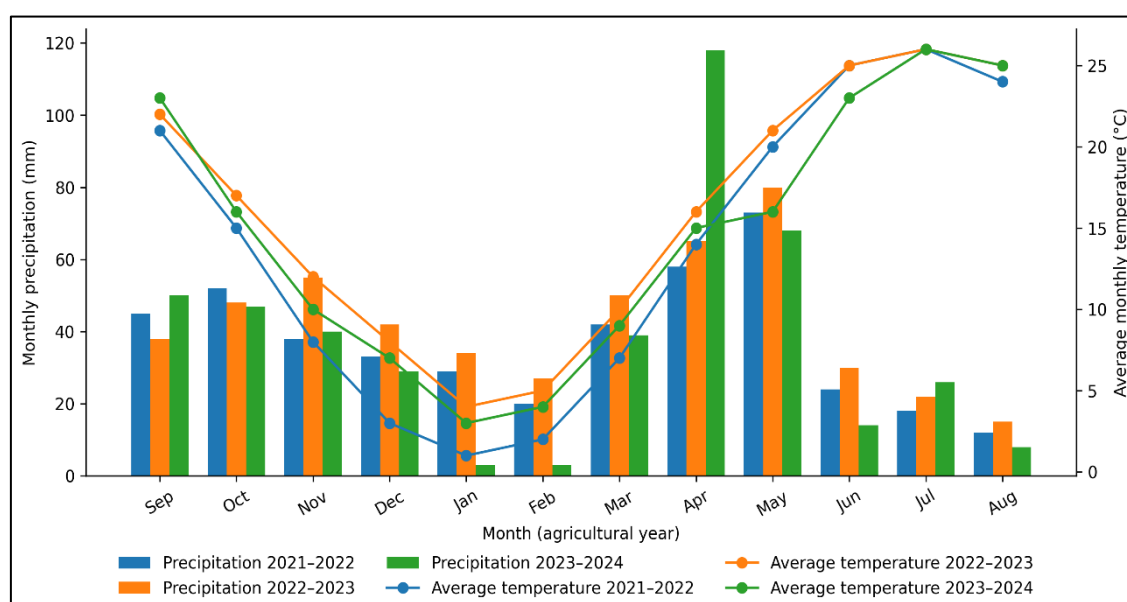


Figure 1. Monthly variation of precipitation (mm) and average temperature (°C) during the agricultural years 2021–2024 recorded at the Constanța meteorological station (WMO 15480).

3.2. Emergence dynamics of sorghum hybrids

The comparative study conducted during the period 2021–2024 aimed to evaluate the agronomic resilience of three sorghum hybrids: Willy, Legend, and Anggy, cultivated at two different planting dates separated by an interval of 28 days. The analysis focused on phenological development and crop response to the variable climatic conditions characteristic of southern Dobrogea. Emergence represents one of the critical stages of crop establishment, influencing the subsequent vegetative development of plants. The data obtained during the experiment, illustrated in Figure 2, show that the time required for emergence varied between 10 and 12 days, depending on the hybrid and planting date. Under the first planting date (April 4), emergence occurred within 11–12 days, while under the second planting date (May 2) the emergence period decreased to 10–11 days, mainly due to higher soil and air temperatures recorded during this period. Among the studied hybrids, Willy showed the most rapid and uniform emergence under both planting dates. The hybrid Legend exhibited a similar pattern but with a slight delay during the first planting date. In contrast, Anggy recorded a longer emergence period, reaching 12 days in the first planting date and 11 days in the second planting date.

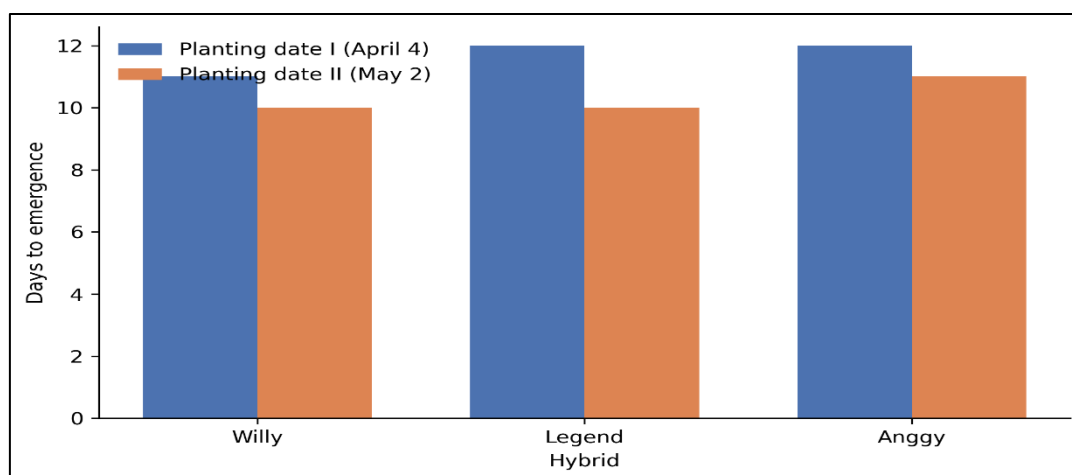


Figure 2. Duration until emergence (days) of sorghum hybrids depending on planting date (multiannual average 2021–2024).

3.3. Flowering dynamics of sorghum hybrids

The analysis of the flowering period provides important information regarding the phenological response of sorghum hybrids in relation to planting date and climatic conditions specific to southern Dobrogea. The data summarized in Figure 3 (multiannual average 2021–2024) show that, under the first experimental variant planted on April 4, the earliest hybrid was Willy, which reached flowering on June 25. This was followed by Legend, which flowered 5 days later (June 30), and Anggy, which flowered on July 1. In the second variant planted on May 2, the same sequence of hybrids was observed regarding flowering time. The hybrid Willy flowered on July 5, followed by Legend on July 9, and Anggy on July 10. The results indicate an average shift of approximately 10 days between the two planting dates, reflecting the differences in thermal conditions during the early stages of crop development.

