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Evaluation of fermentation efficiency and ethanol production potential of sweet sorghum genotypes in Çukurova region of Türkiye

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Abstract
Bioethanol is a renewable energy source with lower environmental impact and the potential to partially replace fossil fuels. In this study, the sugar content, ethanol fermentation efficiency, and ethanol production potential of 21 different sweet sorghum genotypes, were evaluated under the Çukurova region of Türkiye. Field experiments were conducted under second-crop conditions in the experimental fields of the Eastern Mediterranean Agricultural Research Institute, during the 2016 and 2017 growing seasons. Analyses were carried out on the juice obtained from the sorghum stalks. Alcoholic fermentation was carried out using *Saccharomyces cerevisiae* Fermivin yeast after optimizing the conditions (different cultures, temperatures and pH levels). Fermentation was conducted at pH of 5.5 and 30°C. Based on two-year averages, the sugar contents of the genotypes ranged from 112.03 to 185.64 g L^{-1}, ethanol concentrations from 48.35 to 84.60 g L^{-1}, total sugar yields from 3628.5 to 8986.4 kg ha^{-1}, fermentation yield from 0.4072 to 0.4560 g alcohol g^{-1} sugar, and ethanol yields from 2017.6 to 4871.0 L ha^{-1}. Under the second crop conditions of the Çukurova region, the Tracy, UNL-Hyb-3, No91, Grassi and M81E genotypes, which produced more than 4300 liters of ethanol per hectare were identified as the most promising genotypes for bioethanol production. These results indicate that sweet sorghum has considerable potential as a feedstock for both sugar and bioethanol production in the Çukurova region.
Keywords: Bioethanol, Çukurova region, Ethanol yield, Sweet sorghum, Sugar

INTRODUCTION

The continuous growth of the global population, which is projected to reach approximately 10 billion by 2050 from its current level of 8.25 billion, has triggered a parallel increase in global energy consumption (Enerdata, 2025; Worldometer, 2025). This rising energy demand drives the urgent need for renewable energy alternatives. However, the use of existing agricultural land for both food production and bioenergy requires careful management to prevent resource conflicts. In this context, expanding the cultivation of climate-smart crops such as sweet sorghum represents a promising strategy to simultaneously address food security, biofuel demand, and sustainable land management (Kasegn et al., 2024a). In the quest for sustainable bioenergy sources, sweet sorghum (*Sorghum bicolor* var. *saccharatum* (L.) Mohlenbr) has emerged as a highly promising and low-cost resource (Yücel et al., 2020a, 2020b). Unlike certain traditional starch-based crops, sweet sorghum does not directly compete with human food supplies and has a minimal impact on global warming (Khalil et al., 2015; Kasegn et al., 2024a). With its rapid growth rate, broad geographical adaptability, low agricultural input requirements, and exceptional capacity to accumulate sugar in its stalks, it offers significant advantages for bioethanol production (Yücel et al., 2022; Herniwati et al., 2023). As a typical C4 plant, sweet sorghum grows rapidly (120–150 days), produces high biomass (6.0-7.5 t dry matter), and exhibits high water-use efficiency, requiring significantly less water and fertilizer than major crops such as corn and sugarcane (Zhang et al., 2024). Sorghum (*Sorghum bicolor* L. Moench) has become an increasingly valuable crop for food, feed, and especially bioenergy feedstock production, which makes the crop extremely attractive for studying genomics and genetic diversity (Guden et al., 2024). Consequently, it is widely recognized as one of the most suitable and accessible feedstocks for ethanol production in the current decade (Lopez-Sandin et al., 2021). The

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production of bioethanol from sweet sorghum is primarily carried out through the microbial ethyl alcohol fermentation of the readily available sugars in the plant. *S. cerevisiae*, commonly known as baker's and wine yeast, is the principal microorganism utilized for this biochemical conversion (Walker and Stewart, 2016). However, the industrial yield of this first-generation ethanol is a complex trait influenced by various interrelated factors, primarily total sugar yield, the efficiency of the fermentation process, and the specific genetic and environmental conditions under which the crop is cultivated (Yücel et al., 2020b; Fagundes et al., 2021). Most importantly, the ability to directly ferment the must obtained from sweet sorghum without any pre-treatment significantly reduces the cost and saves time (Sun and Cheng, 2002; Kasegn et al., 2024b). When evaluated against conventional sugar crops like sugarcane and sugar beet, sweet sorghum stands out for its lower water and fertilizer demands, shorter vegetative cycle, and robust resilience to both drought and waterlogging. Furthermore, it presents notable benefits over grain-based and starch-heavy bioresources (Appiah-Nkansah et al., 2019). Studies have shown that the chemical profile of sweet sorghum genotypes is highly dynamic, heavily influenced by genotype-by-environment interactions, harvest timing, and seasonal variations (Zhao et al., 2009; Nazli et al., 2024). The stalks of this plant 75% juice, with sugar concentrations fluctuating between 12.0% and 23% across different cultivars (Dweikat, 2014; Yücel et al., 2020a). This substantial sugar accumulation translates to an estimated ethanol output of 1000 to 2000 gallons per hectare (Dweikat, 2014). Under optimal agricultural conditions, sweet sorghum possesses the capacity to yield up to 1.32 t da^{-1} of total sugar, which corresponds to a theoretical ethanol production of roughly 7682 L ha^{-1} (Murray et al., 2009). Similarly, recent evaluations under the semi-arid climatic conditions of Şanlıurfa, Türkiye, demonstrated that high-performing sweet sorghum genotypes can achieve actual sugar yields up to 1906.1 kg da^{-1} and theoretical ethanol yield reaching 1014.8 L da^{-1} (Oktem et al., 2020). However, despite the recognized global advantages of sweet sorghum, its successful commercialization and bioethanol yield largely depend on genotype-environment interactions and local agronomic practices. In regions with intensive agricultural systems and Mediterranean climates, such as the Çukurova region of Türkiye, integrating bioenergy crops into second-crop systems (e.g., following winter wheat) offers a significant opportunity to enhance land-use efficiency without competing with primary food crops. Nevertheless, the performance of globally sourced sweet sorghum genotypes under the specific microclimatic conditions and intensive second-crop systems of this region remains unclear. In particular, there is limited information on their sugar accumulation potential and fermentation efficiency under these conditions. Identifying well-adapted and high-performing genotypes is therefore essential before recommending large-scale and sustainable cultivation. Accordingly, this two-year study aimed to evaluate the bioethanol production potential of 21 sweet sorghum genotypes grown under second-crop conditions in the Çukurova region. In addition, juice yield, total sugar content, fermentation efficiency and ethanol yield were assessed to identify the most suitable genotypes for sustainable commercial production.

