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Optimizing Bioethanol (C_2H_5OH) Yield of Sweet Sorghum Varieties in a Semi-Arid Environment: The Impact of Deheading and Deficit Irrigation

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Abstract: Bioethanol production offers promise in mitigating environmental impacts from ethanol consumption despite water scarcity. This study endeavors to evaluate the nuanced influence of different deheading times (45 days before harvest, 21 days before harvest, and no deheading) along with varying water regimes on select sweet sorghum cultivars (Honey, Willy, MN1500, and Atlas), focusing on yield traits, theoretical ethanol production, and water productivity. Findings underscore the substantial impact of cultivation practices on bioethanol yield. A water deficit ranging from 30% to 70% resulted in a discernible reduction in stalk yields of 17.86% to 18.54% and in sugar yields of 0.2 to 0.31 Mg ha^{-1}, accompanied by a corresponding decline in theoretical ethanol yield of 120.9 to 180.9 L ha^{-1}. Additionally, notable enhancements in Brix and sugar content of 16.32% to 18.42% and 16.81% to 19.03%, respectively, were observed across both seasons. Of particular significance, the Honey variety, subjected to a 30% water deficit and deheading at 21 days before harvest, demonstrated exceptional growth and yield characteristics. These empirical insights furnish valuable guidance for optimizing sweet sorghum cultivation practices, thereby augmenting sustainable bioethanol production and propelling forward the frontier of renewable energy technologies towards a more environmentally sustainable future.

Keywords: *Sorghum bicolor*; biofuel; Brix; drought stress; CWP

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Citation: Alsanad, M.A.; Emara, E.I.R. Optimizing Bioethanol (C_2H_5OH) Yield of Sweet Sorghum Varieties in a Semi-Arid Environment: The Impact of Deheading and Deficit Irrigation. *Water* **2024**, *16*, 1456. https://doi.org/10.3390/w16101456

Academic Editors: Yousef Alhaj Hamoud, Hiba Shaghaleh, Tingting Chang and Fei Gao

Received: 17 April 2024
Revised: 6 May 2024
Accepted: 17 May 2024
Published: 20 May 2024

1. Introduction

Energy serves as a pivotal catalyst for economic growth, spurred by the escalating global demand for petroleum fuels. In response to pressing environmental concerns such as greenhouse gas emissions and climate change, there has been a notable shift towards renewable alternatives [1]. Plants have emerged as promising candidates to address this demand, particularly for bioethanol production [2]. Among the array of potential bioethanol crops including wheat, corn, and sorghum, sweet sorghum stands out [3]. Notably, Davila-Gomez et al. [4] underscored sweet sorghum's competitive advantage in ethanol production, citing its efficacy in ethanol yield, nitrogen utilization, and water efficiency [5,6].

Sweet sorghum (*Sorghum bicolor* L.) presents several advantages over corn. Hills et al. [7] demonstrated its capacity to produce approximately 23% more fermentable sugars while requiring 17% less water and 37% less nitrogen fertilizer. It is pertinent to highlight that sweet sorghum is primarily comprised of sucrose, constituting about 85% of its stalk weight [8]. Notably, it can yield up to 8000 L ha^{-1} of ethanol, which surpasses the yield of maize twofold and exceeds that of sugarcane by 30% [9,10]. Vermerris et al. [11] provided insights into sweet sorghum's biomass yields and sugar content, ranging from 20 to 119 Mg ha^{-1} and 14% to 20%, respectively [5].

Both sweet sorghum and sugarcane exhibit significant biomass production potential, with sweet sorghum yielding approximately 65–95 t ha^{-1} and sugarcane around 55–75 t ha^{-1}. Sweet sorghum can produce about 2500 L ha^{-1} of ethanol, approximately half of sugarcane's yield. Research on second-generation ethanol derived from sorghum has shown yields ranging from 3200 to 5220 L per hectare [12]. The genetic diversity of sorghum contributes to its versatile stem biochemical composition, offering various applications including bioenergy derived from forage [13].

Borrell et al. [14] emphasized grain sorghum's drought tolerance and high water-use efficiency, particularly in water deficit conditions, making it an optimal choice for water-saving practices, especially in semi-arid and arid regions [6,15]. Additionally, grain sorghum's adaptability to water stress and its rapid growth, high sugar accumulation, and biomass production potential have been noted [16,17]. Sweet sorghum also exhibits wide adaptability to subtropical regions, showing tolerance to waterlogging and salinity, while yielding substantial biomass [18,19]. Achieving desirable fresh biomass yield typically requires rainfall in the range of 500–1000 mm [20]. Various research endeavors have explored the cultivation of irrigated sorghum on a global scale. Mastrorilli et al. [21] and Garofalo and Rinaldi [22] delved into the correlation between water availability and the quality of sorghum plants. Additionally, Cotton et al. [23] documented sorghum yields ranging from 13.2 to 30.1 t ha^{-1} in both irrigated and dryland plots.

Several studies have explored the impact of different irrigation treatments on sorghum yield and bioethanol production. Campi et al. [24] reported sorghum yields ranging from 10 to 40 t ha^{-1} under varying irrigation levels. Aydinsakir and Erdurmus [25] found that different irrigation levels significantly affected yield components and bioethanol production in sweet sorghum. The highest yields were obtained under full irrigation, while rain-fed irrigation levels exhibited a higher Brix content [25].

Determining the optimal deheading time holds paramount importance in maximizing ethanol yield in sweet sorghum. This is attributed to the transient accumulation of various carbohydrates such as starch, fructans, isoprenoids, monosaccharides, and sucrose in the stem during the pre-filling stage [26]. By curbing grain formation and enhancing sugar accumulation in the stalks and cellulosic biomass, soluble sugar accumulation can be bolstered, thereby amplifying the potential of sweet sorghum as a feedstock for biofuel and table sugar production. Attaining high biomass and Brix levels is imperative for enhancing the suitability of biofuel sorghum [27].

Optimizing deheading times is crucial for maximizing the bioethanol yield in sweet sorghum by enhancing sugar accumulation in the stalks and cellulosic biomass. Sustainable biofuel production, particularly bioethanol, offers potential solutions for reducing greenhouse gas emissions and fuel consumption [28,29]. Sweet sorghum has gained attention for ethanol production, with various studies investigating its environmental impact, conversion technologies, GHG emissions, energy balance, and economic performance [30,31]. Major biofuel producers such as Brazil, the European Union, and the UK have significantly contributed to global biofuel production, emphasizing the environmental benefits and potential of ethanol in reducing emissions and enhancing energy security [28,29].

In this study, our main objective was to uncover the optimal deheading time for specific sweet sorghum varieties under varying levels of water deficit in a semi-arid environment. We aimed to investigate how different deheading times and water scarcity impact the production of bioethanol, a promising renewable fuel. By delving into this research, we aimed to shed light on the ideal conditions for maximizing bioethanol production from sweet sorghum, considering the intricate interplay between deheading time, water deficit, and bioethanol yield. The findings of this study will contribute to the development of sustainable biofuel production methods, particularly in semi-arid regions, and provide valuable insights for enhancing the efficiency and environmental impact of bioethanol production.

