

Article

Radiation Use Efficiency and Agronomic Performance of Biomass Sorghum under Different Sowing Dates

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Abstract: Accurate estimation of radiation use efficiency (RUE) at variable timed sowing dates will enhance the prediction of plant dry matter accumulation. The objectives of this study were to (1) determine the impact of three sowing dates on the productivity, performance, and economic feasibility of three biomass sorghum hybrids and (2) evaluate the variability of RUE in the production of biomass sorghum under the effects of variable timed sowing dates. Over a two-year experiment, biomass sorghum hybrids were grown and monitored at different sowing seasons under optimal growth conditions. Average dry biomass (DB) productivity at harvest ranged from 22.71 to 32.77 Mg ha⁻¹. Higher leaf area index (LAI) values (>4.0) represented an intercept of over 95% of incident photosynthetically active radiation (PAR). RUE obtained from the slope of the linear relationship between DB produced and accumulated intercepted photosynthetically active radiation (IPAR) ranged from 2.92 to 4.157 g MJ⁻¹ across growing seasons. Higher RUE values were observed for the energy hybrids in the early and mid-season. They converted IPAR efficiently into DB. Lastly, the economic feasibility of each sorghum hybrid and sowing date was evaluated in terms of their expected net returns. Economic results suggest that the sorghum hybrids considered could be a viable source of biomass season long, with net returns ranging from USD 560.55 ha⁻¹ to USD 1255.06 ha⁻¹.

Keywords: biomass sorghum; crop growth analysis; dry biomass; economic analysis; radiation use efficiency; sowing dates



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1. Introduction

Intercepted solar radiation is one of the most critical factors in the productivity and yield of crops. This factor, combined with the uncertainty of the weather, is expected to bring challenges to seasonal production, particularly of biomass crops. Connor, Loomis [1] stated that photosynthetic rates of crops depended on the quantity of radiation intercepted and utilization efficiency. For this reason, the RUE measured at several sowing seasons may provide a better understanding of biomass sorghum's physiological ability to produce DB under different weather conditions, such as temperature and photoperiod. The amount of PAR received from the sun, and the efficiency of the crop canopy for the absorption of PAR principally influences the rate of biomass accumulation. Hence, under optimal crop growth conditions, total dry plant matter depends on the quantity of radiation absorbed

by the crop canopy [2]. Consequently, the estimations of *DB* are based on the concept of RUE (g MJ^{-1}), which is defined as the ratio of dry matter produced (g m^{-2}) and the absorbed *PAR* (MJ m^{-2}) [3]. Thus, the simulation of *DB* production is the central part of many crop-growth models such as EPIC, CERES, and CropSyst, which adopted the concept of RUE as a significant parameter used to predict the accumulation of potential *DB*. In addition, a handful of studies have specifically explored RUE responses among sorghum cultivars. For instance, Houx III and Fritsch [4] observed decreases in RUE and *DB* production of four sweet sorghum cultivars in response to two late sowing dates in a 2-year study. They observed that sweet sorghum converts *IPAR* efficiently to *DB* even when sown late. Rinaldi and Garofalo [5] conducted a three-year field experiment on biomass sorghum under four different irrigation levels in southern Italy. They obtained RUE values that confirmed a high efficiency in biomass production with adequate irrigation water supply for a Mediterranean environment.

Biomass crops such as sorghum (*Sorghum bicolor*), sugarcane (*Saccharum officinarum* L.), maize (*Zea mays* L. subsp. *mays*), and Miscanthus (*Miscanthus* spp.), are warm-season C4 crops that have often been identified for use as energy crops. However, biomass sorghum, especially, is an excellent candidate for bioenergy production because of its high biomass potential, short growing cycle [6], water stress tolerance [7], high water use efficiency [8], and highly efficient in converting solar energy into biomass [9,10]. Biomass sorghums have been genetically improved to increase their biomass accumulation and maximize their cellulosic content. In addition, they can produce high biomass yields in just 90 to 100 days and remain in their vegetative growth phase for more than 200 days at most latitudes [6].

Information about sowing at different dates for sorghum hybrids is limited, and very few studies exist in the literature, probably because farmers looked for optimal production in a single crop cycle. Some of those few studies are from Teetor, Duclos [11], and Rao, Patil [12], who reported that late sweet sorghum typically had lower yields of stalks and sugar than earlier sowings. Another study conducted in the Rio Grande Valley by Hipp, Cowley [13] evaluated the influence of sowing dates and solar radiation on sweet sorghum. They observed that the highest sugar yield was found in crops sown in May. Also, they observed that the solar radiation received by the plants during the period between boot and early seed formation accounted for about 75% of the variation in yield.

Extending the supply of low-cost feedstock through the production season has been identified as a critical factor associated with the economic success of a biofuel enterprise [14]. In particular, lower feedstock production costs are needed to offset the higher conversion and capital costs associated with cellulosic biofuels relative to their counterpart sugar-based biofuels [15]. Feedstock production also needs to compete with other crops in terms of profits; thus, higher return rates may be needed to incentivize growers to switch from any incumbent crop to the new dedicated energy crops.

Strategic plans for efficient use of the intercepted solar radiation to produce sufficient food and fiber for the growing population are needed. So, it is essential to determine accurate RUE values for the agronomic response in the production of *DB*. Therefore, a 2-year experiment with diverse weather conditions was planned to estimate RUE values and *DB* for three biomass sorghum hybrids sown on different dates to quantify the impact of weather on biomass sorghum growth. The objectives of this study were to (1) determine the impact of three sowing dates on the productivity, performance, and economic feasibility of three biomass sorghum hybrids and (2) evaluate the variability of RUE in the production of biomass sorghum under the effects of variable timed sowing dates. The results of this study are relevant not only for comparing sowing dates and the productivity of different biomass sorghum hybrids but RUE is used as a crop parameter for modeling purposes.

2. Materials and Methods

2.1. Field Experiments and Measured Data

Measured data were obtained from experiments conducted during the 2013 and 2016 growing seasons in fields located at the Texas A&M AgriLife Research Center in Weslaco, Texas (latitude 26°09'26" N, longitude 97°57'32" W; elevation 24 m above sea level). The study area has a semi-arid climate with an average annual precipitation of 558 mm, and the soil type is a Hidalgo sandy loam. The biomass sorghum hybrids used in this study were one forage sorghum hybrid from Pioneer®, Pioneer 877F, and two energy sorghum hybrids from Blade® Energy Crops, Blade ES 5140 and Blade ES 5200. The Pioneer 877F (forage) is a hybrid that results from the cross of sorghum and sudangrass parents; it is designed for multiple cuts throughout the season. The Blade ES 5140 (photoperiod-insensitive) is a hybrid that results from the cross of a grain sorghum female parent and a sudangrass male parent; it is designed for multiple cuts throughout the season. The Blade ES 5200 (photoperiod-sensitive) is a hybrid that results from the cross of two sorghum parents. Also, it is designed for a single-harvest production system, so it is not selected for ratooning and should be sown after day lengths exceed 12 h and 20 min.

The field experiments in both years were arranged as a split plot in a randomized complete block design (RCBD) with four replications. The main plots were sowing dates, and subplots were sorghum hybrids. The plots used for experiments were 4.1 m wide and 91.4 m long. The plant density in all plots was approximately 140,000 seeds per hectare, with a sowing depth of 30 to 45 mm. All sorghum hybrids were sown 1.02 m wide. The plant density after emergence showed no differences among the sowing seasons. Full irrigation was applied to all experimental plots by replacing the water used by the crop. Soil water depletion was measured using gravimetric methods at the beginning and end of each sowing season. A subsurface drip irrigation system was installed to assure uniform germination of seeds and better control in measuring water inputs [16]. Drip tape with 15 mm thickness was placed in the center of each bed resulting in an irrigation water application rate of 2.5 mm h⁻¹. The fertilizer urea ammonium nitrate (UAN; 32% mass fraction of N) was applied at 100 kg ha⁻¹ through the drip irrigation system in two equal split applications. The exact total fertilizer was applied to all experimental units.