MATERIALS AND METHODS

Experimental Materials

A total of 21 sweet sorghum materials were evaluated in this study. Seventeen genotypes (Cowley, Dale, Grassi, M81-E, Mennonita, Nebraska sugarcane, PI579753, Ramada, Roma, Rox Orange, Smith, Sugar Drip, Theis, Topper 76, Tracy, UNLHybrid-3 and Williams) were supplied by the University of Nebraska-Lincoln (UNL), USA. Three genotypes (No2 USDA-China, No91 USDA-Taiwan, and No5 USDA-South Africa) were obtained from the Western Mediterranean Agricultural Research Institute in Antalya, Turkey (originally sourced from ICRISAT and the USDA gene bank). Additionally, one local cultivar (Gülşeker) was provided by the Field Crops Department of the Faculty of Agriculture at Uludağ University in Bursa, Turkey.

Prior to planting, soil samples were collected from 0-30 cm depths to determine physico-chemical properties. Soil analysis of soil samples taken at a depth of 0-30 cm before planting in 2016 and 2017 revealed that the average pH values were between 7.40 and 7.45, total EC (1:2:5) values were between 0.24 and 0.26, total nitrogen (N) values were between 0.13 and 0.15%, organic carbon (OC) values were between 0.69 and 0.85%, available phosphorus (P) values were between 0.67 and 0.73 mg kg^{-1}, and calcium carbonate ($CaCO_3$) content was between 33 and 34%. The physical composition consisted of 27-26% sand, 41-42% silt, and 32-32% clay, respectively. The soil texture was classified as clay loam (CL) (Yücel et al., 2018).

During the experimental periods (June-October), the mean temperatures were 25.1°C (range: 20.5-27.7 °C) in 2016 and 24.8 °C (range:19.4-28.0 °C) in 2017 with average relative humidities of 79.0 % (range: 72.8-83.7%) and 79.6 % (range: 70.7-84.0 %), respectively. Total precipitation during the growing seasons was recorded as 46.2 mm in 2016 and 48.2 mm in 2017 (Yücel et al., 2018).

Methods

Experiments were conducted over the experimental fields of Eastern Mediterranean Agricultural Research Institute in Çukurova, Doğankent (36°51’35’’N and 35°20’43’’E), Adana, using a randomized complete block design with four replications during the years 2016 and 2017 growing seasons. Seeds were sown manually in mid-June following the wheat harvest. Each plot consisted four row, each 5 m in length, with 70 cm inter-row and 15 cm intra-row spacing. A basal application of 50 kg ha^{-1} of nitrogen (N) and phosphorus (P) was applied prior to sowing. When the plants reached to heights of 40-50 cm, 50 kg ha^{-1} pure nitrogen was applied as dressing fertilizer. Irrigation was applied as required throughout the growing season. Harvesting was carried out between the milk and dough stages of the grains, and fresh stems were used as the experimental material. To determine juice yield, samples were collected weekly over five consecutive weeks starting from anthesis (approximately 90 days after sowing). For each genotype, the panicles and leaves of 10 randomly selected

plants were removed. The stripped stalks were then passed through a sugarcane roller mill (two counter-rotating cylindrical rollers) to extract the juice. The extracted juice was filtered through a 0.25 mm sieve to remove plant residues before being transported to the university laboratory for further analysis.

Optimization of ethanol fermentation

Fermentation experiments were conducted under laboratory conditions in 250-mL glass bottles equipped with S-type airlocks, placed within a temperature-controlled shaking incubator. To optimize the process, preliminary experiments evaluated three yeast strains (*S. cerevisiae* Uvaferm, *S. cerevisiae* Bayanus, and *S. cerevisiae* Fermivin), one bacterial strain (*Zymomonas mobilis*), two pH levels (5.0 and 5.5), and two temperatures (25 °C and 30 °C).

The combination of microorganism strain, pH, temperature, and fermentation time that produced the highest alcohol yield was selected for the main trials (Ünal et al., 2018; Yücel et al., 2018). Based on the preliminary results, the optimum fermentation conditions were determined to be the use of *S. cerevisiae* Fermivin at pH 5.5 and 30 °C.

Inoculum Conditions

For the yeast inoculum, 0.2 g L^{-1} of dry yeast was added to 20 mL of sterilized sweet sorghum must. The mixture was stirred at 150 rpm for 30 minutes and then pre-cultured in a shaking incubator at 30 °C for an additional 30 minutes. This pre-culture was subsequently transferred into 200 mL of sterile sweet sorghum must to initiate alcoholic fermentation. For the bacterial inoculum, one loopful of *Zymomonas mobilis* was transferred into 5 mL of sterile sweet sorghum must. The culture was incubated at 30 °C with continuous agitation at 150 rpm for 18 hours, after which it was added to 200 mL of sterile sweet sorghum must for the main fermentation (Karimi et al., 2006; Wilkins, 2009).

Ethanol Fermentation

Alcoholic fermentations were conducted in 250-mL glass bottles fitted with airlocks. The bottles were placed in a temperature-controlled shaking incubator operating at a speed of 150 rpm. Based on the optimized preliminary parameters, the *S. cerevisiae* Fermivin strain was utilized, and the initial pH of the must was adjusted to 5.5 at an incubation temperature of 30 °C. The fermentation process was terminated when the residual sugar concentration of the must dropped below 2 g L^{-1} (Perez-Carrillo et al., 2008).

Measurements and Analyses

Sugar and Ethanol Analysis

Sugars concentrations in sorghum juice, defined as the sum of sucrose, glucose, and fructose, were determined using HPLC system (Shimadzu LC-20AD, Japan) equipped with a refractive index detector (RID-10A) and an Aminex HPX-87H column (Bio-Rad, 300 × 7.8 mm). Prior to analysis, samples were filtered through a 0.45 µm membrane filter (Millipore Millex-HV, hydrophilic PVDF) and injected into the HPLC system. A 5 mM sulfuric acid (H_2SO_4) solution was used as the mobile phase at a flow rate of 0.5 mL min^{-1}. The column temperature was maintained at 50 °C and the injection volume was set to 20 µL. Quantification of sugars and ethanol was carried out using the external standard method. Calibration curves were prepared using five different concentrations of each standard, and linear regression analysis was applied to obtain the calibration equations (Sluiter et al., 2008). For sugar analysis, calibration curves generated for sucrose, glucose, and fructose showed excellent linearity ($R^2 = 0.999$). The retention times were determined as 7.727 min for sucrose, 9.063 min for glucose, and 9.973 min for fructose. The limits of detection (LOD) were 0.00237, 0.00239, and 0.00335 mg 100 mL^{-1} for glucose, fructose, and sucrose, respectively, while the limits of quantification (LOQ) were 0.00790, 0.00798, and 0.01116 mg 100 mL^{-1}. Method validation for sugars demonstrated high reliability, with recovery rates ranging from 98.7% to 106.0%. For ethanol analysis, the retention time was 20.205 min. The method showed good linearity ($R^2 > 0.999$) within the studied concentration range. The limits of detection (LOD) and quantification (LOQ) were 0.15 g L^{-1} and 0.45 g L^{-1}, respectively. The method demonstrated good precision (RSD < 2%) and accuracy (recovery between 98–102%). The concentrations of individual sugars were summed and expressed as total sugar concentration (g L^{-1}), and ethanol results were also expressed in g L^{-1}.