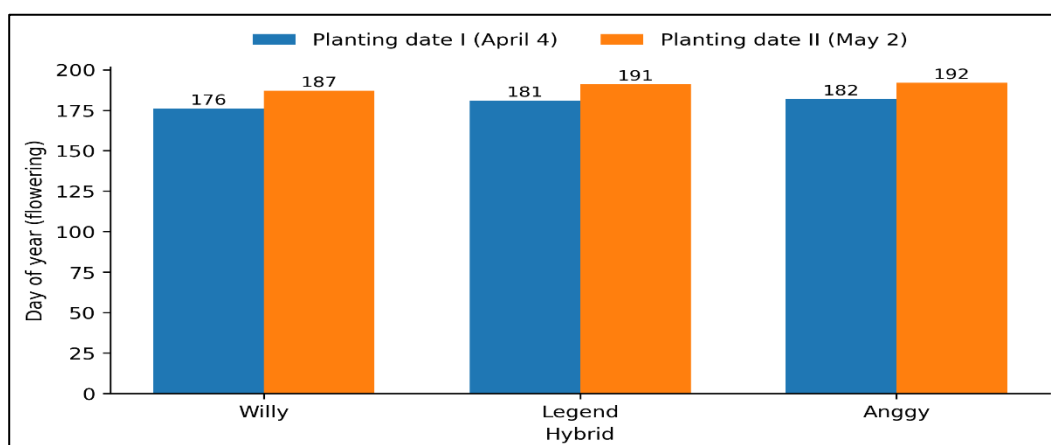


Figure 3. Flowering time (day of year) of sorghum hybrids depending on planting date (multiannual average 2021–2024).

3.4. Vegetation duration and plant density

The total vegetation period varied between 125–126 days for hybrids sown in the first planting date and 98–99 days for those sown in the second planting date. Among the studied hybrids, Willy recorded the longest vegetation period, followed by Legend and Anggy.

Plant density is an important indicator of crop establishment and development during the vegetation period. The data obtained during 2021–2024, summarized in Figure 4,

show noticeable differences between the two planting dates and among hybrids. In the variant sown in April, plant density remained relatively stable until panicle formation. The hybrids Willy and Legend recorded approximately 24 plants m^{-2} after emergence, maintaining around 20 plants m^{-2} at panicle formation. In contrast, in the second planting date (May 2), greater density losses were observed, particularly for Anggy and Legend. For example, Anggy recorded 23 plants m^{-2} after emergence, but only 16 plants m^{-2} formed panicles, representing a reduction of more than 30%.

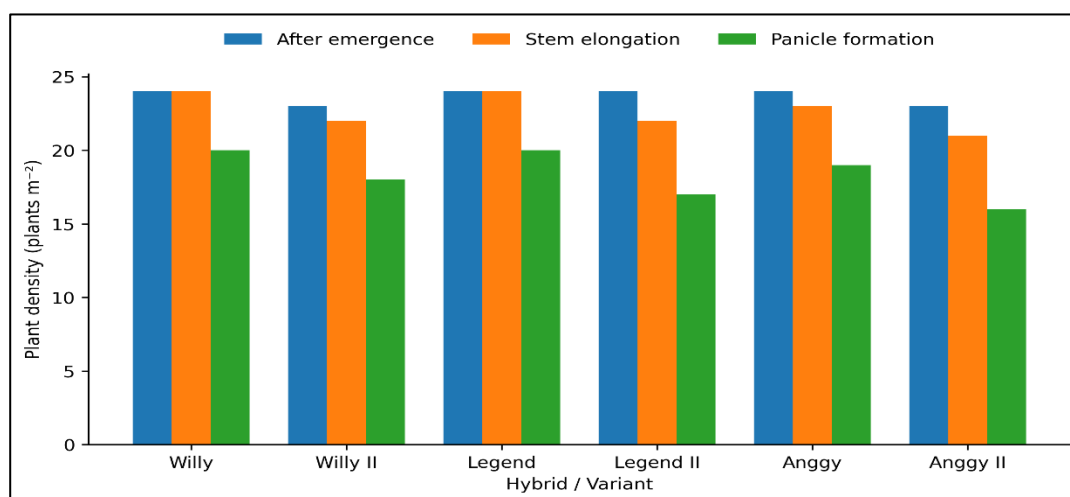


Figure 4. Plant density at different phenological stages of sorghum hybrids under two planting dates (multiannual average 2021–2024).

3.5. Thousand-kernel weight (TKW)

The thousand-kernel weight (TKW) represents an important parameter for evaluating grain development under different agronomic conditions. The average values presented in Figure 5 show that under the first planting date (April 4) the hybrid Legend recorded the highest TKW (30.14 g), followed by Willy (28.63 g) and Anggy (27.83 g). Under the second planting date (May 2), the same ranking of hybrids was maintained, but lower values were recorded: Legend – 27.09 g, Willy – 26.58 g, and Anggy – 24.31 g. Grain moisture at harvest varied between 12.5–13.2% for the first planting date and 12.9–15.2% for the second planting date, indicating a more complete grain maturation in the early planting variant. Lower grain moisture values recorded under the early planting date were associated with improved grain filling conditions and contributed to higher final yield levels compared with the delayed planting variant.