A weather station (model ET106, Campbell Scientific, Logan, UT, USA) located 100 m away from the experimental plots was used to monitor soil and air temperatures, precipitation, relative humidity, and wind speed. Weather data is used for calculations. The weather station was equipped with a tipping bucket rain gauge (model TE525, Texas Electronics, Dallas, TX, USA) for measuring rainfall; a temperature sensor (model CS500, Vaisala, Helsinki, Finland) for measuring maximum and minimum air temperature, and relative humidity; a pyranometer (model LI200X, LI-COR Biosciences, Lincoln, NE, USA) for measuring total solar radiation; and a wind set (model 034A Campbell Scientific, Logan, UT, USA) for measuring average wind speed. Weather data were recorded hourly and daily using a CR10X data logger.

Table 1 shows the dates on which crop development was monitored. Measured plant variables were fresh and dry plant weight and *LAI*. Plant sampling was conducted on each of the experimental units four to five times throughout the sowing season if weather conditions were favorable. *LAI* and biomass were determined using destructive sampling. The destructive samples were randomly collected from a 1 m² area at the center of each plot to avoid the border effects. Dry matter content and plant water content were determined after drying all plant materials at 60 °C until the material reached a stabilized weight. Five times throughout each sowing season, if weather conditions were favorable, *PAR* measurements above and below the canopy were taken at three locations within each experimental plot using a ceptometer (model: AccuPAR LP-80, Decagon, Pullman, WA, USA). The measurements below the canopy were taken at the soil's surface diagonally across the rows. *PAR* readings were taken at noon to eliminate the influence of solar zenith angle and within a short period to reduce variations in readings of solar

irradiance. *PAR* measurements did not account for the radiation reflected from the ground towards the canopy, as neither account for the radiation reflected by the overall crop.

Table 1. Agronomic data of biomass sorghum at the Texas A&M AgriLife Research Center at Weslaco, TX, USA in the 2013 and 2016 sowing seasons.

Agronomic Data	2013			2016		
Sowing date	1 April	9 May	14 June	4 April	11 May	15 June
Harvest date	26 July	29 August	8 October	2 August	8 September	13 October
Length of season	116 days	112 days	116 days	120 days	120 days	120 days
Sampling (DAS)	42, 70, 86, 101, 116	36, 55, 76, 92, 112	26, 53, 80, 98, 116	32, 64, 87, 108, 120	22, 53, 75, 97, 120	26, 50, 77, 104, 120
Min. Temp.	21.9 °C	24.4 °C	24.3 °C	23.7 °C	25.1 °C	24.9 °C
Max. Temp.	32.6 °C	34.8 °C	34.5 °C	33.9 °C	35.4 °C	35.8 °C
Water irrigation	356 mm	457 mm	279 mm	381 mm	406 mm	432 mm
Precipitation	152 mm	141 mm	273 mm	131 mm	201 mm	118 mm
Solar radiation	2331 MJ m ⁻²	2350 MJ m ⁻²	2255 MJ m ⁻²	2642 MJ m ⁻²	2724 MJ m ⁻²	2482 MJ m ⁻²
Total GDU	1961 °C	2141 °C	2179 °C	2177 °C	2336 °C	2342 °C
Daylight > 12:20 h	116 days	112 days	91 days	120 days	120 days	120 days

2.2. Computation and Statistical Analysis of Field Data

Biomass sorghum phenological development was monitored for every sowing season across the two-year study. As a result, sorghum phenological development was made more comparable across years and sowing dates. This development was recorded daily and then converted into growing degree days (GDU, °C) following the 3-segment linear function procedure described by Soltani and Sinclair [3] for each of the sowing seasons from sowing to harvest. The cardinal temperatures for the sorghum phenological development were: base temperature equals 10 °C [17], lower optimal temperature equals 30 °C, upper optimal temperature equals 37 °C, and ceiling temperature equals 45 °C [3].

Accumulated *DB* was determined as the measured *DB* from the sampled area at each sampling date. *DB* accumulation of the three sorghum hybrids over the three sowing seasons was compared by fitting the changes in the *DB* to a sigmoidal growth model [18], as given in the following equation:

$$DB = \frac{DB_{max}}{1 + a \times \exp(-c \times t)} \quad (1)$$

where DB_{max} is the maximal end value of growth, a is a constant parameter ($a > 0$), c is the crop growth rate ($c > 0$), and t is the duration from sowing to harvest. Parameter estimates were derived for each experimental unit following the procedures described by Gregorczyk [19]. After deriving the relationship between *DB* with time from the sigmoidal growth function, the slope of the curve or the crop growth rate (CGR, Mg ha⁻¹ d⁻¹) was calculated. CGR was defined as the rate of change of *DB* with time ($\Delta DB / \Delta t$). CGR is calculated as the increase in biomass (ΔDB) between two dates divided by the increase in time (Δt). For more accurate values, the first derivative (dDB/dt) of Equation (1) was taken. The CGR for each sorghum hybrid at each sowing season was obtained. The first derivative was equated to zero ($dDB/dt = 0$) (which is the time when the tangent to the curve is horizontal) to obtain the day when maximum growth occurred during the sowing season.

According to Monteith and Unsworth [20], *PAR* represents about 48% of total solar radiation ($PAR = 0.48 \times R_s$). The canopy extinction (K) coefficient is a parameter that describes the efficiency of the light interception for the canopy [21]. K is determined by the inclined leaf angle and the solar zenith angle, and it is usually calculated with the Beer Lambert Law [22], which in many cases is simply expressed by $K = -\ln(I_i/I_0)/LAI$, where I_i is the solar radiation under the canopy, I_0 is the solar radiation above the canopy, and LAI is the leaf area index. The ratio of I_i to I_0 is known as transmittance (τ), which is the fraction of irradiance transmitted by the canopy. The τ values and LAI were measured on all the plots at locations with adequate crop stand to estimate K for every sorghum hybrid

during all sowing seasons. The K values, along with LAI , were used to estimate the $IPAR$ by the crop canopy that was calculated as follows: $IPAR = PAR \times [1 - \exp(-K \times LAI)]$.

Radiation use efficiency (RUE), expressed as $g\ MJ^{-1}$ of $IPAR$ or $Kg\ ha^{-1}\ MJ^{-1}\ m^2$, was estimated in two ways. The first, called the CGR method, was estimated as the slope of the linear regression equation with the intercept coefficient forced to zero between the CGR ($g\ m^{-2}\ d^{-1}$) and the quantity of daily $IPAR$ ($MJ\ m^{-2}\ d^{-1}$) for each sampling date. The CGR ($g\ m^{-2}\ d^{-1}$) was calculated from the first derivative of the accumulated DB sigmoidal growth function. This RUE method was used to see the relationship between CGR and fractional light interception and compare the biomass sorghum growth of every hybrid at each of the different sowing seasons. The second method, called the accumulative biomass method, was estimated as the slope of the linear regression equation with the intercept coefficient forced to zero between accumulated DB productivity ($g\ m^{-2}$) and accumulated $IPAR$ ($MJ\ m^{-2}$) beginning after the first sampling for each biomass sorghum hybrid at each sowing season. The RUE regression equations in the second were fitted by using the observed data obtained from the sampling dates. Then, RUE values were determined for each sorghum hybrid at each sowing season of the experiment.