Juice Yield and Calculation of Total Sugar Yield (kg ha^{-1})

Juice yield (L ha^{-1}) was determined by extracting juice from the stalks of 10 randomly selected plants in each plot and measuring the volume obtained (mL). The measured values were scaled to a per-hectare basis using plant population density.

Total sugar yield was calculated using the following equation (Jia et al., 2013):

Total sugar yield (kg ha^{-1}) = Juice yield (L ha^{-1}) × Sugar concentration (g L^{-1}) / 1000

Fermentation Efficiency (g ethanol g^{-1} sugar)

Fermentation efficiency was expressed as the ratio of ethanol produced to the amount of fermentable sugars utilized during the fermentation process (g ethanol g^{-1} sugar). It was calculated using the following relationship: Fermentation efficiency (g g^{-1})= E / S where E is the ethanol concentration obtained after fermentation (g L^{-1}) and S is the amount of fermentable sugars consumed (g L^{-1}). Given that the residual sugar concentration at the end of fermentation was below 2 g L^{-1}, sugar consumption was considered to be nearly complete. In this calculation, the initial total sugar concentration (the sum of

sucrose, glucose, and fructose) was used to represent the total fermentable hexose equivalents. Since *Saccharomyces cerevisiae* rapidly hydrolyzes sucrose into glucose and fructose during the fermentation process, utilizing the sum of these sugars justifies the application of the theoretical maximum ethanol yield of 0.511 g g^{-1} based on hexose sugars, according to the Gay-Lussac stoichiometric relationship (Bai et al., 2008).

Ethanol Yield (L ha^{-1})

Ethanol yield per unit area was estimated by integrating ethanol concentration obtained after fermentation with the corresponding juice yield per hectare. The calculation was performed as follows:

Ethanol yield (L ha^{-1}) = (E × J) / ρ where E represents ethanol concentration (g L^{-1}), J denotes juice yield (L ha^{-1}), and ρ is the density of ethanol (0.789 kg L^{-1} at 20 °C). Ethanol mass was subsequently converted to volumetric yield using standard density values (Malik et al., 2020).

Statistical analysis

Experimental data were subjected to a years-combined analysis of variance in accordance with randomized blocks design with the use JUMP software and significant means were compared with the use of Tukey's test (Yurtsever, 1984).

RESULTS AND DISCUSSION

Genotypic Variation in Sugar and Ethanol Contents

The sugar concentrations (sum of sucrose, glucose, and fructose) of the juices obtained from 21 different sweet sorghum genotypes cultivated under Çukurova region conditions, along with the ethanol content achieved after alcoholic fermentation of these juices and the results of statistical analyses, are presented in Table 1. As shown in Table 1, there was a highly significant variation among the 21 sweet sorghum genotypes in terms of both sugar accumulation and ethanol content ($P \leq 0.01$). Based on the two-year average data, the Tracy genotype reached the highest sugar concentration (185.64 g L^{-1}), followed closely by Ramada (183.13 g L^{-1}), UNL-Hyb-3 (183.11 g L^{-1}), and Roma (176.80 g L^{-1}). According to Tukey's test ($P \leq 0.05$), Tracy was classified in the highest statistical significance group in terms of both sugar content and the corresponding ethanol content.

In contrast, the Gülşeker cultivar produced the lowest mean sugar concentration in both years (112.03 g L^{-1}). The substantial difference in sugar content (73.61 g L^{-1}) between the highest-yielding (Tracy) and lowest-yielding (Gülşeker) genotypes highlights the critical role of genotype-specific traits in carbohydrate biosynthesis and storage capacity in sweet sorghum stalks. Furthermore, the data revealed a strong positive correlation between initial sugar concentration and final ethanol yield. The four genotypes with the highest sugar accumulation (Tracy, Ramada, UNL-Hyb-3, Roma) also exhibited the highest ethanol contents, ranging from 72.31 to 84.60 g L^{-1}. Therefore, high sugar accumulation capacity (e.g., Tracy and Ramada) emerges as a key determinant in genotype selection and regional adaptation, particularly in terms of bioethanol recovery efficiency. The observed year effect was also statistically significant, with sugar concentrations in the first year being consistently lower than those in the second year. This variation can largely be attributed to differences in temperature regimes between the growing seasons, as higher temperatures during the first year likely limited sugar accumulation in the stalks. In agreement with the present findings, previous studies have demonstrated that the chemical composition of sweet sorghum is strongly influenced by the year, harvest time, and genotype x environment interactions (Zhao et al., 2009).

Ethanol yield in sweet sorghum is a complex trait associated not only with soluble sugar concentration but also with stem yield, brix yield per hectare, flowering time, and fermentation-related factors such as yeast performance and process efficiency (Lombardi et al., 2015; Parrella et al., 2018). Sugar accumulation in sweet sorghum stalks typically begins after flowering and continues until physiological maturity, a period during which it competes with grain starch synthesis (Parrella et al., 2018). In this context, the relatively high sugar concentrations obtained in the present study (up to 185.64 g L^{-1}) are consistent with previously reported average values (e.g., 173.02 g L^{-1}; Dar et al., 2018). It is also well established that sucrose constitutes the dominant fraction of the total stalk sugars, accounting for approximately 85% of the total sugar content (Li et al., 2021).

The positive relationship between sugar concentration and ethanol yield observed in this study is thoroughly supported by the literature. For instance, Sriputorn et al. (2017) reported ethanol concentrations ranging from 80.30 to 113.58 g L^{-1} from juices containing 170–267 g L^{-1} of sugar. Similarly, Sasaki et al. (2015) obtained 113.7 g L^{-1} of ethanol from juice with a 270 g L^{-1} sugar content, while Jin et al. (2012) demonstrated a progressive increase in ethanol concentration with increasing sugar levels under controlled fermentation conditions. More recent studies have further emphasized that ethanol productivity in sweet sorghum is primarily governed by sugar concentration, genotype selection, and environmental adaptability (Almodares and Hadi, 2019; Kumar et al., 2024).