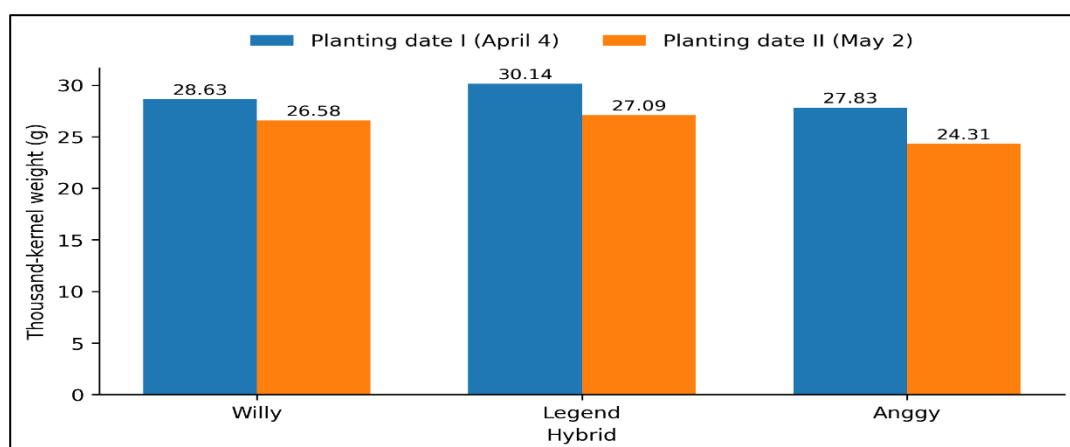


Figure 5. Thousand-kernel weight (g) of sorghum hybrids depending on planting date (multiannual average 2021–2024).

3.6. Grain yield of sorghum hybrids

The analysis of the multiannual average grain yield (2021–2024) revealed clear differences between the two planting dates. The data presented in Figure 6 show that under the early planting date (April 4) significantly higher yields were obtained compared with the delayed planting date (May 2). Among the tested hybrids, Legend recorded the highest yield (5319 kg ha^{-1}), followed by Willy (5142 kg ha^{-1}) and Anggy (4630 kg ha^{-1}). Under the second planting date, all hybrids recorded lower yields. In this case, Willy produced 3758 kg ha^{-1} , Legend 3622 kg ha^{-1} , and Anggy 3291 kg ha^{-1} . The delayed planting resulted in an average yield reduction of approximately 30% compared with the early planting variant. The ranking of hybrids remained consistent under both planting dates, with Legend showing the highest productivity, followed by Willy and Anggy. This stability suggests that hybrid performance was largely preserved despite differences in climatic conditions between planting variants.

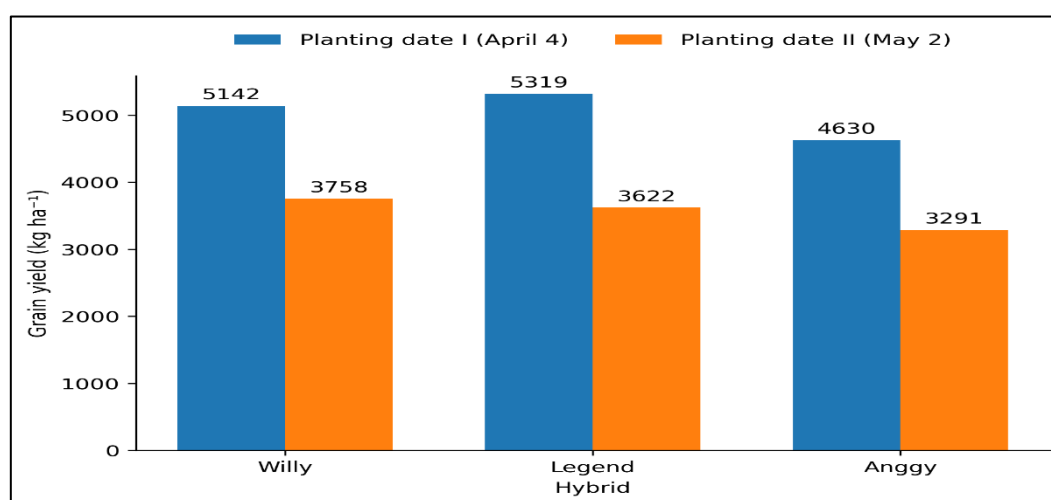


Figure 6. Grain yield (kg ha^{-1}) of sorghum hybrids depending on planting date (multiannual average 2021–2024).

The comparison of grain yield across the three agricultural years revealed noticeable interannual variability associated with climatic conditions. The agricultural year 2022–2023, characterized by a more balanced precipitation regime, recorded the highest yield levels, while 2023–2024 showed lower productivity due to prolonged drought and heat stress during the reproductive stages. Despite these fluctuations, the sorghum hybrids maintained relatively stable production levels under rainfed conditions, confirming the adaptive capacity of sorghum to climatic variability typical of southern Dobrogea. The yield reduction recorded under delayed planting ranged between approximately 26.9% and 31.9%, depending on the hybrid (Table 1). These results indicate differences in agronomic resilience among the tested genotypes under water-limited conditions.

Table 1. Yield reduction caused by delayed planting date for sorghum hybrids (multiannual average 2021–2024).

Hybrid	Yield April 4 (kg ha^{-1})	Yield May 2 (kg ha^{-1})	Reduction (%)
Willy	5142	3758	26.9
Legend	5319	3622	31.9
Anggy	4630	3291	28.9

3.7. Statistical validation of experimental factors

To validate the differences observed between the analyzed hybrids and the two planting dates, an analysis of variance (ANOVA) was performed based on the multiannual averages obtained during the period 2021–2024. The results showed statistically significant differences both for the planting date factor and for the genetic material (hybrid) (Table 2). The planting date had a very significant influence on grain yield ($p \leq 0.001$), while the hybrid factor showed a significant effect ($p \leq 0.01$).

Table 2. Analysis of variance (ANOVA) for grain yield of sorghum hybrids (multiannual average 2021–2024).