Differences in accumulated DB through phenological development across sowing dates and years were evaluated by comparing best-fit lines of biomass. Analysis of variance (ANOVA) was conducted for the two years of biomass sorghum experiments. Biomass sorghum data were analyzed in both separate and combined years. Data from all sowing seasons were examined in a combined ANOVA to explore how biomass sorghum hybrids responded to different weather conditions and provide information on the interaction between treatments (sorghum hybrids), seasons, and years. These analyses were conducted in the software R [23] using the “agricolae” package [24] for DB , LAI at harvest time, and RUE. If treatment effects were significant, mean comparisons were conducted using the least significant difference (LSD) at the alpha level of 0.05. Each hybrid’s K coefficient was estimated using linear regression analysis in R. Additionally, R was used to conduct regression analyses to describe the relationship of CGR to daily $IPAR$ and DB on accumulated $IPAR$. After performing the analyses, if differences were not observed between years, data of each sowing season of both years were pooled, and estimates of RUE were tested using the same approach.

2.3. Economic Analysis

The cost of production of the three sorghum hybrids was estimated for each sowing date evaluated. The input quantities used and production activities conducted were carefully recorded through the experiment. The three biomass sorghum hybrids were employed with identical production management practices within the same sowing date. Consequently, variations in the cost of production between hybrids and sowing dates are primarily given by differences in yields (i.e., due to variable harvesting cost) and inputs used (e.g., frequency and quantity of irrigation water applied (Table 1)), respectively. The overall cost of production was calculated using the estimated mean DB values per hybrid and sowing date. All production expenses were standardized to reflect 2021 input prices. Namely, production expenditures consisted of fixed and variable harvesting and hauling costs ($USD\ 358.30\ ha^{-1} + USD\ 7.10\ Mg^{-1}$), fertilizer ($USD\ 74.69\ ha^{-1}$), seeds ($USD\ 61.60\ ha^{-1}$), irrigation water ($USD\ 0.16\ mm\ ha^{-1}$), farm labor ($USD\ 230.52\ ha^{-1}$), fuel ($USD\ 57.84\ ha^{-1}$), machinery repair and maintenance ($USD\ 45.67\ ha^{-1}$), 5% interest on operating capital, irrigation system investment ($USD\ 136.40\ ha^{-1}$), machinery depreciation and equipment investment ($USD\ 108.08\ ha^{-1}$), and land rent ($USD\ 209.95\ ha^{-1}$). The average cost per Mg of DB produced was also estimated for comparison purposes.

The expected feedstock price at harvest was used to estimate the revenues associated with each sowing date. Specifically, a 5-year (2017–2021) average monthly biomass price was calculated using the weekly straw-based biomass price reported by AMS [25]. Lastly, the average net return of each energy sorghum hybrid and sowing date was calculated to assess their economic feasibility.

3. Results

3.1. Phenological Development

Optimal soil water and nutrients were ensured during the two-year experiment, and the plant response was calculated on a daily basis. Growing degree units from emergence to physiological maturity did not vary among years. Sorghum reached physiological maturity from 94 to 109 days after sowing for early-sowing season, from 79 to 103 days after sowing for mid-sowing season, and from 81 to 106 days for late-sowing season. Accumulated growing degree units from sowing to physiological maturity ranged from 1594 to 1842, 1498 to 1814, and 1604 to 1620 for early-, mid-, and late-sowing seasons, respectively, in 2013, and from 1702 to 1822, 1704 to 2002, and 1829 to 2095 for early-, mid-, and late-sowing seasons, respectively, in 2016.

3.2. Dry Biomass Accumulation

Dry biomass (DB) productivity ranged across hybrids and years from 20.5 to 35.7, 23.1 to 35.0, and 19.2 to 32.4 Mg ha⁻¹ for the early-, mid-, and late-sowing seasons, respectively, while DB productivity averaged across sowing seasons and years were 23.7, 25.4, and 30.4 Mg ha⁻¹, for Pioneer 877F, Blade ES 5140, and Blade ES 5200, respectively. The lowest averaged DB productivities were observed in the late-sowing season for the three sorghum hybrids, while early- and mid-sowing seasons showed the best productivities. This higher productivity was due to the better weather conditions compared to the treatments in the late-sowing season.

Field data from all sowing seasons were examined in an analysis of variance to explore how sorghum hybrids responded to different environmental conditions and provide information on the nature of the interaction among hybrids and seasons. Total DB differs significantly among hybrids and sowing seasons between the two-year study period. Every year, the effect of season was significant ($p < 0.05$), indicating that DB was significantly affected by the season. Similarly, the effect of the hybrid treatment was significant, indicating that DB was significantly affected by the sorghum hybrid (Table 2). However, the interaction between season (S) and hybrid (H) was not significant, which means that these two effects do not act upon each other at all. Early- and mid-sowing seasons showed higher DB productivities, and the difference in sorghum hybrids at each season was highly significant. Blade ES 5200 hybrid achieved the highest yield at every sowing season. This hybrid produced the maximum yield in the three seasons, while the Pioneer 877F produced lower yields in most sowing seasons.

Table 2. Analyses of variance (p values) of total dry biomass (DB) productivity, leaf area index (LAI), and radiation use efficiency (RUE) at harvest during the two-year study period.

Year	Effect	DB	LAI	RUE
2013	Season (S)	0.006	0.025	0.029
	Hybrid (H)	<0.001	<0.001	<0.001
	S × H	0.481	0.354	0.177
2016	Season (S)	0.009	0.032	0.002
	Hybrid (H)	<0.001	<0.001	<0.001
	S × H	0.061	0.159	0.014

Biomass sorghum productivity is the result of the accumulation of DB with time. The accumulation generally follows a sigmoidal curve. The three sorghum hybrids have a comparable accumulated DB across seasons and years (Figure 1). The best fit of accumulated DB on phenological time was similar in the two years. However, minor differences are observed when one pays attention to the same season but different years. These differences are because the length of seasons in the experiments in 2013 was shorter than those in 2016. In this case, the shorter season, the fewer growing degree units.