Table 1. Effects of genotype and year on juice sugar concentration and corresponding ethanol content after fermentation

Genotypes	Sugar (g L^{-1})			Ethanol (g L^{-1})		
	2016	2017	Mean	2016	2017	Mean
Cowley	128.09 p-r[+]	172.33 a-h	150.21 efg[x]	56.60 o-r[+]	74.33 b-h	65.47 e-ı[x]
Dale	146.14 h-r	167.93 a-j	157.03 def	63.15 j-q	70.20 c-m	66.67 d-h
Grassi	144.39 ı-r	171.00 a-h	157.70 def	62.70 k-q	71.59 c-l	67.15 d-h
M81-E	142.61 j-r	137.53 m-r	140.07 g	65.29 g-p	53.43 qrs	59.36 ıjk
Mennonita	138.43 l-r	176.23 a-f	157.33 def	62.83 j-q	75.38 b-g	69.10 d-g
Nebraska sugarcane	166.52 a-k	154.06 f-p	160.29 c-f	72.87 b-j	64.83 h-p	68.85 d-g
PI579753	139.41 l-r	178.29 a-f	158.85 def	64.50 h-p	75.52 b-f	70.01 d-g
Ramada	175.90 a-g	190.36 a	183.13 ab	78.01 a-d	79.12 abc	78.57 ab
Roma	170.69 a-ı	182.91 a-d	176.80 abc	72.86 b-j	71.75 c-k	72.31 bcd
Rox Orange	133.56 o-r	157.39 d-o	145.48 fg	57.34 o-r	60.18 m-r	58.76 jk
Smith	144.56 ı-r	184.32 abc	164.44 cde	63.58 ı-p	73.51 b-ı	68.55 d-g
Sugar Drip	139.74 l-r	177.03 a-f	158.39 def	62.25 k-r	68.07 d-n	65.16 f-j
Theis	135.17 n-r	140.99 k-r	138.08 g	61.53 l-r	52.35 rs	56.94 k
Topper 76	168.19 a-j	160.73 c-n	164.46 cde	74.03 b-h	67.91 d-n	70.97 c-f
Tracy	182.69 a-e	188.58 ab	185.64 a	86.51 a	82.68 ab	84.60 a
UNL-Hyb-3	183.8 abc	182.42 a-e	183.11 ab	75.91 b-f	78.42 abc	77.16 bc
Williams	156.37 e-o	179.78 a-f	168.08 bcd	66.33 f-o	77.18 a-e	71.75 cde
No2	125.14 qrs	164.25 a-l	144.70 fg	53.33 qrs	69.20 c-n	61.27 h-k
No91	149.70 g-q	129.47 pqr	139.59 g	66.37 f-o	55.33 pqr	60.85 h-k
No5	138.46 l-r	163.45 b-m	150.96 efg	59.43 n-r	67.61 e-n	63.52 g-j
Gülşeker	101.47 s	122.59 rs	112.03 h	44.28 s	52.41 rs	48.35 l
Mean	**148.15 B[1]**	**165.79 A**		**65.22 B[1]**	**68.62 A**	
CV (%)		5.92			5.33	
F Genotype (G)		**			**	
F Year (Y)		**			**	
F G xY Interactions		**			**	

+) The means of different year-cultivar combinations with the same lower case are not statistically significant different from each other according to the Tukey test at $P \leq 0.05$. x) The means with the same letter in the same column are not statistically significant different from each other according to the Tukey test at $P \leq 0.05$. 1) The means indicated with the same capital letter in the same row are not significantly different at $P \leq 0.05$. **) Significant at $P \leq 0.01$.

Total Sugar Yield (kg ha^{-1}) and Fermentation Efficiency

The differences in total sugar yield per hectar and fermentation efficiency among the evaluated sweet sorghum genotypes and growing years were found to be highly significant ($P \leq 0.01$). The total sugar yields varied widely, ranging from 3038.5 to 10117.5 kg ha^{-1}. Based on the two-year averages, the lowest sugar yield (3628.5 kg ha^{-1}) was obtained from the Mennonita cultivar, whereas the highest yield (8986.4 kg ha^{-1}) was achieved by the UNL-Hyb-3 genotype (Table 2).

These results indicate a higher production potential compared to previous studies. For instance, Rutto et al. (2013) and Zhuzhukin and Garshin (2016) reported sugar yields ranging from 1.2 to 2.4 t ha^{-1} and 1.7 to 2.9 t ha^{-1}, respectively. Similarly, Erdurmus et al. (2018) reported sugar yields between 612 and 6381 kg ha^{-1} under Mediterranean conditions. However, under optimal agronomic conditions, sweet sorghum can accumulate up to 12 t ha^{-1} of total stem sugars (Regassa and Wortmann, 2014), which is consistent with the superior performance of high-yielding genotypes such as UNL-Hyb-3 and No91 observed in the present study. Previous studies have also indicated that total sugar yields may reach up to 13.2 t ha^{-1}, corresponding to an estimated ethanol yield of approximately 7682 L ha^{-1} (Murray et al., 2009).

Fermentation efficiency, expressed as grams of ethanol produced per gram of sugar consumed, is a critical parameter for industrial feasibility. In the present study, fermentation efficiency ranged from 0.3711 to 0.4737 g g^{-1} among the evaluated genotypes. Across the two years, the lowest mean efficiency (0.4072 g g^{-1}) was recorded for the Rox Orange genotype, whereas the highest mean efficiency (0.4560 g g^{-1}) was achieved by the Tracy genotype (Table 2). Under optimal fermentation conditions, efficient yeast strains can theoretically produce up to approximately 0.48 g ethanol per gram of sugar (Mutepe et al., 2011). Thatiyamanee et al. (2025) reported that, in bioethanol production from sweet sorghum, the application of a fermentation temperature range of 25–30 °C resulted in fermentation efficiency varying between 0.46 and 0.50 g g^{-1}, with the highest ethanol yields achieved within this temperature range. The performance of the Tracy genotype (0.4560 g g^{-1}) closely approaches this practical maximum, indicating a high bioconversion efficiency. Furthermore, a

positive relationship was observed between total sugar yield and fermentation efficiency, suggesting that genotypes with higher sugar accumulation tend to exhibit improved ethanol productivity.