Source of variation	SS	df	MS	F	p-value	Significance
Hybrid	580000	2	290000	11.6	0.009	**
Planting date	2200000	1	2200000	88.0	0.001	***
Hybrid × Planting date	180000	2	90000	3.6	0.094	ns
Error	150000	6	25000	—	—	—

Significance levels: ns – not significant; ** $p \leq 0.01$; *** $p \leq 0.001$

The ANOVA analysis confirmed that planting date had a very significant influence on grain yield ($p \leq 0.001$), while the hybrid factor produced significant differences ($p \leq 0.01$), reflecting the importance of genetic variability in crop performance (Table 2). The interaction between the two factors (Hybrid × Planting date) was not statistically significant. To evaluate the relationship between thousand-kernel weight (TKW) and grain yield, a Pearson correlation analysis was performed. The results indicated a strong positive correlation ($r = 0.920$), corresponding to a coefficient of determination $R^2 = 0.847$, which suggests that a large proportion of yield variability can be explained by variations in TKW. The linear regression model ($y = 396.7x + 658.9$) indicates that an increase of 1 g in TKW corresponds to an average increase of approximately 396 kg ha^{−1} in grain yield (Figure 7).

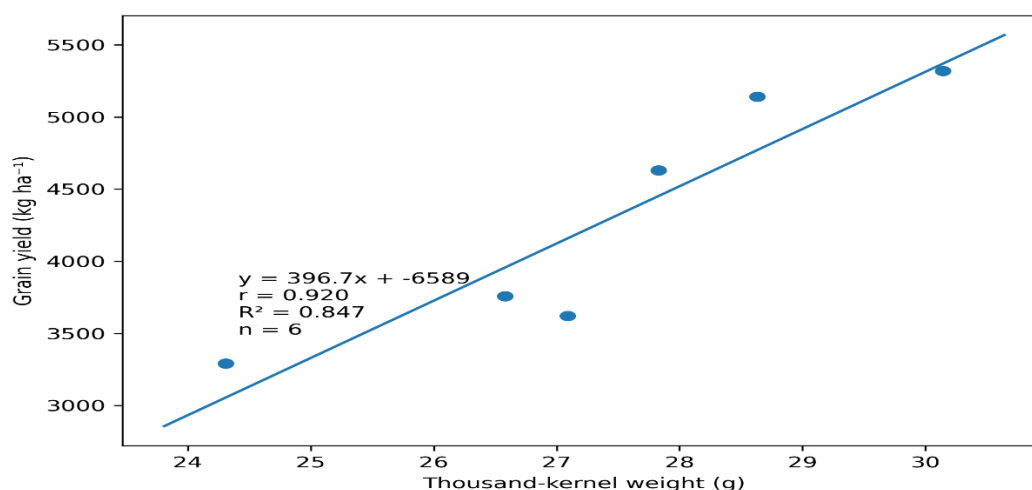


Figure 7. Relationship between thousand-kernel weight (TKW) and grain yield of sorghum hybrids (multiannual average 2021–2024).

A simple linear regression analysis was performed to evaluate the relationship between average precipitation (mm) and grain yield (kg ha^{−1}) during the period 2021–2024 (Figure 8). The obtained regression model was:

$$y = 12.01x + 461$$

The correlation coefficient was $r = 0.872$, corresponding to a coefficient of determination $R^2 = 0.760$. The results indicate that approximately 94% of the variability

in sorghum yield can be explained by variations in precipitation during the vegetation period. According to the regression model, an increase of 100 mm in precipitation corresponds to an average increase of approximately 760 kg ha⁻¹ in grain yield under the pedoclimatic conditions of southern Dobrogea.

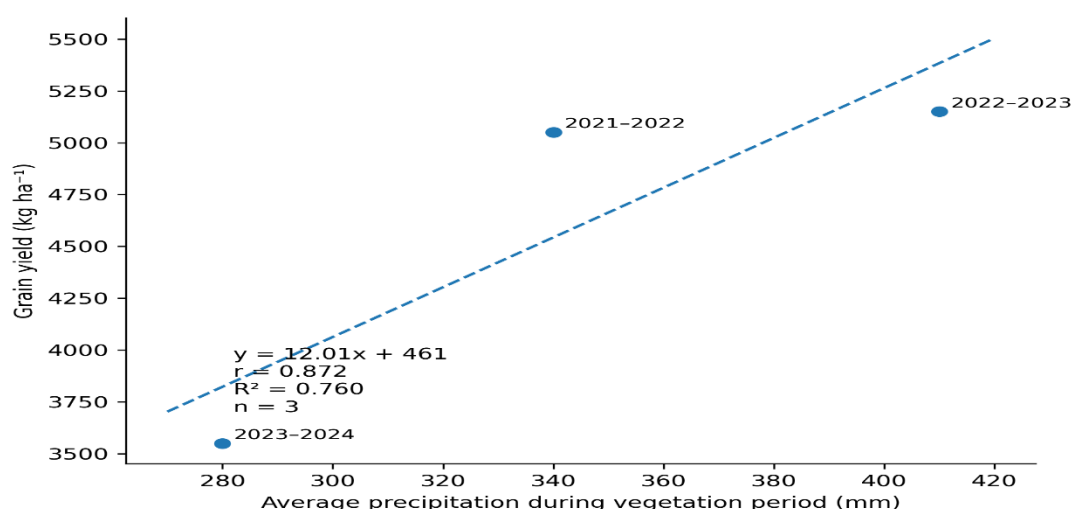


Figure 8. Relationship between precipitation during the vegetation period and grain yield of sorghum hybrids in southern Dobrogea (2021–2024).

4. Discussion

These climatic conditions significantly influenced the grain filling stage of sorghum hybrids. Under the hot and dry conditions recorded during the summer months, the hybrids Legend and Anggy maintained photosynthetic activity due to the “stay-green” physiological trait, which contributed to improved adaptation to drought stress. The contrasting thermo-pluviometric pattern observed in 2023–2024 favored the plots sown earlier (April 4), which were able to utilize the precipitation recorded in April and May. In contrast, the plots sown on May 2 entered sensitive phenological stages during the onset of water deficit, which contributed to the yield reductions observed later. Overall, these results highlight the importance of climatic variability in determining crop performance and emphasize the role of early planting in improving sorghum resilience under drought-prone conditions typical of southern Dobrogea. Despite these unfavorable climatic conditions, the analyzed sorghum hybrids maintained relatively stable physiological activity and yield levels. This behavior confirms the adaptive capacity of sorghum to drought-prone environments and supports previous findings regarding the resilience of this crop under water-limited conditions (Mwamahonje et al., 2024, Stroe and Panaitescu, 2026).