2. Materials and Methods

2.1. Experimental Site and Climate Condition

During the 2019 (1st season) and 2020 (2nd season) summer seasons, two field experiments were carried out at the experimental station of the Faculty of Agriculture, Cairo University, located in Giza, Egypt (30° 01′ 05.3″ N, 31° 12′ 21.1″ E) around 18 m above sea level. The soil-type of the experimental site is classified as a clay loam soil (*Loamic (lo)*), with 0.095, 0.085, and 0.670% of N, P, and K available, respectively, and a pH of 8.54. Figure 1 presents the average meteorological data acquired from a meteorological station located at the Agricultural Research Center in Giza, Egypt.

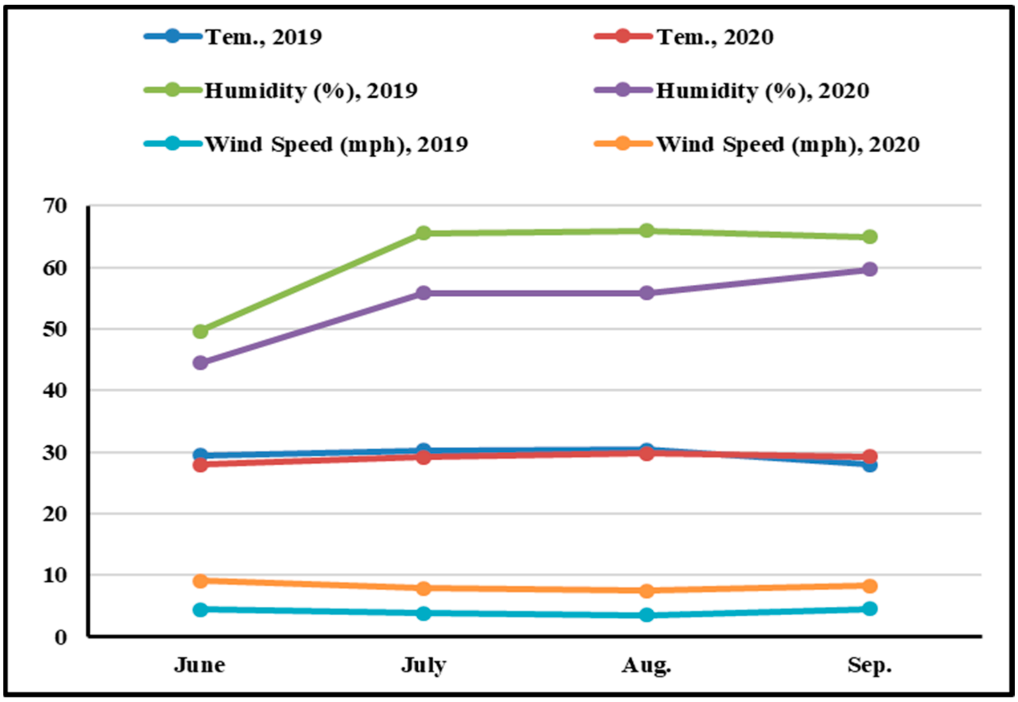

Figure 1. Average meteorological data during the summer for both seasons 2019 and 2020.

2.2. Irrigation Water Characteristics and Applications

The current case study consists of three water regime applications (i.e., 30, 50, and 70% of soil available water (SAW)). The moisture content at root-depth was determined using an TDR electronic sensor, and the level of irrigation water was quantified according to Blaney and Criddle's [32] formula, as follows:

$$\mathrm{Qar} = \mathrm{Dp}(\mathrm{Qf} - \mathrm{Qw}) * \mathrm{R} * \mathrm{plotarea} \tag{1}$$

where Q_{ar}: irrigation level per plot (m^3 $plot^{-1}$), D_p: depletion level (i.e., 0.3, 0.5, or 0.7), Q_f: field capacity (40%), Q_w: wilting point (19%), and R: root length (cm).

Crop water productivity (CWP) for stalks and actual sugar yield (kg m^{-3}) were calculated according to Jensen [33]:

$$\mathrm{CWP} = \frac{\mathrm{Yield}\left(\mathrm{kg\ ha}^{-1}\right)}{\mathrm{Actual\ applied\ water}\left(\mathrm{m}^3\mathrm{ha}^{-1}\right)} \tag{2}$$

2.3. Crop Material, Planting, Deheading, and Chemical Fertilizer Application

Honey, Willy, MN1500, and Atlas sweet sorghum varieties were obtained from the Agriculture Research Center located in Giza, Egypt. Plot size: 12 m^2, with 0.2 m between hills and 0.6 m between ridges. Before planting, plots were fertilized with phosphorus

(15.5% P_2O_5) at a rate of 72 kg P_2O_5 ha^{-1} as a broadcast application. Sowing dates were the 24th and 29th of June in the 2019 and 2020 summer seasons, respectively, with a Sowing rate of 600,000 seed ha^{-1}. The irrigation was immediately applied after planting. Nitrogen (ammonium nitrate 33.5% N), at rate of 238 kg N ha^{-1}, was split into two doses—one applied after thinning (23 days from sowing) and one 2 weeks later, along with potassium sulphate (48% K_2O) at a rate of 81 kg K_2O ha^{-1}, which was applied with the second dose of nitrogen. Three deheading timings: A: 45 days before harvesting, B: 21 days before, and C: no deheading (until harvesting).

2.4. Harvest, Yield, and Their Components

All plants within the middle three rows of each subplot were chopped down at the root. Harvested plots were bundled, divided into leaves, stems, and panicles, and each component was individually weighed in the lab. The number of leaves and nodes and the stalk height were measured. Fresh and dry stalk yield were calculated using the weight of samples taken from the three middle rows and the area of the sample row (m^2), and was converted to mg ha^{-1}. The stems were crushed and the juice was collected, and by using a hand-held refractometer, the Brix was determined. Furthermore, by using the Wortmann et al. [34] formula, the converted sugar yield (CSY) was calculated:

$$\text{CSY} = (\text{FSY} - \text{DSY}) * \text{Brix} * 0.75 \tag{3}$$

where FSY is the fresh stalk yield (Mg ha^{-1}) and DSY is the dry stalk yield (Mg ha^{-1}). Using the following formula by Rutto et al. [35], the theoretical ethanol yield was obtained:

$$\text{Theoretical ethanol yield}\left(\text{L ha}^{-1}\right) = \text{CSY}\left(\text{Mg ha}^{-1}\right) * 0.585$$

The greatest possible output of ethanol produced by fully inverting sucrose and fully fermenting all of the resultant and native glucose was used to calculate the conversion factor (0.585 L ethanol per kilogramme of sugar) [36].