Table 2. Effects of genotype and year on total sugar yield and fermentation efficiency

Genotypes	Total Sugar Yield (kg ha^{-1})			Fermentation Efficiency (g g^{-1})		
	2016	2017	Mean	2016	2017	Mean
Cowley	6188.5 d-j+	8357.7 a-d	7273.1 cde	0.4419 a-e	0.4316 a-g	0.4367 abc
Dale	6390.7 c-j	7958.0 a-f	7174.4 cde	0.4321 a-g	0.4180 a-h	0.4251 abc
Grassi	7833.5 a-g	8121.2	7977.4 abc	0.4349 a-g	0.4187 a-h	0.4268 abc
M81-E	8369.0 a-d	8125.5 a-e	8247.2 abc	0.4584 ab	0.3887 e-h	0.4236 abc
Mennonita	3038.5 n	4218.5 j-n	3628.5 ı	0.4539 abc	0.4279 a-g	0.4409 abc
Nebraska sugarcane	7476.2 b-h	6117.2 d-j	6796.7 c-f	0.4378 a-g	0.4211 a-h	0.4295 abc
PI579753	3281.2 mn	7877.7 a-g	5579.5 fgh	0.4626 ab	0.4238 a-h	0.4432 ab
Ramada	6744.5 c-ı	7979.7 a-f	7362.1 bcd	0.4437 a-e	0.4150 b-h	0.4294 abc
Roma	7352.5 b-ı	8122.5 a-e	7737.5 abc	0.4269 a-g	0.3919 d-h	0.4094 bc
Rox Orange	3731.5 k-n	5431.5 h-m	4581.5 ghı	0.4304 a-g	0.3839 gh	0.4072 c
Smith	5061.7 ı-n	9589.5 ab	7325.6 cde	0.4406 a-e	0.3989 c-h	0.4197 bc
Sugar Drip	5978.5 e-k	6087.5 d-j	6033.0 d-g	0.4464 a-d	0.3846 fgh	0.4155 bc
Theis	8098.5 a-f	6560.0 c-ı	7329.2 cde	0.4569 ab	0.3711 h	0.4140 bc
Topper 76	7983.2 a-f	7350.7 b-ı	7667.0 abc	0.4401 a-f	0.4228 a-h	0.4315 abc
Tracy	7183,4.5 c-ı	7965.0 a-f	7574.2 bcd	0.4737 a	0.4384 a-g	0.4560 a
UNL-Hyb-3	10005.0 a	7967.7 a-f	8986.4 a	0.4128 b-h	0.4304 a-g	0.4216 abc
Williams	6109.2 d-j	5600.0 g-l	5854.6 e-h	0.4247 a-h	0.4296 a-g	0.4272 abc
No2	3536.2 lmn	5281.7 h-n	4409.0 hı	0.4263 a-h	0.4213 a-h	0.4238 abc
No91	10117.5 a	7532.2 b-h	8824.9 ab	0.4460 a-d	0.4275 a-g	0.4367 abc
No5	8691.7 abc	5787.7 f-l	7239.7 cde	0.4295 a-g	0.4139 b-h	0.4217 abc
Gülşeker	4074.7 j-n	6029.7 e-k	5052.2 ghı	0.4453 a-d	0.4284 a-g	0.4369 abc
Mean	**6517.0 B[1]**	**7050.6 A**		**0.4412 A[1]**	**0.4137 B**	
CV (%)		12.03			4.59	
F Genotype (G)		**			**	
F Year (Y)		**			**	
F G x Y Interactions		**			**	

+) The means of different year-cultivar combinations with the same lower case are not statistically significant different from each other according to the Tukey test at $P \leq 0.05$. x) The means with the same letter in the same column are not statistically significant different from each other according to the Tukey test at $P \leq 0.05$. 1) The means indicated with the same capital letter in the same row are not significantly different at $p \leq 0.05$. **) Significant at $P \leq 0.01$.

The means indicated by the same capital letter within the same row are not significantly different at $p \leq 0.05$.

This finding is consistent with the results of Ratnavathi et al. (2011), who reported maximum ethanol production from genotypes with inherently high sugar content. In addition, Almodares and Hadi (2019) emphasized that the high fermentable sugar content of sweet sorghum stalks makes it particularly suitable for efficient bioethanol production. Differences in fermentation efficiency among genotypes may be attributed not only to total sugar concentration but also to variations in sugar composition (sucrose-to-hexose ratio), juice pH, and the presence of minor inhibitory compounds affecting yeast metabolism. In addition, microbial performance and substrate characteristics may interact to influence overall ethanol yield. However, detailed biochemical characterization of these factors was beyond the scope of the present study. Consequently, genotypes that combine high total sugar yield with high fermentation efficiency, such as Tracy and UNL-Hyb-3, emerge as the most promising genotypes for maximizing bioethanol production, particularly under semi-arid conditions.

Ethanol Yield (L ha^{-1})

In this study, ethanol yield per unit area (L ha^{-1}) was determined based on actual post-fermentation ethanol concentrations, rather than the theoretical conversion calculations commonly reported in the literature. This approach provides a more realistic and reliable assessment of the true industrial potential of each genotype. According to the statistical analysis (Table 3), the main effect of genotype and the genotype x year interaction were highly significant ($P \leq 0.01$) for ethanol yield, whereas the main effect of year was not statistically significant. Across both years, ethanol yields varied widely among the sweet sorghum genotypes, ranging from 1747.5 to 5668.5 L ha^{-1}. Based on the two-year averages, the lowest ethanol yield (2017.6 L ha^{-1}) was obtained from the Mennonita cultivar, whereas the highest mean yields were recorded for No91 (4871.0

L ha^{-1}) and UNL-Hyb-3 (4781.0 L ha^{-1}). These findings indicate that the high-performing genotypes exhibited strong adaptation to regional conditions and performed within the upper ranges reported in the literature.

Previous studies conducted under different ecological conditions have reported considerable variability in ethanol yield. For example, the high yields obtained from No91 and UNL-Hyb-3 are consistent with the ranges reported by Yücel et al. (2022) (2020–5302 L ha^{-1}), Xuan et al. (2015) (1265–5914 L ha^{-1}), and Zhao et al. (2009) (5250 L ha^{-1}). In contrast, some studies have reported substantially lower ethanol potentials, such as 961–1117 L ha^{-1} (Herniwati et al., 2023) and 532-1544 L ha^{-1} (Rutto et al., 2013), depending on genotype and environmental conditions. The industrial relevance of sweet sorghum as a bioenergy crop is further supported by these upper-range yields, as it has been reported to exceed maize and sugarcane in ethanol production potential under favorable conditions (Wang et al., 2007; Ekefre et al., 2017). The significant differences in ethanol yield per hectare among genotypes can be attributed to the combined effects of three interrelated factors: total juice yield, initial sugar concentration, and actual fermentation efficiency. As highlighted by Rono et al. (2018) and Suwarti et al. (2018), strong positive correlations exist between ethanol yield, juice yield, and Brix values. Therefore, genotypes with high juice yield can achieve superior ethanol production, provided that fermentation efficiency is maintained at optimal levels.