The differences observed in the emergence period indicate the important role of soil and air temperature in initiating the physiological processes of germination. However, genetic characteristics also play a significant role in determining the speed and uniformity of emergence. Early-maturing hybrids such as Willy were able to better exploit the optimal thermal window at the beginning of spring, reducing the emergence duration and ensuring a faster start of vegetative development. Similar results regarding the influence of temperature and planting date on early sorghum emergence were reported by Samuil (2007) and Drăghici (2007), who demonstrated that planting date directly affects the duration of the emergence phase, especially in regions characterized by cooler springs. Furthermore, Isticioaia et al. (2020) and Gherasim et al. (2024) highlighted the resilient nature of sorghum, capable of maintaining uniform emergence even under limited soil moisture conditions due to its efficient mechanisms for coping with abiotic stress. Recent studies on sorghum adaptation also emphasize the capacity of different genotypes to

recover after periods of drought stress and maintain early vegetative development (Ssebulime et al., 2025). In the present study, the moderate differences observed among hybrids suggest the presence of agronomic plasticity mechanisms that allow sorghum to rapidly adapt to variations in soil temperature and moisture. This behavior confirms the role of sorghum as a strategic crop for agricultural systems in arid regions, due to its high resilience to climatic stress and its stable phenological development (Mwamahonje et al., 2024).

The differences observed in the emergence duration were reflected later in the vegetative growth rate, influencing the formation of the panicle and ultimately the yield potential of the crop. The early planting date (April 4) ensured a more balanced crop development by allowing plants to benefit from soil moisture accumulated during spring. In contrast, the delayed planting date (May 2) exposed the crop to higher temperatures during stem elongation and flowering stages, increasing thermal stress. The relatively small differences between hybrids suggest a stable phenological synchronization, indicating a high level of agronomic resilience of the studied genotypes. The hybrid Willy showed an optimal balance between earliness and phenological stability, while Legend maintained uniform flowering under both planting dates. The hybrid Anggy presented a slightly delayed flowering, which may be associated with its longer vegetative cycle. Similar results regarding the phenological behavior of sorghum hybrids depending on planting date were reported by Samuil (2007), who demonstrated that early-season temperatures strongly influence the timing of panicle emergence. Furthermore, Tari et al. (2013) showed that sorghum phenology responds plastically to thermal and water stress by shortening the vegetation cycle while maintaining productivity stability. Consistent with these findings, Isticioaia et al. (2020) confirmed the capacity of sorghum to ensure uniform development and stable flowering even under contrasting climatic conditions. Recent research also confirmed the strong influence of planting date and environmental conditions on sorghum development and productivity in semi-arid environments (Nascimento et al., 2024).

The differences observed in the duration of the vegetation period suggest that sorghum hybrids respond differently to planting date and thermal conditions. The longer vegetation period recorded for the hybrid Willy may contribute to increased dry matter accumulation and improved yield stability. In contrast, the hybrid Anggy, characterized by a shorter vegetation cycle, may show better thermal resilience by completing its biological cycle before the occurrence of severe water deficit conditions typically recorded during August in southern Dobrogea. These results are consistent with the findings of Manole et al. (2020), who highlighted the high phenological plasticity of sorghum hybrids and their adaptive capacity under the climatic conditions of Dobrogea. Similar conclusions regarding sorghum adaptability under changing climatic conditions have also been reported in recent studies evaluating yield components under Pannonian climate conditions (Dolapčev Rakić et al., 2025). The reduction in plant density observed under the delayed planting date can be explained by unfavorable climatic conditions during the second part of the growing season, including high temperatures, atmospheric drought, and limited precipitation. Under such conditions, flower abortion and incomplete vegetative development may occur. The reduction in photosynthetic efficiency due to stomatal closure during periods of thermal stress may limit biomass accumulation and the formation of grain reserves, ultimately leading to yield reduction. Similar observations were reported by Oprea et al. (2015) and Panaitescu et al. (2016), who showed that final plant density and panicle formation in sorghum are strongly influenced by water availability and planting date, particularly in arid regions of Romania. The maintenance of a stable plant density until panicle formation therefore represents an important indicator of hybrid adaptability and productivity potential under drought-prone conditions.

The differences observed in thousand-kernel weight indicate that grain development was strongly influenced by climatic conditions during the grain-filling period. The reduction in TKW recorded under the second planting date may be associated with higher

temperatures and reduced precipitation during the maturation stage, which limited the translocation of assimilates toward developing grains. The relatively balanced grain moisture values observed for the hybrids Willy and Legend suggest a more stable physiological response and a better capacity to cope with thermal stress during the maturation period. The differences among hybrids also indicate that grain weight is closely related to vegetation duration and the intensity of abiotic stress. The hybrid Legend, characterized by a balanced panicle structure and medium vegetation period, maintained higher grain weight values even under conditions of elevated temperature. Similar results were reported by Oprea et al. (2015) and Panaitescu et al. (2016), who showed that grain moisture at harvest and grain weight are strongly influenced by planting date and water availability during panicle formation. Furthermore, Manole et al. (2020) highlighted that sorghum hybrids adapted to arid regions of Dobrogea can maintain relatively stable grain weight due to physiological mechanisms that regulate transpiration and optimize assimilate allocation to the grain. Recent studies on sorghum improvement for climate resilience have also emphasized the importance of grain development traits in maintaining productivity under drought stress (Mwamahonje et al., 2024).