The equation of Liu et al. [37] was used to calculate the total soluble sugar content:

$$\text{Total soulble sugar content} = 0.8111 * \text{Brix} - 0.37285 \tag{4}$$

2.5. Varietal Tolerance

According to the formula of Fernandez [38], the stress tolerance index (STI) was obtained:

$$\text{STI} = \frac{\text{yn} - \text{ys}}{(\text{Yn})^2} \tag{5}$$

where y_n: yield of the variety without stress, y_s: yield of the variety under stress, and Y_n: the mean yield of varieties without stress. Varieties with high values of STI will be tolerant to drought stress [39].

2.6. Experimental Design and Statistical Analysis

The experimental design involved a split plot design; differing water deficits were employed in the main plots, with subplots undergoing 3 different deheadings (three levels: deheading 21 days before harvesting, deheading 45 days before harvesting, and no deheading), and 4 varieties/cultivars were employed as a sub-sub plot. Each treatment was replicated three times to ensure robustness and reliability in our findings. Furthermore, the acquired data were tested statistically by examining the variance of the split plot design, as described by Snedecor and Cochran [40]. According to Steel and Torrie [41], L.S.D. was employed to compare treatment averages at a 5% level of significance. The Mstat-C [42] computer software package (v6.5.1) analysis of variance approach was used for all statistical studies.

3. Results

3.1. Deficit Applications Effect on Sweet Sorghum

The results presented in Table 1 highlight the impact of different water deficit levels on various growth parameters and quality characteristics of sweet sorghum in both seasons. With the exception of the theoretical ethanol yield and converted sugar yield (CSY), statistically significant effects were observed for all measured variables.

Table 1. Effect of water deficit on plant fresh weight (g), Number of leaves, Number of nodes, stalk fresh weight (g), and stalk height (cm) in the 2019 and 2020 summer seasons.

Water Deficit	Plant Fresh Weight (g)		No. of Leaves		No. of Nodes		Stalk Fresh Weight (g)		Stalk Height (cm)	
	1st Season	2nd Season	1st Season	2nd Season	1st Season	2nd Season	1st Season	2nd Season	1st Season	2nd Season
30%	935.5 a	951.0 a	18 a	17 a	17 a	16 a	720.6 a	738.1 a	230.9 a	234.1 a
50%	872.8 b	902.7 b	16 b	16 b	15 b	15 b	649.6 b	649.0 b	202.1 b	215.7 b
70%	767.6 c	789.3 c	15 c	14 c	14 c	13 c	591.8 c	601.2 c	184.6 c	186.4 c
L.S.D.	33.1	48.1	1	1	1	1	25.8	26.4	7.5	8.0

Reducing the water deficit stress from 70% to 30% resulted in notable improvements in plant growth and quality attributes. Specifically, in the first season, the plant fresh weight increased by 21.9%, the stalk fresh weight increased by 21.8%, and the stalk height increased by 25.1% compared to the highest water deficit level. Additionally, the 30% water deficit condition led to the highest number of leaves and nodes. Similar trends were observed in the second season, with respective increases of 20.5%, 22.8%, and 25.6% in plant fresh weight, stalk fresh weight, and stalk height under the 30% water deficit.

Conversely, increasing the applied water deficit from 30% to 70% resulted in significant enhancements in the Brix (BX) percentage and total soluble sugar content. In the first season, the Brix percentage increased by 16.3% and the total soluble sugar content increased by 16.8% compared to the lowest water deficit level. These values further increased to 18.4% for the Brix percentage and 19.0% for the total soluble sugar content in the second season.

These findings demonstrate the influence of water deficit levels on the growth, quality, yield, and ethanol component characteristics of sweet sorghum. They provide valuable insights into optimizing water management strategies to enhance the production of bioethanol from sweet sorghum in a semi-arid environment.

The results presented in Table 2 reveal the relationship between water application and stalk yields in sweet sorghum. An increase in the amount of water applied resulted in higher stalk yields, with the greatest stalk fresh yield (120.33 and 123.26 Mg ha^{-1}) and stalk dry yield (71.90 and 72.46 Mg ha^{-1}) observed under the 30% water deficit treatment.

Table 2. Effect of water deficit on Brix (%), total soluble sugar content (%), stalk dry yield, and stalk fresh yield (Mg ha^{-1}) in the 2019 and 2020 summer seasons.

Water Deficit	Brix (%)		Total Soluble Sugar Content (%)		Stalk Dry Yield (Mg ha^{-1})		Stalk Fresh Yield (Mg ha^{-1})	
	1st Season	2nd Season	1st Season	2nd Season	1st Season	2nd Season	1st Season	2nd Season
30%	14.46 c	14.39 c	11.36 c	11.30 c	71.90 a	72.64 a	120.33 a	123.26 a
50%	15.89 b	15.67 b	12.51 b	12.34 b	64.28 b	61.52 b	108.49 b	108.38 b
70%	16.82 a	17.04 a	13.27 a	13.45 a	58.84 c	60.07 c	98.83 c	100.40 c
L.S.D.	0.35	0.48	0.28	0.25	4.10	3.97	4.30	6.31

Significant differences were observed between the 50% and 70% water deficit treatments, indicating the impact of varying water levels on stalk yield production. These findings highlight the importance of water management in sweet sorghum cultivation and emphasize the potential benefits of implementing a 30% water deficit treatment to maximize stalk yield in a semi-arid environment.

Table 3 presents the results for the effect of water deficit treatments on the converted sugar yield (CSY) and theoretical ethanol yield in both seasons. Interestingly, the 50% water deficit treatment stood out, demonstrating the highest values of CSY (5.39 Mg ha^{-1}) and theoretical ethanol yield (3152.0 L ha^{-1}).

Table 3. Effect of water deficits on CSY (Mg ha^{-1}) and theoretical ethanol yield (L ha^{-1}) in the 2019 and 2020 summer seasons.

Water Deficit	CSY (Mg ha^{-1})		Theoretical Ethanol Yield (L ha^{-1})	
	1st Season	2nd Season	1st Season	2nd Season
30%	5.25 a	5.46 ab	3072.45 a	3196.12 a
50%	5.27 a	5.51 a	3082.00 a	3221.93 a
70%	5.05 a	5.15 b	2951.55 a	3015.22 a
L.S.D.	N.S.	0.29	N.S.	N.S.

Compared to the other water deficit treatments, the 50% water deficit treatment showed a significant average increase of 7.0% in CSY and 168.6 L ha^{-1} in ethanol production. These findings suggest that moderate water deficit levels does not reduce the theoretical production of ethanol, theoretically enhancing the overall efficiency and productivity of bioethanol production.

3.2. Varieties' Effects

Tables 4–6 provide valuable insights into the influence of different sweet sorghum varieties on the examined characteristics. The data reveal significant variations between varieties regarding productivity and quality traits.