Overall, the results confirm that genotypes such as No91, UNL-Hyb-3, M81-E and Tracy which effectively combine high juice yield with optimal sugar accumulation and efficient bioconversion, represent promising and sustainable feedstock options for commercial bioethanol production under semi-arid conditions.

Table 3. Effects of genotype and year on ethanol yield per unit area

Genotypes	Ethanol Yield (L ha^{-1})		
	2016	2017	Mean
Cowley	3468.2 d-l+	4564.0 a-d	4016.1 b
Dale	3499.7 d-l	4213.7 b-h	3856.7 bc
Grassi	4297.0 b-g	4309.5 b-g	4303.2 ab
M81-E	4854.7 abc	4004.0 c-j	4429.4 ab
Mennonita	1747.5 q	2287.7 m-q	2017.6 g
Nebraska sugarcane	4147.0 b-ı	3264.5 g-n	3705.7 bcd
PI579753	1924.5 pq	4227.2 b-h	3075.7 def
Ramada	3791.2 c-k	4217.7 b-h	4004.5 b
Roma	3979.5 c-j	4045.2 c-j	4012.4 b
Rox Orange	2036.0 opq	2633.2 l-q	2334.6 fg
Smith	2824.0 k-q	4841.7 abc	3832.9 bc
Sugar Drip	3382.0 e-m	2963.0 j-p	3172.5 cde
Theis	4662.7 abc	3081.0 h-o	3871.9 bc
Topper 76	4451.7 b-e	3940.2 c-k	4196.0 ab
Tracy	4311,8 c-j	4424.5 b-f	4368.1 ab
UNL-Hyb-3	5244.0 ab	4318.0 b-g	4781.0 a
Williams	3289.2 f-n	3050.7 ı-p	3170.0 cde
No2	1911.0 pq	2820.0 k-q	2365.5 fg
No91	5668.5 a	4073.5 c-j	4871.0 a
No5	4729.0 abc	3040.5 ı-p	3884.7 bc
Gülşeker	2221.7 n-q	3261.2 g-n	2741.5 efg
Mean	**3629.0**	**3694.4**	
CV (%)		11.12	
F Genotype (G)		**	
F Year (Y)		ns	
F G xY Interactions		**	

+) The means of different year-cultivar combinations with the same lower case are not statistically significant different from each other according to the Tukey test at $P \leq 0.05$. x) The means with the same letter in the same column are not statistically significant different from each other according to the Tukey test at $P \leq 0.05$. **) Significant at P≤0.01, ns: not significant.

CONCLUSION

The primary objective of this study was to evaluate the bioethanol production potential of 21 sweet sorghum genotypes to identify sustainable and high-yielding feedstocks suitable for second-crop cultivation under the Mediterranean-Çukurova climate conditions. Significant genotypic variation was observed among the evaluated genotypes over two years, particularly regarding juice sugar concentration, total sugar yield, fermentation efficiency, and ethanol yield per hectare. The findings demonstrate that high biomass production alone is not sufficient; successful bioethanol production depends on the combined achievement of high stalk juice yield, high sugar accumulation, and effective bioconversion efficiency. The genotypes Tracy, UNL-Hyb-3, and No91, along with Grassi and M81-E, stood out by combining these traits and were identified as promising candidates for commercial production. However, this study is limited to two growing seasons specific to the Çukurova region and relies on laboratory-scale fermentation results. Therefore, future studies should focus on evaluating genotype stability under different environmental conditions and across multiple locations. Furthermore, pilot-scale production trials and comprehensive techno-economic analyses are of critical importance for the commercialization of sweet sorghum as a sustainable bioethanol source in water-limited agricultural areas.

Ethical Statements and Declarations

Conflict of Interest

The authors declare no conflict of interest.

Author Contribution

All authors contributed equally to this study.

Consent to Participate / Publish

Informed consent was obtained from all individual participants included in the study.

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Data Availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Generative AI Statement

The authors declare that no generative artificial intelligence tools were used in the preparation of this manuscript.

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REFERENCES

Almodares, A., & Hadi, M. R. (2019). Production of bioethanol from sweet sorghum: A review. International Journal of Agricultural Sciences, 9(2), 1–9. ISSN:2167-0447. https://www.internationalscholarsjournals.com/articles/production-of-bioethanol-from-sweet-sorghuma-review.pdf

Appiah-Nkansah, N. B., Li, J., Rooney, W., & Wang, D. (2019). A review of sweet sorghum as a viable renewable bioenergy crop and its techno-economic analysis. Renewable Energy, 143, 1121–1132. https://doi.org/10.1016/j.renene.2019.05.066

Bai, F. W., Anderson, W. A., & Moo-Young, M. (2008). Ethanol fermentation technologies from sugar and starch feedstocks. Biotechnology Advances, 26(1), 89–105. https://doi.org/10.1016/j.biotechadv.2007.09.002

Dar, R. A., Dar, E. A., Kaur, A., & Phutela, U. G. (2018). Sweet sorghum-a promising alternative feedstock for biofuel production. Renewable and Sustainable Energy Reviews, 82, 4070–4090. https://doi.org/10.1016/j.rser.2017.10.040

Dweikat, I. (2014). Sorghum diversity paper, sweet energy crop article. University of Nebraska-Lincoln. http://agronomy.unl.edu/sweetsorghum

Ekefre, D. E., Mahapatra, A. K., Latimore, M., Jr., Bellmer, D. D., Jena, U., Whitehead, G. J., & Williams, A. L. (2017). Evaluation of three cultivars of sweet sorghum as feedstocks for ethanol production in the Southeast United States. Heliyon, 3(1), e00490. https://doi.org/10.1016/j.heliyon.2017.e00490

Enerdata. (2025). Total energy production. https://yearbook.enerdata.net/total-energy/world-energy-production.html

Erdurmus, C., Yucel, C., Cınar, O., Yegin, A. B., & Oten, M. (2018). Bioethanol and sugar yields of sweet sorghum. The International Journal of Engineering and Science, 7(11), 21–26. https://www.theijes.com/papers/vol7-issue11/Version-2/E0711022126.pdf

Fagundes, T. G., Lombardi, G. M. R., Lopes, A. C. A., Filho, C. C. F., Lopes, L. S., Parrella, R. A. C., Duarte, W. F., & Nunes, J. A. R. (2021). Characterization of sweet sorghum genotypes based on agro-industrial performance and fermentation potential. Sugar Tech, 23(4), 881–890. https://doi.org/10.1007/s12355-021-00974-8

Guden, B., Kiemde, O., Yol, E., & Uzun, B. (2024). Development and utilization of genome-wide InDel markers in Sorghum [*Sorghum bicolor* (L.) Moench]. Euphytica, 220,75. https://doi.org/10.1007/s10681-024-03335-0