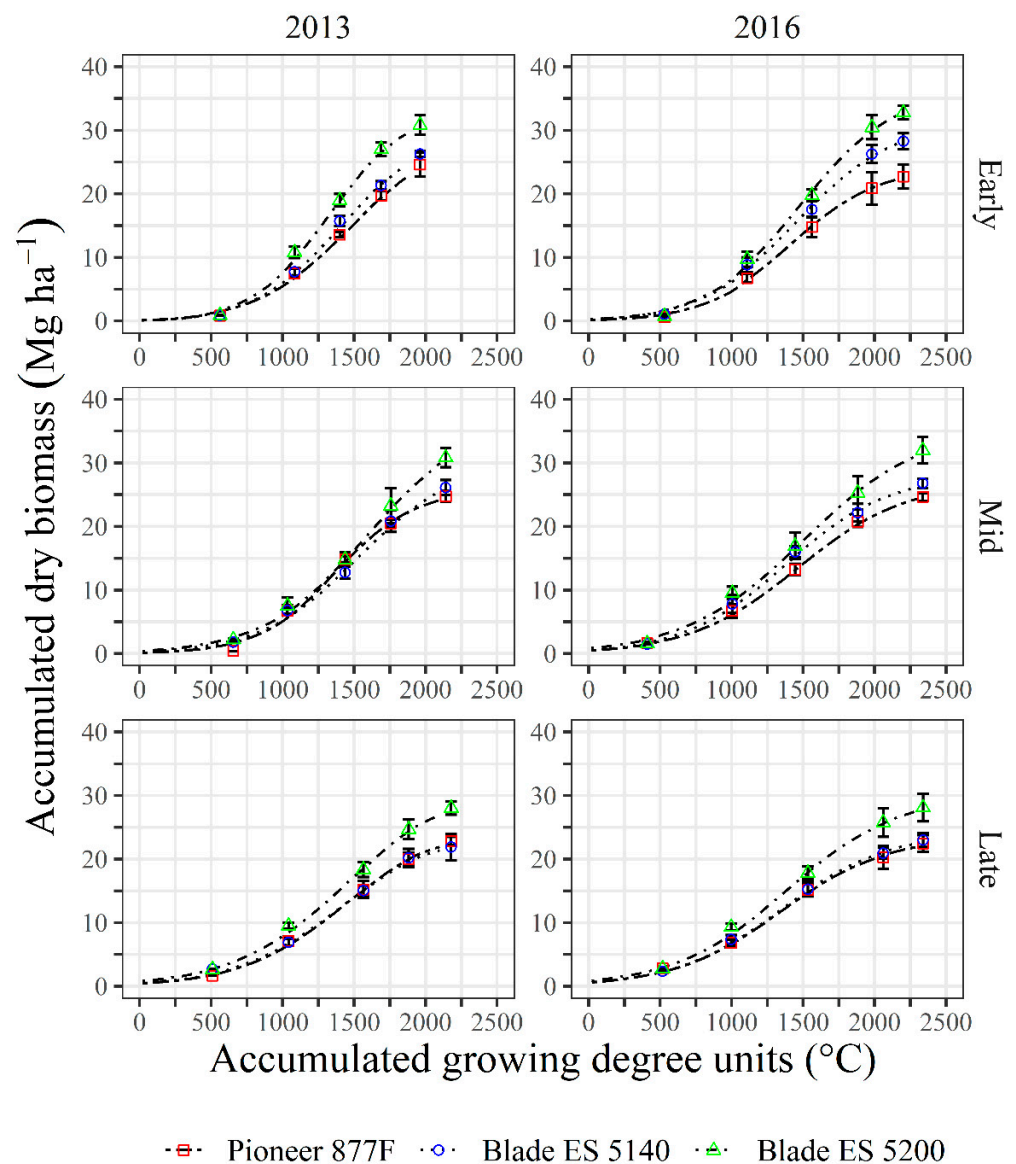


Figure 1. Observed (symbols and error bars) average dry biomass (DB) productivity across sowing seasons at the two-year experiment and the best fit of the sigmoidal equation for the three biomass sorghum hybrids at the three sowing dates during the two-year experiment.

3.3. Leaf Area Index, Canopy Extinction Coefficients and Intercepted Photosynthetic Active Radiation

Leaf area index (LAI) ranged across hybrids and years at final harvest from 5.0 to 6.0, 4.9 to 6.1, and 4.7 to 5.2 $\text{m}^2 \text{m}^{-2}$, for the early-, mid-, and late-sowing seasons, respectively, while LAI ranged across sowing seasons and years were 4.7 to 5.2, 4.9 to 5.9, and 4.9 to 6.1 Mg ha^{-1} , respectively, for Pioneer 877F, Blade ES 5140, and Blade ES 5200. The lowest averaged LAI values were observed in the late-sowing season for the three sorghum hybrids, while early- and mid-sowing seasons showed the best LAI values. These higher LAI values were due to the better weather conditions than the late-sowing season treatment. Leaf area index (LAI) differed significantly among hybrids and sowing seasons during the two-year experiment (Table 2). There were significant differences in LAI among the three hybrids ($p < 0.05$) at harvest for every sowing season in the two-year experiment. However, the calculated p -values for the Season $\times$ Hybrid (S $\times$ H) interaction were not significant ($p > 0.05$). This result implies that these two effects do not act upon each other at all. Higher LAI values at final harvest were observed in sorghums that were sown in the early- and

mid-sowing seasons, then decreased by approximately 20% of the maximum *LAI* values in the late season (Figure 2). The hybrids' ranking over the sowing seasons was consistent among hybrids (Blade ES 5200 > Blade ES 5140 > Pioneer 877F). The *LAI* of the hybrid Blade ES 5200 showed averaged values higher than $6 \text{ m}^2 \text{ m}^{-2}$ when sown in the early season (in the two-year study). The Pioneer 877F hybrid showed the lowest *LAI* values during the experiments.

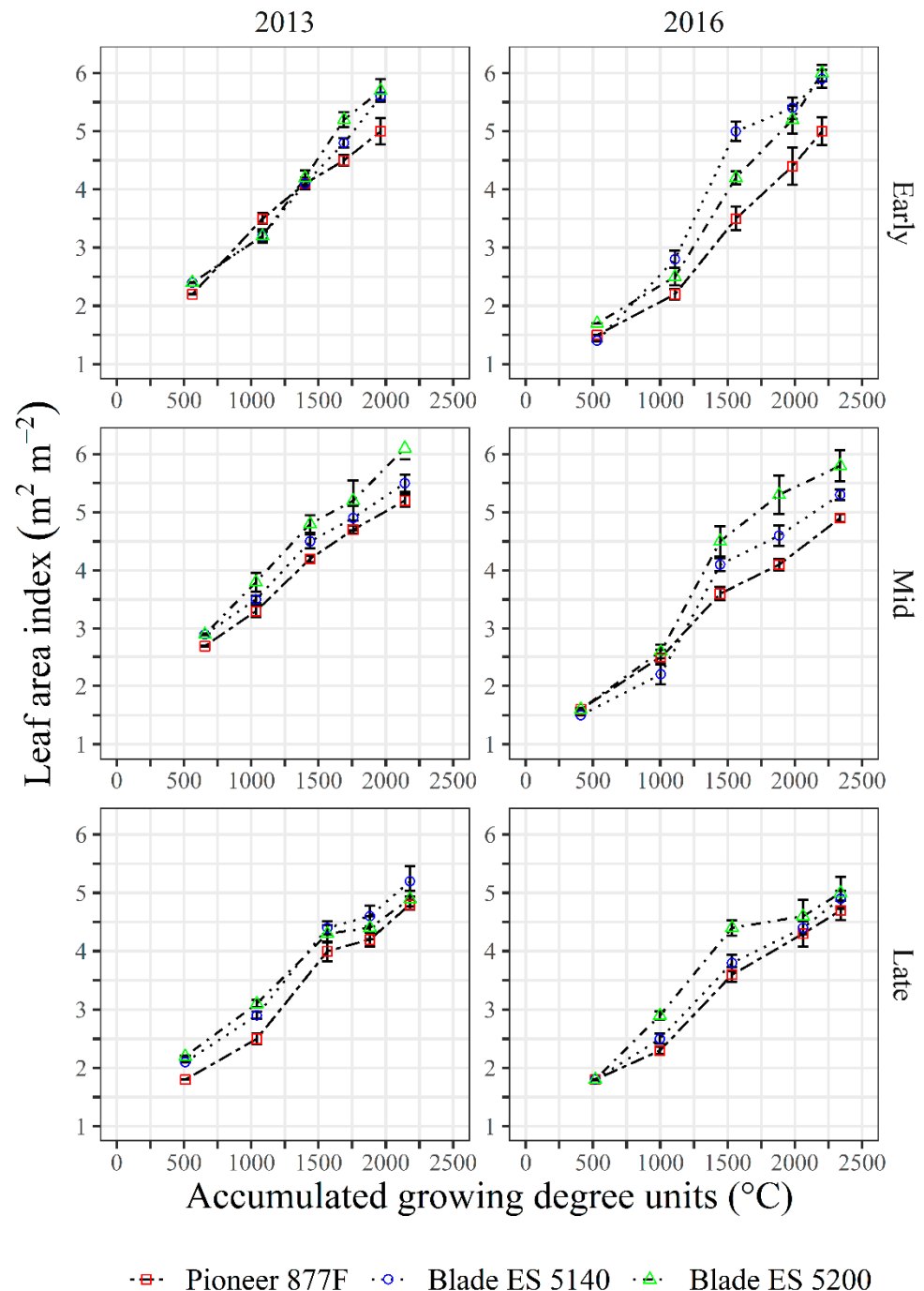


Figure 2. Observed (symbols and error bars) average leaf area index (*LAI*) across sowing seasons at the two-year experiment for the three biomass sorghum hybrids at the three sowing dates during the two-year experiment.