Table 4. Effect of sweet sorghum varieties on plant fresh weight (g), Number of leaves, Number of nodes, stalk fresh weight (g), and stalk height (cm) in the 2019 and 2020 summer seasons.

Varieties	Plant Fresh Weight (g)		No. of Leaves		No. of Nodes		Stalk Fresh Weight (g)		Stalk Height (cm)	
	1st Season	2nd Season	1st Season	2nd Season	1st Season	2nd Season	1st Season	2nd Season	1st Season	2nd Season
Honey	891.1 a	883.2 a	16 b	16 b	15 b	14 c	712.7 a	710.0 a	237.3 a	336.1 a
Willy	834.4 b	840.0 b	19 a	18 a	18 a	17 a	654.3 b	656.1 b	228.0 b	230.0 b
MN1500	850.6 b	829.4 b	14 c	14 d	13 c	13 d	623.0 c	627.2 bc	175.7 c	170.1 d
Atlas	858.4 ab	861.1 ab	16 b	15 c	15 b	15 b	625.9 bc	614.7 c	182.5 c	185.0 c
L.S.D.	38.3	39.1	1	1	1	1	29.8	37.1	8.7	8.9

Table 5. Effect of sweet sorghum varieties on Brix (%), total soluble sugar content (%), stalk dry yield, and stalk fresh yield (Mg ha^{-1}) in the 2019 and 2020 summer seasons.

Varieties	Brix (%)		Total Soluble Sugar Content (%)		Stalk Dry Yield (Mg ha^{-1})		Stalk Fresh Yield (Mg ha^{-1})	
	1st Season	2nd Season	1st Season	2nd Season	1st Season	2nd Season	1st Season	2nd Season
Honey	14.38 c	14.24 c	11.29 c	11.18 c	68.37 a	61.74 b	119.03 a	118.57 a
Willy	18.09 a	17.98 a	14.30 a	14.21 a	65.42 ab	60.23 b	109.27 b	109.57 b
MN1500	16.32 b	16.45 b	12.87 b	12.97 b	62.59 b	63.20 a	104.05 c	104.74 b
Atlas	14.10 c	14.20 c	11.06 c	11.14 c	63.64 ab	62.72 ab	104.52 bc	102.65 b
L.S.D.	0.41	0.43	0.33	0.35	4.74	5.41	4.97	7.83

Table 6. Effect of sweet sorghum varieties on CSY (Mg ha^{-1}) and theoretical ethanol yield (L ha^{-1}) in the 2019 and 2020 summer seasons.

Varieties	CSY (Mg ha^{-1})		Theoretical Ethanol Yield (L ha^{-1})	
	1st Season	2nd Season	1st Season	2nd Season
Honey	5.46 ab	6.07 ab	3195.64 ab	3550.62 b
Willy	5.95 a	6.65 a	3480.60 a	3892.19 a
MN1500	5.07 b	5.13 b	2968.82 b	2998.30 c
Atlas	4.32 c	4.25 c	2529.11 c	2488.04 d
L.S.D.	0.51	0.59	299.90	304.10

Across both seasons, the Honey variety exhibited superior performance compared to the other varieties in several aspects. It displayed higher values of plant fresh weight, measuring 891.1 g and 883.3 g in the first and second seasons, respectively. Additionally, the Honey variety showcased greater stalk fresh weight per plant, with values of 712.7 g and 710.0 g in the respective seasons. Moreover, this variety attained the tallest plant height, reaching 237.3 cm in the first season and 336.1 cm in the second season. Furthermore, the Honey variety demonstrated impressive stalk fresh yield, achieving 119.03 Mg ha^{-1} and 118.57 Mg ha^{-1} in the first and second seasons, respectively.

These results highlight the significant variations between sweet sorghum varieties, with the Honey variety demonstrating superior productivity and quality characteristics in terms of plant growth and stalk yield.

3.3. Deheading Time Effect on Sweet Sorghum

Tables 7–9 present compelling evidence regarding the effects of deheading at different time intervals on the growth and quality of sweet sorghum. The results demonstrate notable improvements in various parameters when deheading was performed 21 days before harvest, followed by deheading at 45 days before harvest and no deheading.

Table 7. Effect of head-cutting time on the effect of sweet sorghum varieties on plant fresh weight (g), Number of leaves, Number of nodes, stalk fresh weight (g), and stalk height (cm) in the 2019 and 2020 summer seasons.

Head Cutting Time	Plant Fresh Weight (g)		No. of Leaves		No. of Nodes		Stalk Fresh Weight (g)		Stalk Height (cm)	
	1st Season	2nd Season	1st Season	2nd Season	1st Season	2nd Season	1st Season	2nd Season	1st Season	2nd Season
A	834.3 b	837.7 a	15 c	15 c	14 c	14 c	645.5 a	647.3 a	214.6 a	215.3 a
B	861.8 ab	859.4 a	16 b	16 b	15 b	15 b	670.4 a	669.2 a	198.7 bc	197.0 bc
C	879.8 a	881.0 a	17 a	17 a	16 a	16 a	646.1 a	647.6 a	204.4 c	203.0 c
L.S.D.	33.1	N.S.	1	1	1	1	N.S.	N.S.	7.5	8.0

Table 8. Effect of head-cutting time on Brix (%), total soluble sugar content (%), stalk dry yield, and stalk fresh yield (Mg ha^{-1}) in the 2019 and 2020 summer seasons.

Head Cutting Time	Brix (%)		Total Soluble Sugar Content (%)		Stalk Dry Yield (Mg ha^{-1})		Stalk Fresh Yield (Mg ha^{-1})	
	1st Season	2nd Season	1st Season	2nd Season	1st Season	2nd Season	1st Season	2nd Season
A	15.40 b	15.51 b	12.12 b	12.21 b	63.79 a	64.30 a	107.80 a	108.10 a
B	17.42 a	17.63 a	13.75 a	13.93 a	66.66 a	63.78 a	111.95 a	111.76 a
C	14.36 c	14.42 c	11.27 c	11.32 c	64.57 a	65.02 a	107.90 a	108.15 a
L.S.D.	0.35	0.48	0.28	0.25	N.S.	N.S.	N.S.	N.S.

Table 9. Effect of head-cutting time on CSY (Mg ha^{-1}) and theoretical ethanol yield (L ha^{-1}) in the 2019 and 2020 summer seasons.

Head Cutting Time	CSY (Mg ha^{-1})		Theoretical Ethanol Yield (L ha^{-1})	
	1st Season	2nd Season	1st Season	2nd Season
A	5.08 b	5.09 b	2974.10 b	2980.53 b
B	5.92 a	6.34 a	3460.47 a	3711.05 a
C	4.66 c	4.66 c	2728.76 bc	2728.69 bc
L.S.D.	0.44	0.29	259.70	265.12

Deheading at 21 days before harvest emerged as the most effective treatment in enhancing sweet sorghum growth and quality characteristics in both seasons. This treatment resulted in significant increases in plant and stalk height, stalk fresh weight, Brix content, total soluble sugar content, fresh and dry yield, converted sugar yield (CSY), and ethanol yield.