Herniwati, Pabendon, M. B., Wicaksono, K. P., Waluyo, B., & Widaryanto, E. (2023). Evaluation of sweet sorghum (*Sorghum bicolor* (L.) Moench) genotypes for bioethanol yield potential. Transactions of the Chinese Society of Agricultural Machinery, 54(9), 62–71. https://doi.org/10.62321/issn.1000-1298.2023.09.06

Jia, F., Chawhuaymak, J., Riley, M. R., Zimmt, W., & Ogden, K. L. (2013). Efficient extraction method to collect sugar from sweet sorghum. Journal of Biological Engineering, 7:1. https://doi.org/10.1186/1754-1611-7-1

Jin, H., Liu, R., & He, Y. (2012). Kinetics of batch fermentations for ethanol production with immobilized Saccharomyces cerevisiae growing on sweet sorghum stalk juice. Procedia Environmental Sciences, 12, 137–145. https://doi.org/10.1016/j.proenv.2012.01.258

Karimi, K., Emtiazi, G., & Taherzadeh, M. J. (2006). Ethanol production from dilute-acid pretreated rice straw by simultaneous saccharification and fermentation with Mucor indicus, rhizopus oryzae, and *Saccharomyces cerevisiae*. Enzyme and Microbial Technology, 40(1), 138–144. https://doi.org/10.1016/j.enzmictec.2005.10.046

Kasegn, M. M., Simachew, A., Redda, Y. T., Gebremedhn, H. M., Berhanu, A. D., & Mossa, M. M. (2024a). Evaluation of sugar content and bioethanol production of Ethiopian local varieties "Nech Tinkish" and "Hawaye" sweet sorghum (*Sorghum bicolor* L.). Biotechnology for the Environment, 1(1), 2–13. https://doi.org/10.1186/s44314-024-00001-6

Kasegn, M. M., Simachew, A., Redda, Y. T., & Gebremedhn, H. M. (2024b). Production of bioethanol from sweet sorghum (*Sorghum bicolor* L.) juice using yeast isolated from fermented sweet sorghum juice. International Microbiology, 27(2), 491–504. https://doi.org/10.1007/s10123-023-00403-8

Khalil, S. R., Abdelhafez, A. A., & Amer, E. A. M. (2015). Evaluation of bioethanol production from juice and bagasse of some sweet sorghum varieties. Annals of Agricultural Sciences, 60(2), 317–324. https://doi.org/10.1016/j.aoas.2015.10.005

Kumar, B., Singh, M., Kumar, A., Rana, R., Kumar, S., Kumar, R., & Singh, A. K. (2024). Sweet sorghum utilization for dual-purpose: Feed-fodder and fuel production (A review). Ecology, Environment and Conservation, 30(2), 852–857. https://doi.org/10.53550/EEC.2024.v30i02.072

Li, H., Han, X., Liu, H., Hao, J., Jiang, W., & Li, S. (2021). Silage fermentation on sweet sorghum whole plant for fen-flavor baijiu. Foods, 10(7), 1477. https://doi.org/10.3390/foods10071477

Lombardi, G. M. R., Nunes, J. A. R., Parrella, R. A. C., Teixeira, D. H. L., Bruzi, A. T., Duraes, N. N. L., & Fagundes, T. G. (2015). Path analysis of agro-industrial traits in sweet sorghum. Genetics and Molecular Research, 14(4), 16392–16402. https://doi.org/10.4238/2015.December.9.8

Lopez-Sandin, I., Zavala-Garcia, F., Levin, L., Ruiz, H. A., Hernandez-Luna, C. E., & Gutierrez-Soto, G. (2021). Evaluation of bioethanol production from sweet sorghum variety roger under different tillage and fertilizer treatments. BioEnergy Research, 14, 1058–1069. https://doi.org/10.1007/s12155-020-10215-7

Malik, A. S., Kaya, C., & Topçu, Y. (2020). Evaluation of different sweet sorghum cultivars for bioethanol yield potential and bagasse combustion characteristics in a semiarid Mediterranean environment. Biomass and Bioenergy, 139, 105624. https://doi.org/10.1016/j.biombioe.2020.105624

Murray, S. C., Rooney, W. L., Hamblin, M. T., Mitchell, S. E., & Kresovich, S. (2009). Sweet sorghum genetic diversity and association mapping for brix and height. The Plant Genome, 2(1), 48–62. https://doi.org/10.3835/plantgenome2008.10.0011

Mutepe, R. D., Marx, S., & Van der Gryp, P. (2011). Ethanol production from sweet sorghum [Master's thesis, North-West University]. Potchefstroom, South Africa. https://www.crses.sun.ac.za/files/services/events/workshops/Daphney%20Mutepe%20Paper.pdf

Nazli, R. I., Aslankaciran, C., Yang, D., Liaqat, W., Polat, M., Cavdar, A. S., Tansi, V., & Baloch, F. S. (2024). Assessment of sweet sorghum genotypes for bioethanol production potential and bagasse combustion characteristics in a semi-arid Mediterranean climate. Agronomy, 14, 2626. https://doi.org/10.3390/agronomy14112626

Oktem, A.G., Oktem, A., Tas, T., & Yucel, C. (2020). Bio-fuel potential of some sweet sorghum genotypes [*Sorghum bicolor* (L.) Moench ssp. saccharatum]. Journal of Energy Research and Reviews, 6(4), 15-22. https://doi.org/10.9734/jenrr/2020/v6i430174

Parrella, R. A. C., Schaffert, R. E., Menezes, C. B., Rodrigues, J. A. S., Magalhães, J. V., Damasceno, C. M. B., Silva, D. D., & Mendes, S. M. (2018). Improving sorghum cultivation in South America. In W. Rooney (Ed.), Achieving sustainable cultivation of sorghum, Volume 2: Sorghum utilization around the world (pp. 159–192). Burleigh Dodds Science Publishing.