A canopy extinction coefficient (*K*) was obtained from *PAR* measurements (transmitted and incident) for each sorghum hybrid and crop *LAI* from emergence to maturity. The

K coefficient is an important crop parameter that describes the crop's leaf architecture, which is essential for determining the $IPAR$ for each day. The K coefficient is a constant that is used during the entire crop life cycle [3]. Figure 3 shows the K results for each sorghum hybrid in all growing seasons. Combining readings from all seasons, a one-way ANOVA determined differences among sorghum hybrids. It was observed that the F statistic value was 21.148, and it was highly significant ($p < 0.001$). Thus, it is prudent to reject the null hypothesis of the equal mean value of K across the sorghum hybrids. The average ($\pm$ sd) K coefficients were greater for Pioneer 877F ($K = 0.77 \pm 0.07$), followed by Blade ES 5140 ($K = 0.67 \pm 0.08$) and Blade ES 5200 ($K = 0.66 \pm 0.08$). A Tukey's HSD (honest significance difference) test showed the pair-wise difference of average K of the three sorghum hybrids at a 0.05 level of significance. Three possible pair-wise comparisons were obtained. The results showed that only for the pair between the hybrids Blade ES 5140 and Blade ES 5200, there was no statistical difference between them ($p = 0.666$). This result implies that the average K coefficient from Pioneer 877F is statistically different from the other hybrids ($p < 0.05$).

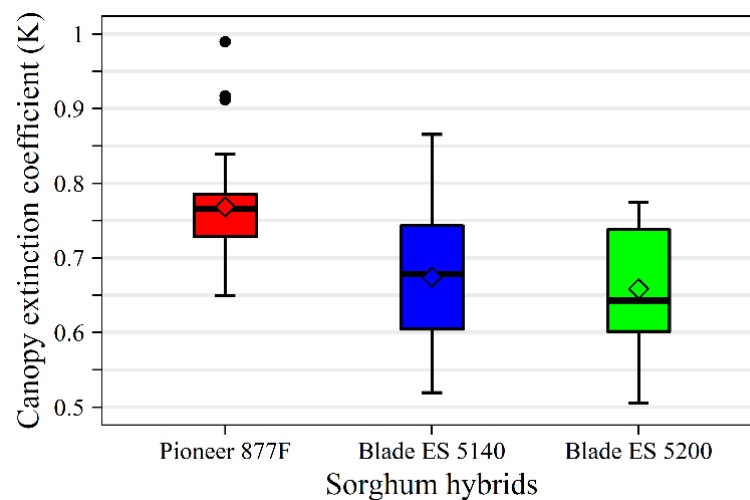


Figure 3. Estimated canopy extinction coefficients (K) during the 2-year experiment for the three sorghum hybrids. Mean values are indicated by rhombus symbols and outliers are indicated by black circles.

The fraction of PAR intercepted by the biomass sorghum canopy was estimated for all biomass sorghum hybrids at all sampling dates. High LAI drove the higher light interception. Figure 4 shows the relationship between the fraction of PAR intercepted by the canopy and LAI . That relationship resulted in a sigmoidal function. Combining estimations from all seasons, a one-way ANOVA determined no differences among the sorghum hybrids. An F statistic value of 0.15 was obtained with a $p = 0.861$. Therefore, the null hypothesis of the equal mean values of the fraction of intercepted PAR across the sorghum hybrids is accepted. The three sorghum hybrids captured over 95% of incident PAR at $LAI > 4.0$. It principally occurred during the vegetative growth phase.

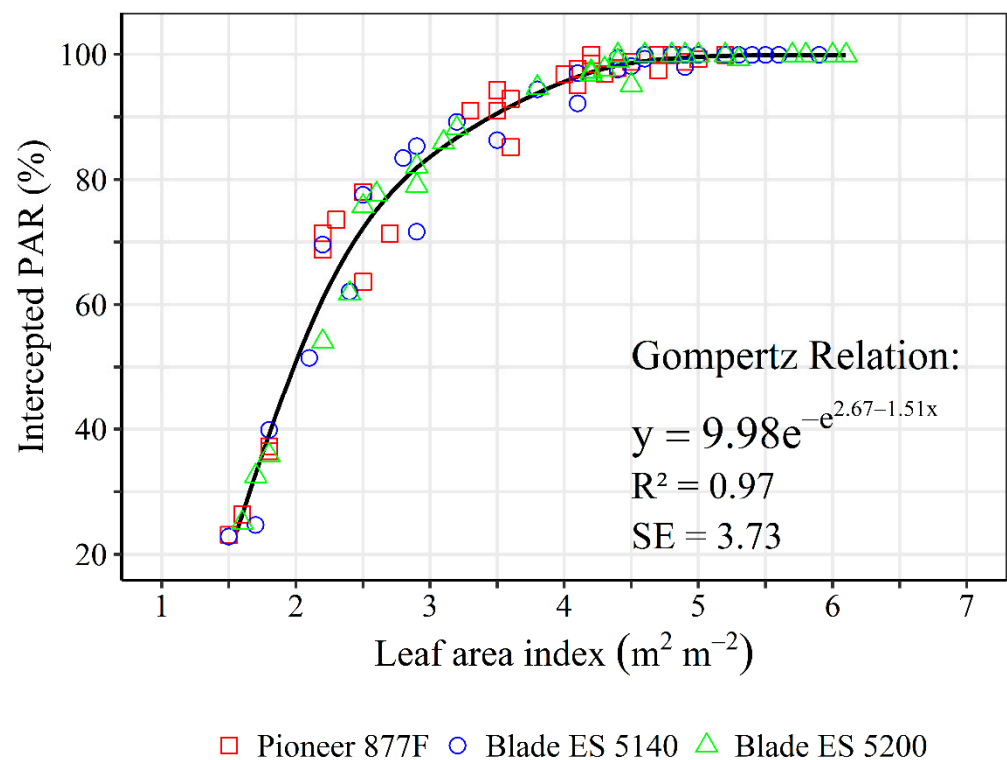


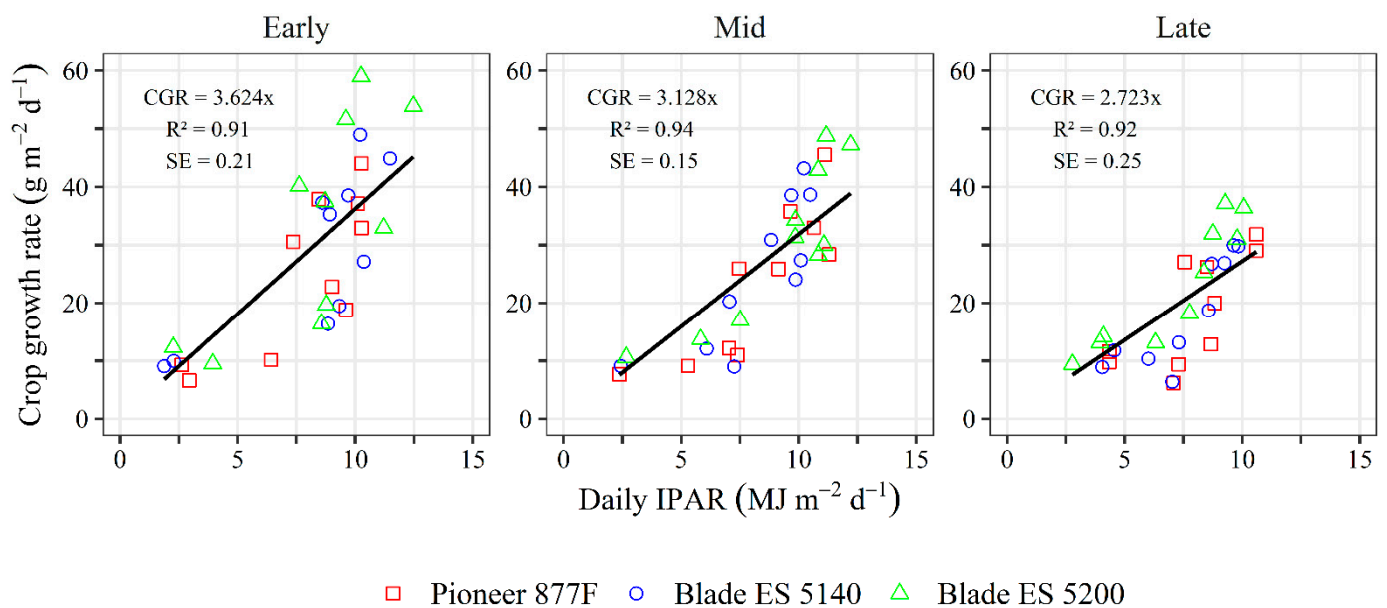
Figure 4. Fraction of intercepted photosynthetic active radiation (*IPAR*) as a function of leaf area index (*LAI*) for the three biomass sorghum hybrids.