Compared to the no deheading treatment (harvest time), deheading at 21 days before harvest resulted in a substantial improvement in Brix content, with increases of 21.3% and 22.26% in the first and second seasons, respectively. Similarly, the total soluble sugar content showed significant enhancements of 22.01% and 23.06% in the respective seasons. Furthermore, this treatment led to a boost in stalk fresh yield of 3.75% and 3.34%, in CSY of 27.10% and 36.10%, and in ethanol output of 26.82% and 36.00% in the first and second seasons, respectively.

These findings highlight the positive impact of deheading, particularly when performed 21 days before harvest, on various growth and quality parameters of sweet sorghum. The results emphasize the potential of this practice to enhance the overall productivity and ethanol yield of sweet sorghum crops.

3.4. Sweet Sorghum Drought Tolerance and Crop Water Productivity

The effect of different water deficit levels (30%, 50%, and 70%) on sweet sorghum cultivation and crop water productivity (CWP) is elucidated in this study. The total amounts of water applied varied based on the irrigation deficit, with values of 5367, 4045, and 2820 m^3 ha^{-1} in the first season and 5298, 4010, and 2796 m^3 ha^{-1} in the second season for the respective deficit levels.

Crop water productivity (CWP) exhibited substantial variations in both seasons, depending on the severity of water deficit. Remarkably, the 70% water deficit treatment displayed the highest CWP values for stalk yield (35.04 and 35.91 kg m^{-3}), converted sugar yield (1.79 and 1.84 kg m^{-3}), and ethanol production (1.05 and 1.08 L m^{-3}) in the first and second seasons, respectively. Increasing the water deficit from 30% to 70% resulted in a progressive rise in all CWP values. Specifically, CWP_{sy} (crop water productivity for stalk yield) increased by 55.1% and 54.3%, CWP_{csy} (crop water productivity for converted sugar yield) increased by 82.7% and 78.6%, and $CWP_{ethanol}$ (crop water productivity for ethanol production) increased by 84.2% and 80.0% in the first and second seasons, respectively.

Regarding the varieties, the Honey variety exhibited the highest CWP_{sy} values, followed by Willy, MN1500, and Atlas in descending order. Notably, the Willy variety outperformed the other varieties in terms of CWP for both converted sugar yield and ethanol production. The response of sweet sorghum varieties to water stress varied, with the Atlas variety demonstrating the highest stress tolerance index for both stalk and converted sugar yields. This was followed by the Willy, MN1500, and Honey varieties in descending order, indicating their varying levels of tolerance to water stress (Table 10).

Table 10. Stress tolerance index (STI).

STI	Varieties			
	Honey	**Willy**	**MN1500**	**Atlas**
Stalk yield	0.0004	0.0009	0.0009	0.0011
CSY	−0.0028	−0.0036	−0.0006	0.0391

These results shed light on the impact of water deficit levels on crop water productivity and the response of different sweet sorghum varieties to water stress. These findings contribute to the understanding of water management strategies and the selection of suitable varieties for enhancing productivity and resource efficiency in sweet sorghum cultivation.

The impact of deheading times on crop water productivity (CWP) was investigated in this study, focusing on CWP_{sy} (crop water productivity for stalk yield), CWP_{csy} (crop water productivity for converted sugar yield), and $CWP_{ethanol}$ (crop water productivity for ethanol production). Although there were no significant differences observed in CWPcsy in the first season and $CWP_{ethanol}$ in the second season, the deheading times showed notable effects on CWP_{sy}.

Across both seasons, deheading performed 21 days before harvesting resulted in the highest values for CWP_{sy}. However, it is important to note that the variations in deheading times did not yield statistically significant differences in CWP_{sy}, CWP_{csy}, and $CWP_{ethanol}$, except for the aforementioned exceptions. These findings suggest that the timing of deheading may have a limited influence on crop water productivity in terms of stalk yield, converted sugar yield, and ethanol production.

These results contribute to the understanding of the relationship between deheading times and crop water productivity, indicating that deheading 21 days prior to harvesting may potentially enhance CWPsy. However, further investigation is needed to explore the underlying mechanisms and optimize the deheading process for improved water productivity in sweet sorghum cultivation.

3.5. Water Deficit Levels, Cultivated Varieties, and Deheading Time Interactions Effect

The results presented in Figures 2–8 demonstrate the interactions between water deficit levels, varieties, and deheading time in influencing various aspects of sweet sorghum growth, yields, quality, crop water productivity (CWP), and ethanol production.

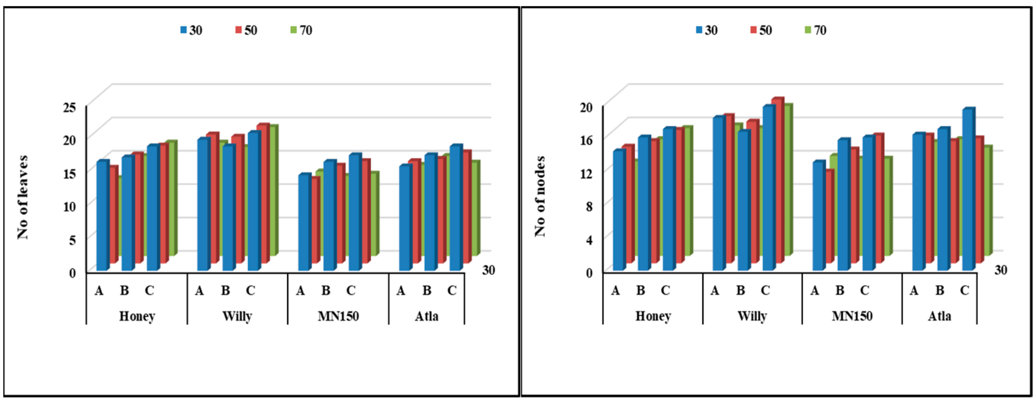

Figure 2. Number of leaves and Number of nodes as affected by water deficit, varieties, and deheading time interaction—L.S.D at 5%; 2.03 and 2.22, respectively. **A**: 45 days before harvesting, **B**: 21 days before, and **C**: no deheading (until harvesting).