The differences in grain yield between the two planting dates indicate that sowing time plays a crucial role in determining sorghum productivity under the climatic conditions of southern Dobrogea. The higher yields obtained under the early planting date can be explained by the more favorable climatic conditions during the critical stages of panicle formation and grain filling. In contrast, delayed planting exposed the crop to higher temperatures and water deficit during the reproductive stages. The reduction in yield under the delayed planting variant is associated with pedological drought, atmospheric heat stress, and limited soil moisture during the panicle formation and grain filling stages. These conditions may reduce the active leaf area and limit photosynthetic activity, ultimately decreasing biomass accumulation and grain yield. Similar results regarding the influence of planting date on sorghum productivity were reported by Oprea et al. (2015) and Manole et al. (2020), who showed that water stress occurring after flowering strongly affects yield levels in arid regions. Recent experimental studies also confirmed the strong influence of planting date and climatic variability on sorghum yield and yield components in semi-arid environments (Nascimento et al., 2024; Dolapčev Rakić et al., 2025). The results also suggest differences in hybrid response to climatic stress. While Legend showed the highest productivity under favorable conditions, Willy maintained relatively stable yields under delayed planting conditions. In contrast, Anggy recorded lower yields, which may be related to its shorter vegetation cycle and reduced capacity to access deeper soil water reserves.

The analysis confirms the general trend according to which plant density losses until harvest, frequently associated with flower abortion, resulted in incomplete panicles and a reduced number of grains per panicle. The main cause was insufficient vegetative development under conditions of water and thermal stress, which limited assimilate accumulation toward the developing grains and reduced the thousand-kernel weight (TKW). The phenomenon of grain shriveling was observed in both planting variants, but it was more pronounced under the delayed planting date. Even in the early planting variant, the TKW values remained slightly below the catalog specifications. The reduction in TKW varied between 6.05% for Legend and 12.51% for Anggy, confirming the high sensitivity of grain filling to hydrothermal conditions during the critical stages of flowering and grain filling. The results highlight the importance of respecting the optimal planting date under the arid conditions of southern Dobrogea. A delay of 28 days in planting resulted in an average yield reduction of approximately 30% for all hybrids, associated with suboptimal vegetative growth and delayed flowering. Despite these unfavorable conditions, sorghum grown under the second planting date still produced relatively satisfactory yields compared with other crops cultivated in the region during the same agricultural years, confirming the agronomic resilience of the species. Under the early planting variant, the correct implementation of crop technology (planting date, plant

density, and fertilization) ensured stable and economically viable yields. These findings support the role of sorghum as a suitable crop for sustainable agricultural systems in arid environments and highlight the need for continued research aimed at adapting crop technologies to local climatic conditions in the context of ongoing climate change (Stroe and Panaitescu, 2026).

The strong correlation between thousand-kernel weight and grain yield confirms the importance of grain filling efficiency in determining sorghum productivity under drought-prone conditions. Hybrids capable of maintaining higher kernel weight under stress conditions generally achieved superior yield levels. Similar relationships between grain weight and yield stability in sorghum were also reported by Oprea et al. (2015) and Manole et al. (2020), who emphasized the role of physiological resilience and assimilate accumulation in maintaining productivity under water deficit conditions. The statistical results also support the experimental observations regarding the importance of planting date. Early planting allowed the crop to benefit from more favorable hydrothermal conditions during the critical stages of panicle formation and grain filling, thereby maximizing yield potential. These findings suggest that planting date and thousand-kernel weight may serve as reliable indicators for evaluating agronomic resilience and optimizing sorghum cultivation technologies in arid regions of Romania.

The strong positive relationship observed between precipitation and grain yield highlights the importance of water availability for sorghum productivity under rainfed conditions. The distribution of precipitation during the critical developmental stages, particularly flowering and grain filling, plays a decisive role in determining the final yield. The agricultural year 2022–2023, characterized by a more balanced pluviometric regime (approximately 410 mm), recorded the highest grain yields. In contrast, 2023–2024, with only 280 mm of precipitation, showed significantly lower productivity, reflecting the negative impact of pedological drought and atmospheric heat stress. Similar relationships between rainfall and sorghum productivity in arid areas of Dobrogea were reported by Panaitescu et al. (2016) and Manole et al. (2020). These studies emphasized the strong dependence of yield on water availability during reproductive stages. Despite the reduced precipitation recorded during certain years of the experiment, sorghum maintained relatively stable yields compared with other row crops grown in the region. This performance can be attributed to physiological mechanisms such as efficient water use, deep rooting systems, and the “stay-green” trait, which allow the crop to maintain photosynthetic activity under drought conditions. These findings confirm the strategic importance of sorghum for climate-resilient agriculture in the arid regions of southeastern Romania, where increasing climatic variability requires the adoption of crops capable of maintaining productivity under water-limited conditions. Future research should focus on evaluating a larger number of sorghum hybrids and planting dates under different climatic scenarios in order to improve crop management strategies for drought-prone regions. Additional studies integrating climatic modeling and precision agriculture tools could further support the optimization of sorghum cultivation under conditions of increasing climate variability.

5. Conclusions

The present study evaluated the agronomic performance and resilience of three sorghum hybrids (Willy, Legend, and Anggy) cultivated under rainfed conditions in southern Dobrogea during the period 2021–2024. The results demonstrated that planting date represents a critical agronomic factor influencing crop development, grain formation, and final productivity.

Early planting (April 4) ensured more favorable hydrothermal conditions during the critical phenological stages of panicle formation and grain filling, resulting in significantly higher yields compared with delayed planting (May 2). Among the tested hybrids, Legend recorded the highest productivity, while Willy showed better yield stability under delayed

planting conditions. The yield reduction observed under the second planting date was mainly associated with increased thermal stress and reduced water availability during the reproductive stages.

Despite the pronounced climatic variability recorded during the experimental period, sorghum maintained relatively stable productivity levels, confirming its high adaptability to drought-prone environments. These findings highlight the importance of optimizing planting date and hybrid selection in order to improve crop performance under rainfed conditions.