3.4. Plant Growth Analysis

The periodic sampling of crops to measure leaf area and aboveground *DB* is essential in developing methodologies for estimating *CGR* and light interception, features that define crop productivity. Average and maximum *CGR* values of biomass sorghum during the two-year experiment are presented in Table 3. Average *CGR* per sowing season was 23.0, 22.9, and 19.8 g m⁻² d⁻¹ for early, mid-, and late seasons, respectively, while the average *CGR* per hybrid was 19.4, 20.9, and 25.4 g m⁻² d⁻¹ for Pioneer 977F, Blade ES 5140, and Blade ES 5200, respectively. Maximum *CGR* observed at the vegetative phase ranged from 31.6 to 60.8 g m⁻² d⁻¹. While *CGR* at harvest ranged from 6.2 to 28.8 g m⁻² d⁻¹. In Figure 5, the slope of the regressions of *CGR* on the rate of *IPAR* for every sowing season can be observed. This method also provides an estimate of *RUE* per sowing season; however, this method was used to evaluate the performance of the sorghum hybrids at each sowing season. Estimates of *CGR* did not differ between both years, so all *CGR* estimates were pooled to obtain a single parameter per sowing season. Combining *CGR* estimation of all sorghum hybrids per sowing season, one-way ANOVA determined significant differences among sowing seasons. An *F* statistic value = 4.002 and a *p* = 0.022 were observed. Thus, it is prudent to reject the null hypothesis of the equal mean value of *CGR* across the sowing seasons. The highest *CGR* values were observed in the early-sowing season, while the lowest *CGR* values were observed in the late-sowing season. The Blade ES 5200 hybrid showed the highest *CGR* values at all sowing seasons, while the Pioneer 877F hybrid showed the lowest.

Table 3. Average and maximum crop growth rates (CGR, $\text{g m}^{-2} \text{d}^{-1}$) of biomass sorghum hybrids per sowing date during the two-year experiment.

Sorghum Hybrid	Sowing Date	Average CGR	Maximum CGR
2013			
Pioneer 877F	Early	20.8	44.2
	Mid	21.6	46.6
	Late	19.1	34.1
Blade ES 5140	Early	22.3	49.1
	Mid	23.0	43.7
	Late	18.5	32.3
Blade ES 5200	Early	26.3	60.8
	Mid	27.1	50.4
	Late	23.3	39.1
2016			
Pioneer 877F	Early	18.6	39.2
	Mid	20.1	35.8
	Late	17.8	31.6
Blade ES 5140	Early	23.4	45.9
	Mid	21.5	39.2
	Late	18.3	32.5
Blade ES 5200	Early	27.2	54.6
	Mid	25.6	43.0
	Late	22.4	38.3

**Figure 5.** Absolute biomass sorghum crop growth rate (CGR) as a function of intercepted photosynthetically active radiation (IPAR) for each of the sowing seasons. The equation reports the slope of the linear regression (forced to zero intercept) of CGR on IPAR.

3.5. Radiation Use Efficiency

Radiation use efficiency was determined as the slope of the linear regression of accumulated DB with the intercept forced to zero at the different samplings, and the corresponding intercepted IPAR. The RUE values were different from sowing seasons and hybrids ($p < 0.05$) (Table 2); however, they were similar between years ($p > 0.05$); thus, both years were pooled. Figure 6 shows statistics for the linear regression (intercept forced to 0) between cumulative DB and cumulative IPAR for each biomass sorghum hybrid for each

sowing season. The relationship resulted in a considerable estimate of RUE with a lower standard error. In general, the highest values of RUE were observed in the energy hybrids (Blade ES 5200 > Blade ES 5140 > Pioneer 877F). However, the response in RUE varied significantly among the sowing seasons. RUE varied from 2.920 to 4.157 g MJ⁻¹ among all experimental plots. For the Pioneer 877F, the highest RUE value was observed on those sorghums sown in the early season with 3.155 g MJ⁻¹, and the lowest when sown in the late season with 2.920 g MJ⁻¹. For the hybrid Blade ES 5140, the highest RUE values were observed on those sorghum plants sown in the early season with 3.639 g MJ⁻¹ and the lowest in the late season with 2.943 g MJ⁻¹. For the hybrid Blade ES 5200, the highest RUE values were observed in the early season at 4.157 g MJ⁻¹, and the lowest values were observed in the late season with 3.597 g MJ⁻¹, respectively. Early sowing of biomass sorghum used *IPAR* more efficiently than those sown in mid and late sowing since it produced more biomass with less *IPAR*.

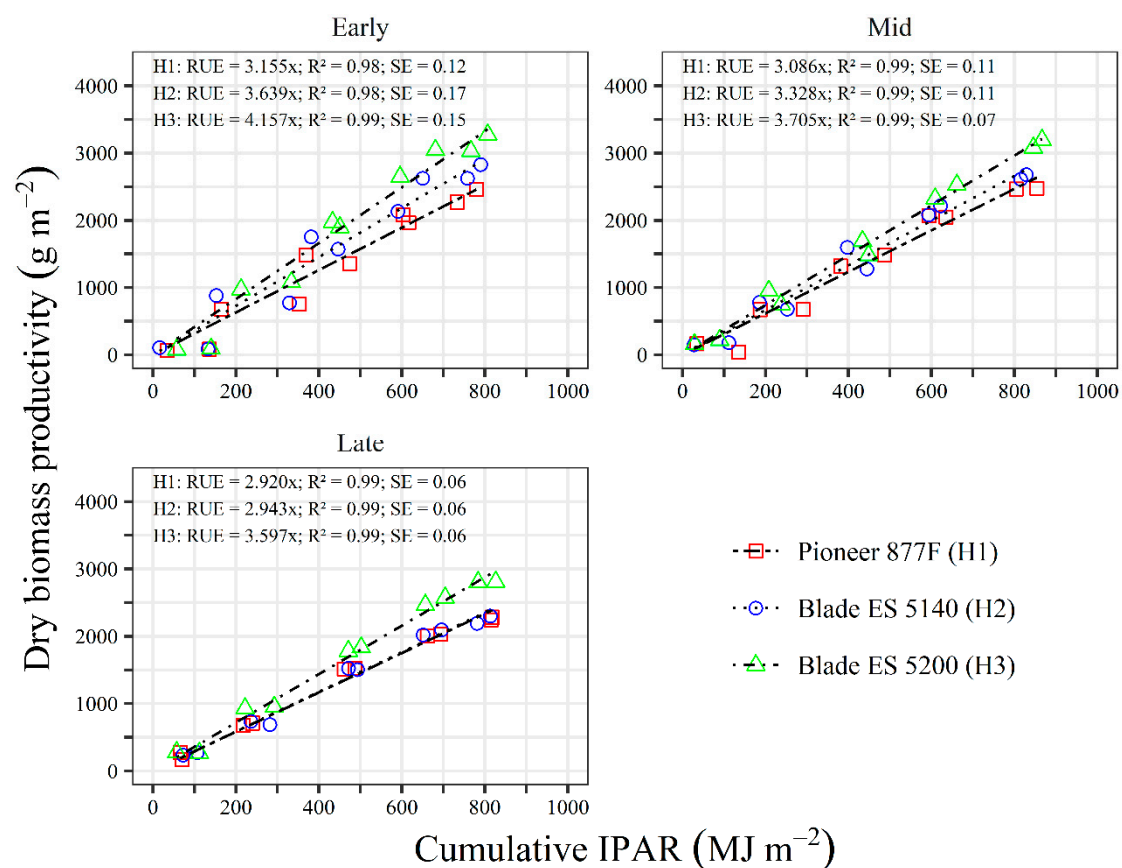


Figure 6. Linear regressions (intercept coefficient forced to 0) between *DB* productivity and cumulative *IPAR* for the three biomass sorghum hybrids at each sowing season.