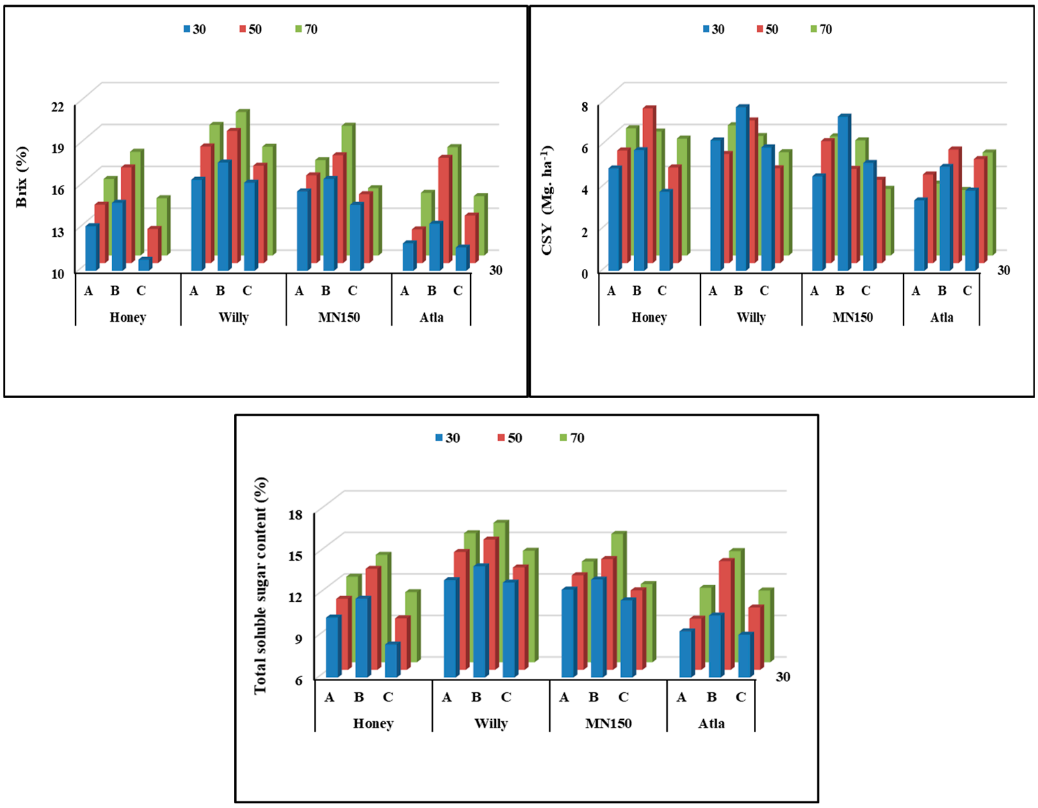

Figure 3. Brix (%), converted sugar yield (Mg ha^{-1}), and total sugar (%) as affected by water deficit, varieties, and deheading time interaction—L.S.D at 5%; 1.21, 1.53 and 0.98, respectively. **A**: 45 days before harvesting, **B**: 21 days before, and **C**: no deheading (until harvesting).

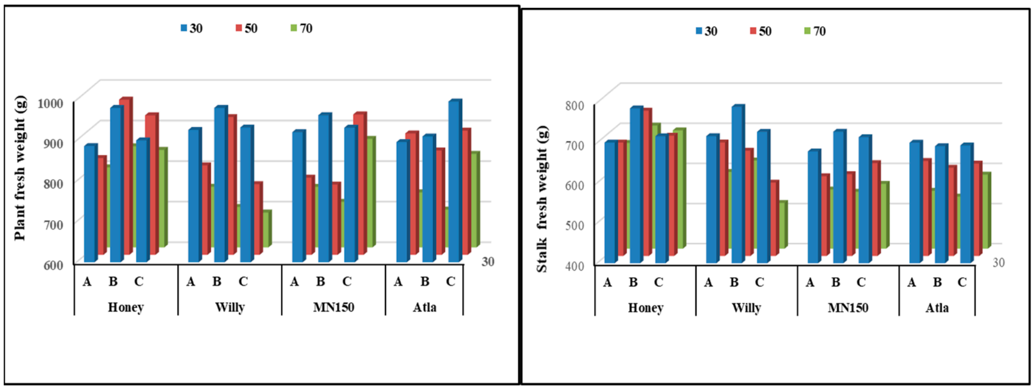

Figure 4. Plant fresh weight and stalk fresh weight (g) as affected by water deficit, varieties, and deheading time interaction—L.S.D at 5%; 114.8 and 89.26, respectively. **A**: 45 days before harvesting, **B**: 21 days before, and **C**: no deheading (until harvesting).

Both the Willy and Honey varieties demonstrated a remarkably similar performance in our study. Specifically, when subjected to a 30% water deficit and deheading 21 days before harvesting, both varieties exhibited impressive outcomes; this included high plant fresh weight, stalk fresh weight, stalk fresh yield, and stalk dry yield. These findings underscore the potential of both the Willy and Honey varieties to significantly enhance sweet sorghum productivity under specific water deficit and deheading conditions.

In terms of leaf and node numbers, the Willy variety displayed the highest values when subjected to a 50% water deficit without deheading. Additionally, when the Willy variety experienced a 70% water deficit with a deheading treatment 21 days before harvesting, it exhibited a superior Brix content (20.28%) and total soluble sugar content (16.08%).

Furthermore, significant yields of converted sugar (7.82 Mg ha^{-1}) and theoretical ethanol (4572 L ha^{-1}) were achieved when cultivating Willy under a 30% water deficit with deheading at 21 days prior to harvest, as well as with Willy and Honey varieties under a 50% water deficit level.

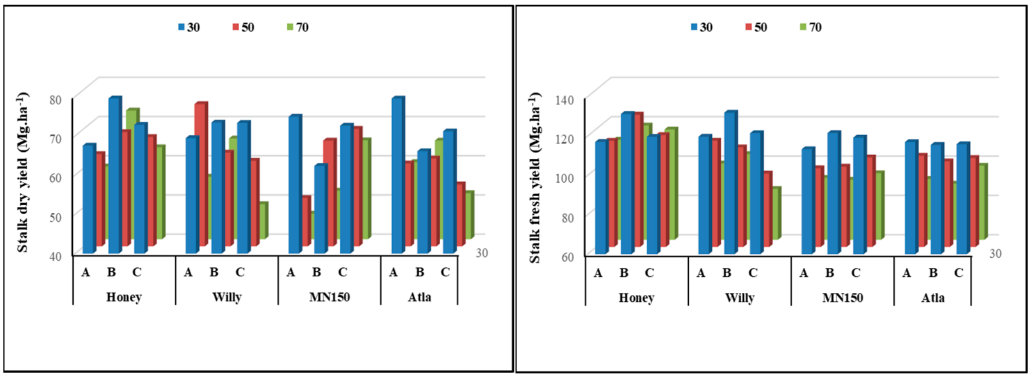

Figure 5. Stalk dry yield and stalk fresh yield (Mg ha^{-1}) as affected by water deficit, varieties, and deheading time interaction—L.S.D at 5%; 14.22 and 14.91, respectively. **A**: 45 days before harvesting, **B**: 21 days before, and **C**: no deheading (until harvesting).