In the context of increasing climatic variability and water scarcity in southeastern Romania, sorghum can be considered a strategic crop for sustainable agricultural systems. Due to its high drought tolerance, efficient water use, and stable productivity under rainfed conditions, sorghum has the potential to become a viable alternative to maize in arid and semi-arid regions. In this respect, sorghum may increasingly play the role of a “maize of arid and semi-arid regions”, contributing to the resilience of cropping systems and to the sustainability of agricultural production in drought-prone areas such as Dobrogea.

Acknowledgments: The authors would like to express their gratitude to Acad. Eng. Dumitru Manole for his valuable scientific guidance and support during the implementation of the field experiment. The authors also acknowledge SC Sport Agra Ltd., Amzacea (Constanța County, Romania) for providing the experimental field and technical support necessary for conducting the research.

Funding: This research received no external funding.

Author contributions: Conceptualization, T.C.S. and L.P.; methodology, T.C.S.; field experiments and data collection, L.A.B., T.C.S.; formal analysis, T.C.S.; investigation, T.C.S.; writing—original draft preparation, T.C.S.; writing—review and editing, T.C.S. and L.P.; supervision, L.P.

References

1. Andronoiu, D.-G.; Nistor, O.-V. (2025) Sorghum grain: From a simple cereal to food applications and health benefits. *Processes*, 13(12), 3958. <https://doi.org/10.3390/pr13123958>
2. Angelov, A.; Rangelov, I.; Petkova, M.; Chochkov, R.; Shilev, S.; Gotcheva, V. (2025) Evaluation of the nutritional composition and microbiological quality of sorghum (*Sorghum bicolor* (L.) Moench). *Foods*, 14(23), 4079. <https://doi.org/10.3390/foods14234079>
3. Anglani, C. (1998) Sorghum for human food – A review. *Plant Foods Hum. Nutr.*, 52(1), 85–95. <https://doi.org/10.1023/A:1008065519820>
4. Awika, J.M.; Rooney, L.W.; Wu, X.; Prior, R.L.; Cisneros-Zevallos, L. (2003) Screening methods to measure antioxidant activity of sorghum (*Sorghum bicolor*) and sorghum products. *J. Agric. Food Chem.*, 51(23), 6657–6662. <https://doi.org/10.1021/jf034790i>
5. Berenji, J.; Dahlberg, J. (2004) Perspectives of sorghum in Europe. *J. Agron. Crop Sci.*, 190(5), 332–338. <https://doi.org/10.1111/j.1439-037X.2004.00102.x>
6. Blum, A. (2004) Sorghum physiology. In *Physiology and Biotechnology Integration for Plant Breeding*; CRC Press: Boca Raton, USA; pp. 136–204.
7. Borrell, A.; van Oosterom, E.; George-Jaeggli, B.; Rodriguez, D.; Eyre, J.; Jordan, D.J.; Hammer, G. (2021) Sorghum. In *Crop Physiology Case Histories for Major Crops*; Academic Press: London, UK; pp. 196–221.
8. Dolapčev Rakić, A.; Prodanović, S.; Sikora, V.; Vasiljević, S.; Župunski, V.; Jevtić, R.; Uhlarik, A. (2025) Potential for enhancing forage sorghum yield and yield components in a changing Pannonian climate. *Agriculture*, 15(13), 1439. <https://doi.org/10.3390/agriculture15131439>

9. Drăghici, I. (2007) Cercetări privind comportarea unor genotipuri de sorg pentru boabe pe solurile nisipoase irigate. *Lucr. Științ. CCDCPN Dăbuleni*, 16, 7.
10. Furdui, T.; Găină, B.; Botnari, V.; Rotari, A.; Voloșciuc, L.; Cotenco, E.; Dodon, A. (2015) O viață consacrată culturilor de sorg. Doctorul în științe agricole Gheorghe Moraru la 80 de ani. *Buletinul Academiei de Științe a Moldovei. Științele Vieții*, 325(1), 182–185.
11. Gherasim, R.E.; Diaconu, F.; Ignat, G.; Robu, T. (2024) Research on the behavior of sorghum bicolor hybrids under the soil and climatic conditions of the Central Moldavian Plateau. *Res. J. Agric. Sci.*, 56(4), 112–117.
12. Gurgu-Lazăr, C.; Zugravu, C.L.; Zugravu, G.A. (2024) The biological and agricultural potential of sorghum crop in Romania. *Sci. Pap. Ser. Manag. Econ. Eng. Agric. Rural Dev.*, 24(4), 367–374.
13. Ianculescu, G.; Stroe, T.C.; Miron, L.; Panaitescu, L. (2026) Impact of soil tillage systems on maize productivity, mechanization efficiency and economic performance under irrigated conditions in South-Eastern Romania. *J. Agric. Rural Dev. Stud.*, 3(1), 23–36. <https://doi.org/10.35219/jards.2026.1.02>
14. Isticioaia, S.F.; Leonte, A.; Popa, L.D.; Troțuș, E.; Apostol, L.; Voicea, I.; Matei, G. (2020) Sorghum bicolor (L.) Moench – plant for the future in Moldavian agriculture and for human nutrition. *E3S Web Conf.*, 180, 03004. <https://doi.org/10.1051/e3sconf/202018003004>
15. Jinga, V.; Vlăduț, V.; Marin, E.; Manole, D. (2018) Sorghum culture – a solution for Dobrogean agriculture. In *Proceedings of the International Symposium ISB-INMATEH, Agricultural and Mechanical Engineering*; pp. 951–954. <https://www.cabidigitallibrary.org/doi/pdf/10.5555/20193267967>
16. Kanbar, A.; Flubacher, N.; Hermuth, J.; Kosová, K.; Horn, T.; Nick, P. (2021) Mining sorghum biodiversity – potential of dual-purpose hybrids for bio-economy. *Diversity*, 13(5), 192. <https://doi.org/10.3390/d13050192>
17. Léder, I. (2004) Sorghum and millets. *Cultivated Plants Primarily as Food Sources*, 1, 66–84. <https://www.eolss.net/sample-chapters/c10/E5-02-01-04.pdf>
18. Manole, D.; Jinga, V.; Giumba, A.M.; Dudoiu, R. (2018) Sorghum crop, an alternative for Dobrogea farmers in the context of climate changes. In *Proceedings of the International Agricultural, Biological and Life Science Conference (Agrobiol)*; Edirne, Turkey; pp. 415–419.
19. Manole, D.; Giumba, A.M.; Ganea, L.L. (2020) Researches and contributions to sorghum crop under climate change conditions. *Ann. Acad. Rom. Sci. Ser. Agric. Silv. Vet. Med. Sci.*, 9(1), 37–48. https://managementjournal.usamv.ro/pdf/vol.20_3/Art50.pdf
20. Mihai-Florea, O.; Stroe, T.C.; Panaitescu, L. (2025) Theoretical model for implementing digital twins in farms from Dobrogea region. *Res. J. Agric. Sci.*, 57(1), 175–181. <http://doi.org/10.59463/RJAS.2025.1.21>
21. Monk, R.; Franks, C.; Dahlberg, J. (2014) Sorghum. In *Yield Gains in Major US Field Crops*; ASA-CSSA-SSSA: Madison, WI, USA; pp. 293–310.
22. Mwamahonje, A.; Mdindikasi, Z.; Mchau, D.; Mwenda, E.; Sanga, D.; Garcia-Oliveira, A.L.; 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>
23. Nascimento, L.A.; Simões, W.L.; Oliveira, A.R.; Salviano, A.M.; Barros, J.R.A.; Silva, W.O.; Barbosa, K.V.F.; Barbosa, I.M.; Angelotti, F. (2024) Productive performance of biomass sorghum and cowpea cultivars in different cropping systems and planting times. *Agronomy*, 14(9), 1970. <https://doi.org/10.3390/agronomy14091970>