3.6. Economic Feasibility Analysis

Estimated revenues, costs of production, and net returns are summarized in Table 4. The economic analysis is conducted at the farm level; thus, reported revenues represent the potential farm cash receipts to farmers for supplying biomass to a biofuel refinery. Higher revenues were estimated for hybrids Pioneer 877F (USD 2263.04 ha⁻¹) and Blade ES 5200 (USD 2804.78 ha⁻¹) when they sowed late and in early sowing for Blade ES 5140 (USD 2392.86 ha⁻¹). Higher revenues were associated with higher biomass yields (within sowing dates) and relatively higher feedstock prices at harvest. However, it is essential to note that biomass yields and prices moved in the opposite direction through the growing season. As a result, we observed a mixed effect on revenues with higher revenues when yields are lower, but prices are higher. For instance, expected prices at harvest were

estimated at USD 87.88 Mg⁻¹, USD 84.77 Mg⁻¹, and USD 99.91 Mg⁻¹ for the early, mid-, and late-sowing seasons, respectively. On the other hand, the lowest revenue for hybrid Pioneer 877F was calculated in early sowing, mid sowing for Blade ES 5200, and late sowing for Blade ES 5140.

Table 4. Estimated revenue, production cost, the net return, and the average cost of DB by biomass sorghum hybrid and sowing date.

Sowing Date	Biomass Sorghum Hybrid	Revenue (USD ha ⁻¹)	Production Cost (USD ha ⁻¹)	Net Return (USD ha ⁻¹)	Average Cost per Unit of Mass (USD Mg ⁻¹)
Early	Pioneer 877F	2082.67	1522.12	560.55	64.43
	Blade ES 5140	2392.86	1560.74	832.12	57.30
	Blade ES 5200	2774.12	1592.10	1182.01	50.41
Mid	Pioneer 877F	2102.25	1540.54	561.71	62.12
	Blade ES 5140	2254.70	1515.89	738.82	56.99
	Blade ES 5200	2669.90	1551.21	1118.68	49.26
Late	Pioneer 877F	2263.04	1512.72	750.32	66.79
	Blade ES 5140	2243.72	1509.18	734.54	67.22
	Blade ES 5200	2804.78	1549.72	1255.06	55.20

Higher yields were also associated with higher production costs per hectare due to the variable harvest and hauling costs. Overall, lower production costs per hectare were estimated for all hybrids on late-sowing dates. In particular, hybrid Blade ES5200 had the highest cost of production per unit of area but, at the same time, the lowest cost per unit of biomass produced (Table 4). Regarding sowing dates, relatively lower average production costs per unit of biomass were obtained when sowing in mid-season. For instance, the lowest average biomass production costs were USD 62.12 Mg⁻¹ for Pioneer 877F, USD 56.99 Mg⁻¹ for Blade ES5140, and USD 49.26 Mg⁻¹ for Blade ES5200. Conversely, the highest average costs of production per unit of biomass were obtained when sowing late for all hybrids.

Expected net returns above specified costs are positive for all three sorghum hybrids. Like gross returns, the highest net returns were also estimated when sowed late for Pioneer 877F (USD 750.32 ha⁻¹) and Blade ES 5200 (USD 1255.06 ha⁻¹) and in early sowing for Blade ES 5140 (USD 832.12 ha⁻¹). Regarding individual performance, in general, higher net returns were obtained for hybrid Blade ES5200, followed by hybrids Blade ES5140 and Pioneer 877F, respectively.

4. Discussion

This study evaluated the potential productivity and growth response of three biomass sorghums under variable timed sowing dates regarding the accumulation of DB and LAI with time, CGR, and DB per unit of incident light. The experiments conducted in this study were designed to provide optimal growth conditions for the three sorghum hybrids.

The accumulated DB differed among the three hybrids across the different sowing seasons. Sorghums sown in the early and mid season showed similar yields, while the yield was lower for those sown in late sowing. The DB productivity was lower by around 20% when the sorghum hybrids were sown in the late-sowing season despite being well irrigated and fertilized. The observed difference in DB accumulation in biomass crops is generally affected by weather conditions, crop management, photoperiod, and the plant's efficiency to intercept solar energy and convert it into biomass. In this study, the reduced DB observed for energy sorghums in the late season was possibly due to the decreased number of days with more than 12:20 h of daylength (Table 1) and the changes in temperature in both forage and energy sorghums. Additionally, the reduced biomass in the late-sowing season resulted from the reduced PAR interception due to the lower LAI in the growing season. The maximum observed yield on the hybrid Blade ES 5200 (more than 35 Mg ha⁻¹ from early and mid-season) was comparable to those reported in Temple, TX, by Meki, Ogoshi [26], who obtained a maximum yield of 37.4 Mg ha⁻¹. Similarly, Rinaldi and

Garofalo [5] obtained 34.07 Mg ha^{-1} under full irrigation in Southern Italy; Dercas and Liakatas [27] reported 31 Mg ha^{-1} in Greece with 680 mm of cumulative ET.

The term *LAI* describes the sum of areas of all leaves in the foliage per unit area of ground. Leaf area development is critical for crop light interception and dry matter production, and hence it has a substantial influence on crop yield [28]. With a decrease in *LAI*, the interception of solar radiation and photosynthesis are also both reduced. Therefore, *LAI* is a determinant parameter that affects the amount of *IPAR* and respiration, which are essential functions in achieving maximum crop production. Observed *LAI* accumulation was highest in the early and mid-season but lower in the late season (Figure 2). The lower *LAI* observed in the late season may be due to the late sowing that altered the environmental factors, such as light quantity, temperature, and photoperiod, that are directly related to plant growth. Thus, this alteration shortened the time between emergence and maturity, affecting the leaf development. The *LAI* values obtained in our study are comparable to those reported by Rinaldi and Garofalo [5], who reported the *LAI* values between 5.52 and $6.39 \text{ m}^2 \text{ m}^{-2}$ of biomass sorghum in a full irrigation experiment, but less than those reported by Ceotto et al. [29] and Olson et al. [30], who in a similar experiment reported higher *LAI* values that ranged from 7.0 to $8.4 \text{ m}^2 \text{ m}^{-2}$, respectively. According to Bégué [31], crops with *LAI* greater than 4.0 can intercept more than 90% of the incident *PAR*. In this study, however, the sorghum hybrids reached a higher capacity to intercept more than 95% of the incident *PAR*, with an *LAI* greater than 4.0 when they were sown in the early and mid seasons. In contrast, *LAI* observed in late sowing was not sufficient to reach maximum light interception resulting in less biomass accumulation throughout the growing season.