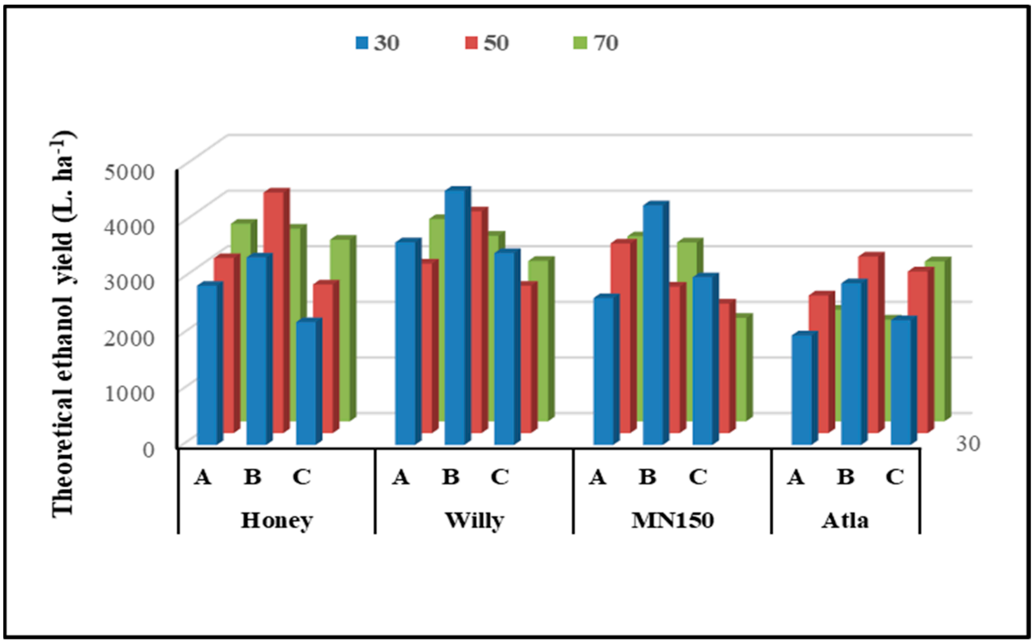

Figure 6. Theoretical ethanol yield (L ha^{-1}) as affected by water deficit, varieties, and deheading time interaction—L.S.D at 5%; 899.7. **A**: 45 days before harvesting, **B**: 21 days before, and **C**: no deheading (until harvesting).

Crop water productivity (CWP_{sy}) values varied depending on the specific treatment combinations. The highest CWP_{sy} value of 42.10 kg m^{-3} was obtained when cultivating Willy+ with a 70% water deficit and deheading at 45 days. Notably, the Honey+ variety with a 70% water deficit and deheading 21 days before harvesting displayed the highest CWP_{csy} value of 2.21 kg m^{-3}, along with the highest crop water productivity for ethanol ($CWP_{ethanol}$) value of 1.30 L m^{-3}.

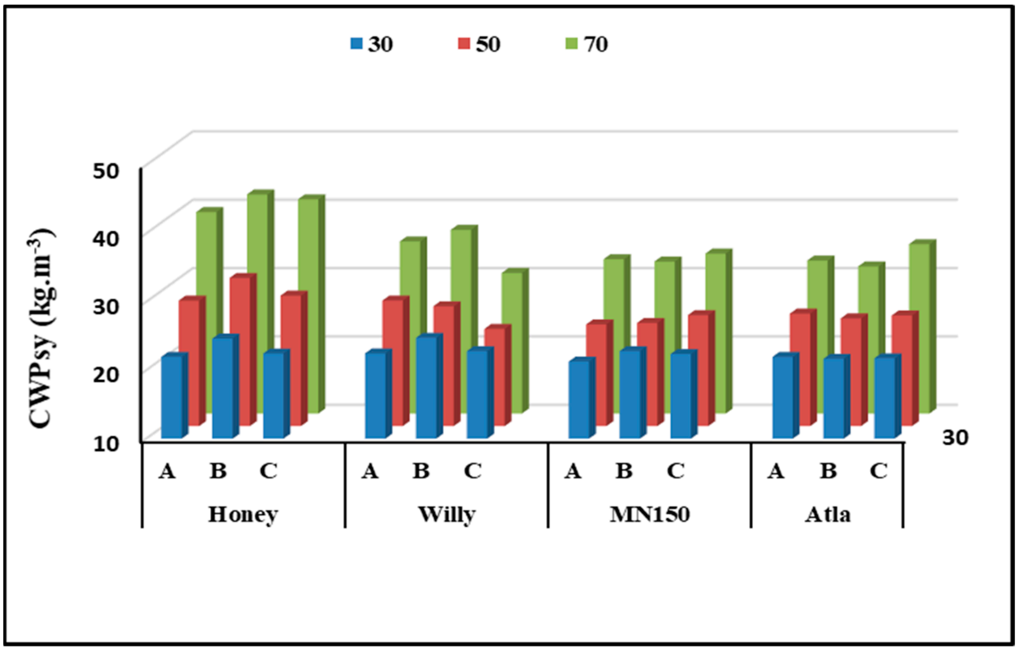

Figure 7. Crop water productivity of stalk yield as affected by water deficit, varieties, and deheading time interaction—L.S.D at 5%; 4.25. **A**: 45 days before harvesting, **B**: 21 days before, and **C**: no deheading (until harvesting).

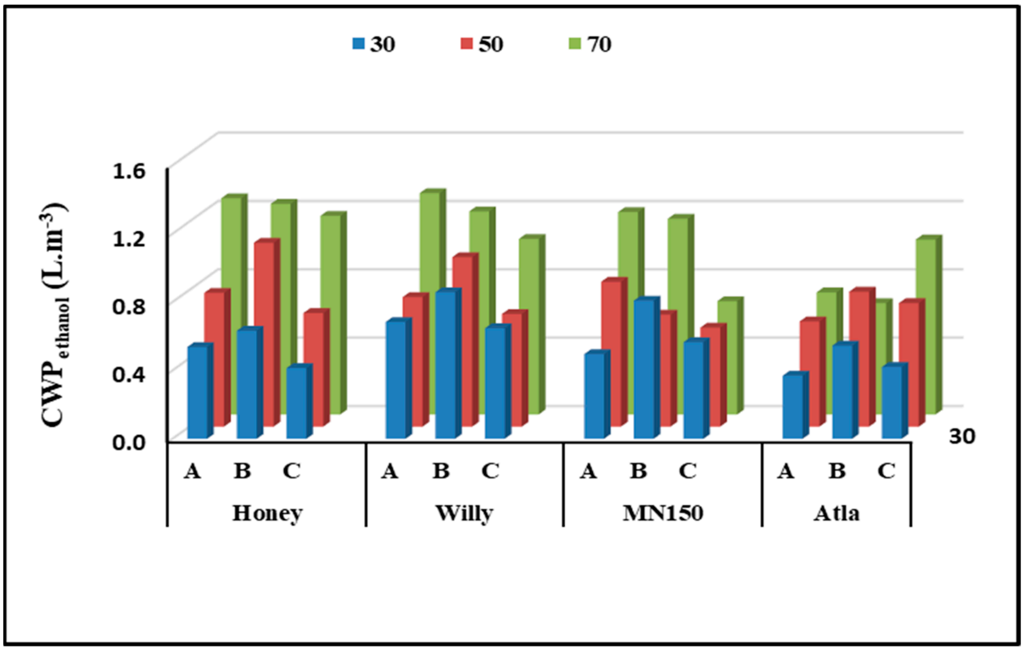

Figure 8. Crop water productivity of theoretical ethanol as affected by water deficit, varieties, and deheading time interaction—L.S.D at 5%; 0.33. **A**: 45 days before harvesting, **B**: 21 days before, and **C**: no deheading (until harvesting).