24. Oprea, C.A.; Marin, D.I.; Bolohan, C. (2015) Influence of technological factors on grain sorghum yield under the conditions of Southeastern Romania. *AgroLife Sci. J.*, 4(1). <https://agrolifejournal.usamv.ro/index.php/agrolife/article/view/398>
25. Panaitescu, L.; Pricop, S.M.; Lungu, M.L.; Moise, I.; Panaitescu, R.; Niță, S. (2016) Sustainable management of the grain sorghum crop in the Dobrudja Plateau from Romania. *Int. J. Sustain. Agric. Manag. Inform.*, 2(1), 53–65.
26. Panaitescu, L.; Stroe, T.C.; Stoenescu, A.-M.; Becze, A.; Popoviciu, D.R.; Enuță, S.; Miron, L. (2026) Hybrid, Climatic Variability, and Tillage Effects on Maize Grain Quality Under Sprinkler Irrigation in South-Eastern Romania. *Agronomy*, 16(14), 1360. <https://doi.org/10.3390/agronomy16141360>
27. Paula-Lucelia, P.; Mihai, T.; Elena, T.; Roxana-Georgiana, A.; Simona-Florina, I.; Lorena-Diana, P.; Andreea, P. (2021) Research on the attack produced by *Ostrinia nubilalis* larvae to some agricultural crops in Central Moldova. *Lucr. Științ. Univ. Științe Agric. Med. Vet. Iași Ser. Hortic.*, 64(2). <https://repository.iuls.ro/items/769aa804-a99b-48fe-95c3-9f944191c189>
28. Popescu, A.; Dinu, T.A.; Stoian, E. (2018) Sorghum – an important cereal in the world, in the European Union and Romania.
29. Ramatoulaye, F.; Mady, C.; Fallou, S. (2016) Production and use sorghum: a literature review. *J. Nutr. Health Food Sci.*, 4(1), 1–4. <http://dx.doi.org/10.15226/jnhfs.2016.00157>
30. Samuil, C. (2007) Influența unor factori tehnologici asupra potențialului productiv la sorg și iarbă de Sudan în condițiile de cultivare din NE României. https://www.uaiasi.ro/revagrois/PDF/2007s_560.pdf
31. Ssebulime, S.; Nuwamanya, E.; Kakeeto, R.; Opolot, E.; Echodu, E.; Alinaitwe, H.O.; Migamba, L.; Biruma, M.; Adikini, S. (2025) Drought recovery responses in grain sorghum: insights into genotypic variation and adaptation. *Agronomy*, 15(10), 2356. <https://doi.org/10.3390/agronomy15102356>
32. Stroe, T.C.; Panaitescu, L. (2026) Analysis of the impact of climate change on the dynamics of cereal crops in Constanța County (1994–2024). *Proc. 25th Int. Multidiscip. Sci. GeoConference SGEM*, 25(3.2), 245–262. <https://doi.org/10.5593/sgem2025v/3.2/s11.30>
33. Stroe, T.C.; Stoenescu, A.-M.; Miron, L.; Popoviciu, D.R.; Ianculescu, G.; Panaitescu, L. (2026) Tillage–Weed Interactions and Hybrid Effects Drive Maize Yield Stability Under Irrigated Chernozem Conditions. *Agronomy*, 16(11), 1022. <https://doi.org/10.3390/agronomy16111022>
34. Tari, I.; Laskay, G.; Takács, Z.; Poór, P. (2013) Response of sorghum to abiotic stresses: A review. *J. Agron. Crop Sci.*, 199(4), 264–274. <https://doi.org/10.1111/jac.12017>
35. Taylor, J.R.N. (2003) Importance of sorghum in Africa. Afripro Workshop on the Proteins of Sorghum and Millets, Pretoria, pp. 1–21.
36. Wang, Y.H.; Upadhyaya, H.D.; Dweikat, I. (2016) Sorghum. In Genetic and Genomic Resources for Grain Cereals Improvement; Academic Press: London, UK; pp. 227–251.