The canopy extinction coefficient (*K*) is a dimensionless parameter that combines all factors affecting *PAR* in the canopy and is assumed constant throughout crop cycle life. It is a crop-species-specific parameter that involves plant canopy characteristics such as leaf angle, size, shape and thickness, and leaf area properties. However, the *K* values are affected by management factors, such as plant density, row spacing, and sun angle. The results of this study are comparable to those reported by Narayanan, Aiken [32]. They found $K = 0.668$ in a field experiment performed to evaluate eight sorghum genotypes for biomass production at Kansas State University. However, the *K* values obtained for the energy hybrids (0.66 and 0.67 , for Blade ES 5140 and Blade ES 5200, respectively) obtained in this study were lower than that reported by Rinaldi and Garofalo [5] ($K = 0.75$) in a three-year field experiment conducted to determine the RUE of biomass sorghum production over different irrigation regimes in Southern Italy. Smaller estimates of *K* were observed in the experimental units that showed higher *LAI* values, and larger estimates were obtained during maturity due to many dead leaves on the plants. This result agreed with Sinclair [33], who concluded that *K* decreased with an increase in *LAI*. The sorghum hybrids differed in the cumulative *IPAR*, which was calculated from *LAI* and a given constant value of *K*. Therefore, the differences in *IPAR* were due mainly to differences in *LAI* among the sorghum hybrids.

Crop growth rate (CGR) is the principal determinant analyzing biomass growth and its relation to light interception. Based on the *DB* samples obtained in the field experiments across all sowing seasons, the accumulated *DB* was modeled for each sorghum hybrid at each sowing season. The constant parameters that describe the shape of the growth curve were obtained by nonlinear regression analysis. After deriving a relationship between productivity and date from a sigmoidal equation, it was essential to know the rate of how sorghum grew at each sowing season. The curve slope is the CGR, defined as the rate of *DB* change with time. Therefore, analysis of CGR was necessary for evaluating the sowing date treatment differences among the sorghum hybrids with productivity. In the early and mid-seasons, the highest CGR values were observed (Figure 5). These results may be due to the better weather conditions, such as light interception, temperature, and photoperiod, contributing to higher leaf development and thus higher biomass accumulation. However, during the late season, reduced *LAI* values caused lower *IPAR*, resulting in a low biomass accumulation during the crop growing cycle. Additionally, energy sorghums also resulted

affected in the late-sowing season by the reduced number of days with daylight >12:20 h, which resulted in a decreased duration of the vegetative stage, hastening maturation. The results obtained from those analyses were similar to those reported by Meki, Ogoshi [26], who observed an average CGR in biomass sorghum of $22.5 \text{ g m}^{-2} \text{ d}^{-1}$ in 2013 in Temple, Texas.

Radiation use efficiency (RUE) was determined as the slope of the first-order linear regression (the intercept coefficient forced to 0) of *DB* at different sampling dates and the corresponding cumulative *IPAR* (Figure 6). Most of the RUE values obtained in the present study were within the published seasonal RUE values for sorghum, which varied from 1.2 to $4.3 \text{ g MJ}^{-1} \text{ IPAR}$ [2,34,35]. Similar to our RUE values, for sorghum, the values were 3.4 g MJ^{-1} [36], 3.48 g MJ^{-1} [29], and 3.55 g MJ^{-1} [27]. The results of this study agree with those reported by Houx III and Fritsch [4]. They found a decrease in RUE in late sowing of sweet sorghum in a study conducted to evaluate the influence of sowing dates on sweet sorghum in Columbia, MO, USA. The highest RUE values were found in early and mid-sowing seasons for the three sorghum hybrids. Then, the RUE values decreased for late sowing (Figure 6). The RUE values obtained in this study agree with Demetriades-Shah [37], who reported that RUE values for a given crop vary with the site and growing seasons. Generally, our results confirmed that RUE was a sensitive crop parameter significantly dependent on sorghum hybrid, *IPAR*, sowing date, and the number of days with daylight > 12:20 h. Estimated values of RUE obtained from both the CGR method and the accumulative biomass method did not differ significantly in the early and mid-seasons; however, they do in the late season. It may be due to the environmental constraints that change shoot biomass by altering leaf area expansion, maintenance, respiration, and crop cycle duration [38]. Therefore, RUE is a parameter that can be used as a constant at different sowing seasons when estimated biomass sorghum production is predicted for forage sorghum hybrids. In contrast, it cannot be used as a constant when estimated *DB* is predicted for energy sorghum hybrids. Rinaldi and Garofalo [5] reported that RUE was significantly dependent on crop water consumption and that it cannot be considered a constant crop parameter for biomass sorghum.

The rate of biomass accumulation is primarily influenced by the amount of light intercepted by plants over an optimum temperature range [39]. Therefore, sorghum hybrids were entirely regulated by the accumulation of growing degree units and daylength photoperiod triggers because. According to Childs, Miller [40], daylength is the most critical climatic factor regulating sorghum hybrids' flowering. According to Rooney, Blumenthal [6], photoperiod-sensitive sorghums will not flower and produce high biomass through continued vegetative growth if sown when the daylength is more than the photoperiod trigger of 12:20 h. Sorghum entered the vegetative period when full canopy cover, light interception, and photosynthesis were maximal. Thus, the sorghum growth rate varied mainly with changes in daylength across sowing seasons. Seasonal sorghum production was highest when the full cover was achieved early in the sowing seasons and maintained through the growing season with favorable weather conditions. Water and nutrient uptake mainly occurred during the vegetative growth phase when large amounts of water and nutrients were needed to create a photosynthesis mechanism in leaves. Thus, a more significant portion of biomass accumulation was obtained during the linear growth period.

Extending the harvesting seasons is one of the main challenges that dedicated biomass energy crops must overcome [41]. This study evaluated the economic feasibility of the considered sorghum hybrids and sowing dates in terms of the resulting expected net returns. Economic results suggest that maintaining a steady supply of sorghum-based biomass from late July to mid-October is a viable option. Specifically, positive net returns were estimated for all sorghum hybrids and throughout the evaluated production season. Furthermore, hybrid Blade ES 5200 had the highest net returns and lowest average production costs per unit of biomass produced. The economic analysis also highlighted the positive role that higher yields have on the viability of potential biomass feedstock crops. In particular, it was found that higher net returns and lower average biomass costs were associated with higher yields. Moreover, revenue losses due to decreasing yields in late sowing were offset

by higher market biomass prices during that time of the year. A similar yield effect was found by Zapata, Ribera [14], where a 1 percent increase in the yield of energy cane is expected to lead to a 1.52 percent increase in the overall probability of economic success of a biofuel enterprise.

5. Conclusions

The results obtained in this study show that crop variety and sowing date have a crucial impact on sorghum development. Hybrids' sorghum development was sensitive to temperature, solar irradiance, and photoperiod. Variations in sorghum hybrids' responses were observed on *DB*, *LAI*, *CGR*, and *RUE* under different sowing seasons. Energy sorghums exhibited the highest potential in *DB* productivity and *LAI*. They were most cost-effective when sown during early and mid-seasons (April and May), producing more than 30 Mg per ha if supplied with adequate water and nutrients. The biomass sorghum growth rate is influenced mainly by the sorghum hybrid, light interception, temperature, and photoperiod. Maximum growth rates are obtained with energy sorghums when they are sown in the early and mid-seasons. *RUE* values varied among hybrids across sowing seasons. Energy sorghums (Blade ES 5200 and Blade ES 5140) resulted in higher *RUE* values if sown in early and mid-seasons to forage sorghum (Pioneer 877F). These results suggest that energy sorghums are more efficient at converting solar radiation to biomass in non-stress water or nutrient conditions and if weather conditions are favorable. Based on our results, we recommend that crop simulation models that base their biomass accumulation on *RUE* should use values of at least 3.5 g MJ⁻¹ for energy sorghum and 3.1 g MJ⁻¹ for forage sorghum. The positive expected net returns obtained throughout the evaluated production season suggest that dedicated biomass sorghum varieties can be an economically viable source of cellulosic feedstock. Additional energy-efficient metrics, such as energy efficiency and greenhouse emissions, can complement our analysis to comprehensively evaluate novel biomass crops.

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