These results highlight the intricate relationships between water deficit levels, varieties, deheading time, and their combined effects on sweet sorghum performance. The findings provide valuable insights for the optimization of cultivation practices and selecting the most effective combinations to maximize yield, quality, and water productivity in sweet sorghum production for ethanol production.

4. Discussion

These findings underscore the significance of water management in sweet sorghum cultivation. Effective irrigation strategies can boost plant growth, biomass production, and sugar accumulation—thereby influencing ethanol yield. Understanding the interplay between water availability, crop physiology, and ethanol production is essential for maximizing efficiency and sustainability in sweet sorghum bioenergy feedstock production.

The choice of variety profoundly impacts sweet sorghum yield and quality. The Honey variety stands out for its robust growth, high fresh weight, and increased stalk height, resulting in superior biomass production. Conversely, the Willy variety boasts the highest leaf count, contributing to sugar production and elevated Brix and total soluble sugar content, thus augmenting sugar and ethanol yields.

Bellmer et al. [43] also noted diverse sweet sorghum yields (ranging from 32 to 112 Mg ha^{-1} for fresh biomass and 15 to 25 Mg ha^{-1} for dry biomass) depending on varieties and production strategies. These studies underscore the importance of selecting appropriate sweet sorghum varieties to optimize yield and quality parameters such as biomass accumulation, sugar content, and ethanol production [10,13,43–45]. Proper variety selection, considering traits related to drought tolerance and productivity, can enhance sweet sorghum's performance as a bioenergy feedstock.

Sweet sorghum harvesting can occur at various developmental stages, from early dough to physiological maturity [46], with minimal impact on sugar yields. Sugar concentrations typically increase as the growing season progresses [47]. At flowering, stalks contain 8.3% to 14.0% total sugar, while at the soft dough stage, it ranges from 12.8% to 16.6%. The total sugar yield varies from 4.3 to 8.5 Mg ha^{-1} at flowering and from 6.6 to 11.7 Mg ha^{-1} at soft dough. There is a linear relationship between sugar accumulation and growing season length [6].

Recent research has underscored the pivotal role of deheading time in shaping the key traits of sweet sorghum. Specifically, deheading conducted 21 days prior to harvesting yielded optimal results across parameters such as Brix levels, converted sugar yield, ethanol production, and total soluble sugar content, outperforming both earlier (45 days pre-harvest) and no deheading treatments. This phenomenon is attributed to the stem serving as an alternative storage site, diverting resources from grain development to additional storage. Conversely, delaying deheading to 45 days before harvesting resulted in diminished trait values, likely due to new tiller growth in deheaded plants, causing significant sucrose losses. This highlights the stem's inferiority as a storage sink compared to developing grains. Maturity stage post-blooming did not affect stalk yield, but extraction efficiency decreased while the Brix and starch content increased with maturity.

Consistent findings emphasizing the importance of deheading were corroborated by Jebril et al. [27], who observed an 18% increase in Brix, a 43% rise in sugar yield, and a 28% boost in biomass in headless rows. This surge can be attributed to enhanced translocation of photoassimilates to grain filling in no-heading treatments, while deheaded plants exhibited increased nodal tillers and stalk girth. The augmented sugar content and juice yield may be linked to stalk thickening, facilitating greater juice accumulation. Similar results were reported by Rajendran et al. [48] and Kering et al. [49], indicating that deheading during anthesis substantially enhances productive tiller count, main stalk width (by 20%), juice output (by 30%), and sugar yield (by 10%), albeit at a slight reduction in Brix concentration, sucrose content, and juice purity (approximately 5%). Zhao et al. [47] recommend harvesting sweet sorghum hybrids around 20 days post-anthesis, increasing stalk dry yield and estimated ethanol yield significantly. These studies underscore the importance of selecting the right harvesting stage and employing deheading practices to optimize yield and quality [45–47].

Crop water productivity (CWP) decreases with increasing water deficit levels due to drought-induced photoinhibition, reducing stem biomass [50]. Under normal conditions, photoinhibition is avoided, resulting in improved stem biomass but decreased CWP. Zegada-Lizarzu and Monti [51] have noted irrigation levels' impact on sweet sorghum

CWP in Mediterranean conditions. Mastrorilli [52] showed that short-term soil water stress reduces CWP significantly. Proper irrigation management is crucial for optimizing crop productivity [50–52].

5. Conclusions

Agronomic practices of water regimes and deheading times, combined with the selection of specific varieties, significantly influence sweet sorghum traits. Modulating deficit irrigation levels from 30% to 70% of the water regime affects growth and yields, with higher deficits limiting growth but increasing the Brix and total soluble sugar content. This underscores the importance of water availability and timing in maximizing sweet sorghum production, as water shortages adversely affect leaf and node development, reducing sugar production primarily in leaves.

Among the varieties, Honey and Willy outperformed MN1500 and Atlas, attributed to robust growth enhancing photosynthesis, resulting in a higher Brix and sugar content, and increased yields of converted sugar and ethanol.

Deheading 21 days before harvesting yielded the highest Brix, sugar, and ethanol yields, compared to other deheading times or no deheading treatments.

In conclusion, optimizing agronomic practices such as water regimes, variety selection, and deheading times enhances sweet sorghum production, contributing to efficient bioethanol production from renewable agricultural feedstock. Ethanol, a component of blended fuels, aids in mitigating ozone depletion, contributing to a more sustainable energy landscape.

Further research should explore wider ranges of deficit irrigation levels to determine optimal water regimes. Comparative studies with more varieties can identify superior varieties. Investigating genetic and physiological factors underlying performance in varities such as Honey and Willy would aid breeding programs. Research on deheading times could determine the optimal timings for different varieties and regions. Continued research in these areas supports sustainable and efficient sweet sorghum production, contributing to bioethanol production and a sustainable energy landscape.

Author Contributions: All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by E.I.R.E. and M.A.A. The first draft of the manuscript was written by E.I.R.E. and all authors commented on previous versions of the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Deanship of Scientific Research, Vice Presidency for Graduate Studies and Scientific Research, King Faisal University, Saudi Arabia [GRANT5183].

Data Availability Statement: The data supporting the findings of this study are available from the corresponding author, Eman I. R. Emara, upon request.

Conflicts of Interest: The authors declare no conflicts of interest.

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