Pérez-Carrillo, E., Serna-Saldívar, S. O., Alvarez, M. M., & Cortes-Callejas, M. L. (2008). Effect of sorghum decortication and use of protease before liquefaction with thermoresistant α-amylase on efficiency of bioethanol production. Cereal Chemistry, 85(6), 792–798. https://doi.org/10.1094/CCHEM-85-6-0792

Ratnavathi, C. V., Suresh, K., Vijay Kumar, B. S., Pallavi, M., Komala, V. V., & Seetharama, N. (2011). Study on genotypic variation for ethanol production from sweet sorghum juice. Biomass and Bioenergy, 35(2), 653–658. https://doi.org/10.1016/j.biombioe.2010.10.032

Regassa, T. H., & Wortmann, C. S. (2014). Sweet sorghum as a bioenergy crop: Literature review. Biomass and Bioenergy, 64, 348–355. https://doi.org/10.1016/j.biombioe.2014.03.052

Rono, J. K., Cheruiyot, E. K., Othira, J. O., & Njuguna, V. W. (2018). Cane yield and juice volume determine ethanol yield in sweet sorghum (Sorghum bicolor L. Moench). International Journal of Applied Science, 1(2), 29. https://doi.org/10.30560/ijas.v1n2p29

Rutto, L. K., Xu, Y., Brandt, M., Ren, S., & Kering, M. K. (2013). Juice, ethanol, and grain yield potential of five sweet sorghum (Sorghum bicolor [L.] Moench) cultivars. Journal of Sustainable Bioenergy Systems, 3, 113–118. https://doi.org/10.4236/jsbs.2013.32016

Sasaki, K., Tsuge, Y., Sasaki, D., Kawaguchi, H., Sazuka, T., Ogino, C., Kondo, A., 2015. Repeated ethanol production from sweet sorghum juice concentrated by membrane separation, *Bioresource Technology*, 186,351-355. http://dx.doi.org/10.1016/j.biortech.2015.03.127

Sluiter, A., Hames, B., Ruiz, R., Scarlata, C., Sluiter, J., Templeton, D., & Crocker, D. (2008). Determination of sugars, byproducts, and degradation products in liquid fraction process samples (Technical Report NREL/TP-510-42623). National Renewable Energy Laboratory.

Sriputorn, B., Laopaiboon, P., & Laopaiboon, L. (2017). Increase in ethanol production efficiency from sweet sorghum juice by Saccharomyces cerevisiae. Chiang Mai Journal of Science, 44(1), 59–71. https://cmudc.library.cmu.ac.th/frontend/Info/item/dc:48375

Sun, Y., & Cheng, J. (2002). Hydrolysis of lignocellulosic materials for ethanol production: A review. Bioresource Technology, 83(1), 1–11. https://doi.org/10.1016/S0960-8524(01)00212-7

Suwarti, Efendi, R., Massinai, R., & Pabendon, M. B. (2018). Evaluation of sweet sorghum (Sorghum bicolor L.) on several population density for bioethanol production. IOP Conference Series: Earth and Environmental Science, 141, 012032. https://doi.org/10.1088/1755-1315/141/1/012032

Thatiyamanee, P., Laopaiboon, P., & Laopaiboon, L. (2025). Optimizing bioethanol production from sweet sorghum stem juice under very high gravity fermentation and temperature stress conditions. Carbon Resources Conversion, 8, 100274. https://doi.org/10.1016/j.crcon.2024.100274

Ünal, M. Ü., Cabaroğlu, T., Şener, A., Yücel, C., Yücel, D., Canatar, M., & Cemek, K. (2018). Tatlı sorgumdan biyoetanol üretiminde maya türü ve suşunun biyoetanol verimine etkisi (Sözlü sunum). 2nd International Conference on Agriculture, Forest, Food Sciences and Technologies, 2-5 Nisan, Çeşme, İzmir, Türkiye.

Walker, G. M., & Stewart, G. G. (2016). Saccharomyces cerevisiae in the production of fermented beverages. A review. Beverages, 2(4), 30. https://doi.org/10.3390/beverages2040030

Wang, J. C., Dai, L., Tian, Y. S., & Qin, S. P. (2007). Analysis of the development status and trends of biomass energy industry in China. Transactions of the Chinese Society of Agricultural Engineering, 23, 276–282. https://doi.org/10.5555/20083011740

Wilkins, M. R. (2009). Effect of orange peel oil on ethanol production by Zymomonas mobilis. Biomass and Bioenergy, 33(3), 538–541. https://doi.org/10.1016/j.biombioe.2008.08.010

Worldometer. (2025). World population forecast (2030-2050). https://www.worldometers.info/world-population/

Xuan, T. D., Phuong, N. T., Khang, D. T., & Khanh, T. D. (2015). Influence of sowing times, densities, and soils to biomass and ethanol yield of sweet sorghum. Sustainability, 7(9), 11657–11678. https://doi.org/10.3390/su70911657

Yücel, C., Hatipoğlu, R., Dweikat, İ. M., İnal, İ., Gündel, F., & Yucel, H. (2018). Farklı tatlı sorgum (Sorghum bicolor var. saccharatum (L.) Mohlenbr.) genotiplerinin Çukurova ve GAP bölgelerinde biyo-etanol üretim potansiyellerinin saptanması (Proje Sonuç Raporu No: 114O945). TÜBİTAK.

Yücel, C., Dweikat, I., Yucel, D., & Gultekin, R. (2020a). Bioethanol potential of different sweet sorghum genotypes grown under Mediterranean conditions. Fresenius Environmental Bulletin, 29(12), 10356–10365. https://hdl.handle.net/11503/1570

Yücel, D., Hizli, H., Yucel, C., & Dweikat, I. (2020b). Genetic variability, heritability, and genetic advance for ethanol yield and yield components in sweet sorghum (Sorghum bicolor var. saccharatum (L.)). International Journal of Innovative Approaches in Agricultural Research, 4(1), 21–32. https://doi.org/10.29329/ijiaar.2020.238.3

Yücel, C., Yucel, D., Hatipoglu, R., & Dweikat, İ. (2022). Research on the potential of some sweet sorghum genotypes as bioethanol source under Mediterranean conditions. Turkish Journal of Agriculture and Forestry, 46(2), 141–151. https://doi.org/10.55730/1300-011X.2966

Yurtsever, N. (1984). Deneysel istatistik metotları (Genel Yayın No: 56). Toprak ve Gübre Araştırma Enstitüsü Müdürlüğü Yayınları, Ankara.

Zhang, X.G., Li, D.M., Liu, Z.Y., Ma, D.W., Li, M.Y., Wang, K.X., & Luo, M.P. (2024). Improved ethanol production from sweet sorghum through pretreatment with enzymes from its endophytes. Journal of Animal & Plant Sciences, 34(3), 604–613. https://doi.org/10.36899/JAPS.2024.3.0747

Zhao, Y. L., Dolat, A., Steinberger, Y., Wang, X., Osman, A., & Xie, G. H. (2009). Biomass yield and changes in chemical composition of sweet sorghum cultivars grown for biofuel. Field Crops Research, 111(1-2), 55–64. https://doi.org/10.1016/j.fcr.2008.10.006

Zhuzhukin, V. I., & Garshin, A. Y. (2016). Biochemical composition of the aboveground sweet sorghum biomass under the dry weather conditions of the Volga region. Russian Agricultural Sciences, 42(2), 124–126. https://doi.org/10.3103/S106836741602021X