Turkish Journal of Agriculture - Food Science and Technology, 13(4): 917-926, 2025
DOI: https://doi.org/10.24925/turjaf.v13i4.917-926.7347

Turkish Journal of Agriculture - Food Science and Technology

Available online, ISSN: 2148-127X | www.agrifoodscience.com | Turkish Science and Technology Publishing (TURSTEP)

Sugar Potential of Populations and Varieties of Sorghum in Algeria Performing as Promising Bioethanol Source

Farida Alane[1,a], Hakim Bachir[2,b], Azzedine Mazari[3,c,*]

[1]*Animal Production Research Division, Algeria's National Institute of Agronomic Research, Station Mehdi Boualem, BP37, Baraki, Algiers, Algeria.*
[2]*Bioclimatology and Agricultural Hydraulics Research Division, Algeria's National Institute of Agronomic Research, Station Mehdi Boualem, BP37, Baraki, Algiers, Algeria.*
[3]*Food Technology Research Division, Algeria's National Institute of Agronomic Research, Station Mehdi Boualem, BP37, Baraki, Algiers, Algeria.*
[*]*Corresponding author*

A R T I C L E I N F O

Research Article

Received : 19.11.2024
Accepted : 07.12.2024

Keywords:
Bioethanol
Growth cycle
Sorghum
Physiological stage
Sugar yield

A B S T R A C T

The study explored the potential of local Oasian sorghums from the Algerian Sahara, alongside the Arab Center for the Studies of Arid Zones and Dry Lands (ACSAD) varieties, focusing on their sap and sugar yield capabilities, for selecting the most appropriate ones as good sources for bioethanol production. The method used in this study consisted of a complete randomized block design with three repetitions in open field. Harvesting was carried out at two vegetative stages: milky-pasty and hard-grain. Morphometric measurements and estimation of the produced biomass yields followed. The second step of the study concerned the extraction of the sap from the stems and the determination of its volume and sugar content. Depending on the physiological stage, the volume of produced sap fluctuated as much as the sugar rate. The diameter of the stems varied the bark-to-pith ratio of populations. According to this ratio, the largest fraction of pith, which contains sap, was found in the populations: *Hamra*, *Kharssi*, *Beïda-Adrar*, respectively, 0.65, 0.83, and 0.91. The stems yield of *Biofuel* and *Beïda-Adrar* were notably high at milky-pasty stage, approximately 1.87 and 1.51 kg m^{-2}, respectively; indicating their suitability for bioethanol production. The research highlighted the variation in sap volume across different growth stages and populations, with a proportional relationship observed between sap volume and sugar concentration. The analysis demonstrated significant differences across all the studied parameters. Principal Component Analysis (PCA) further categorized the parameters into two distinct groups based on growth phases, facilitating a deeper understanding of the determinants of sorghum's bioethanol potential. The findings emphasize the need for a balanced selection of sorghum populations for bioethanol production, considering sap volume, sugar yield, and biometric parameters. This study not only underscores the viability of sorghum as a bioethanol source but also aligns with sustainable agriculture and renewable energy goals, especially in arid regions like the Algerian Sahara.

[a] alanefarida@hotmail.fr https://orcid.org/0000-0001-8564-8786
[b] akm7.62@hotmail.fr https://orcid.org/0000-0002-2902-1310
[c] azzedine.mazari@inraa.dz https://orcid.org/0000-0001-8391-0146

Introduction

Sorghum (*Sorghum bicolor* L.) stands as the fifth most cultivated cereal globally, owing to its significant production volume and the expansive cultivation area, which spans 42 million hectares across 66 countries. Remarkably, it holds the third position in Africa's cereal hierarchy, trailing only behind maize and rice (Dalton & Hodjo, 2020). In the Sahel region, sorghum, alongside millet, dominates, covering 50 to 70% of the cultivable land, showcasing its leading role in agricultural practices (Ouedraogo et al., 2014). The crop's widespread adoption can largely be attributed to its varietal diversity and exceptional adaptability to challenging environmental conditions, such as low rainfall (200~600 mm), marginal soils, and high temperatures (Hariprasanna & Rakshit, 2016). Sorghum's success in the Sahel is further bolstered by its role as a staple food, contrasting with its utilization primarily for animal feed in developed countries like the United States (FAO, 2016).

Algeria, with a landmass of 2.381.741 km², finds 80% of its territory classified as arid to semi-arid, predominantly within the Sahara, characterized by ergs, regs, and hamadas (Baameur et al., 2015). Sweet sorghum emerges as a versatile crop, capable of grain production for human and animal consumption while simultaneously accumulating sugars in its stems. Believed to have been introduced from India to Italy around sixty years before A.D., the consensus among scholars points to Africa as the true cradle of sorghum, where it still grows wild over extensive areas (Popescu & Condei, 2014). The mid-19th century saw the introduction of several sweet sorghum varieties to France, China, South Africa, and subsequently the United States.

The cultivation of sorghum for sugar and alcohol production received significant attention from the Italian and French press starting in 1936. By 1938, Italy had produced 8000 hL of pure sorghum alcohol, and the following year, an alcohol fuel factory was inaugurated by the Duce, producing 350 hL of pure alcohol from sorghum juice. This success catalyzed the establishment of several sorghum distilleries in Algeria (Miège, 1940). While the development of intensive energy crops has been viewed as a means to mitigate reliance on fossil fuels and chemicals, their large-scale cultivation often comes at the expense of food production and has been shown to have long-term detrimental environmental impacts, diminishing their anticipated benefits (Fritsche et al., 2010; Zegada-Lizarazu & Monti, 2011).

The by-products of sorghum, such as leaves and bagasse, offer valuable fodder for livestock, which can be processed into silage, sweet juice for syrup or fuel (liquid or gelled ethanol), or even beverages (Deribe & Kassa, 2020). These diverse applications address food, energy, and environmental challenges, empowering rural communities to enhance their living standards through improved agricultural production and the creation of new local industries that generate added value (Çakmakçı et al., 2023). Achieving the selection of successful varieties and disseminating high-quality seeds requires exploring a wide genetic base and testing plant material from various origins to identify cultivars that resonate with local populations, aiming for high productivity, yield stability, suitability for high-density planting, early maturity, and low seasonal interaction (Atlin et al., 2017; Reddy et al., 2004; Swarup et al., 2021).

In this study, we endeavor to shed light on the agricultural and food-related prospects of local sorghum varieties from southern Algeria and selections provided by the Arab Center for the Studies of Arid Zones and Dry Lands (ACSAD), focusing on novel aspects that distinguish our work from existing research within the same domain. Unlike prior studies that primarily concentrated on the basic agronomic characteristics and biofuel potential of sorghum, our research delves into the detailed process of sap extraction and quantifies the total sugar content, providing a comprehensive analysis of the crop's utility for both food and energy purposes.

A significant novelty of our approach is the in-depth examination of the pressing residues from these sorghum populations. While previous investigations might have overlooked the value of these by-products, our study proposes innovative uses for them, particularly in the feeding of ruminants. This dual-focus not only enhances the sustainability of sorghum cultivation by minimizing waste but also contributes to the circular economy within agricultural systems, offering a cost-effective feed solution that can potentially improve livestock health and productivity.

Moreover, our research stands out by integrating traditional knowledge with modern scientific techniques, specifically targeting the adaptation strategies of local oasis sorghum varieties. This approach aims to uncover genetic traits and cultivation practices that could bolster the crop's resilience to climate change, a critical factor given the increasing environmental challenges facing arid and semi-arid regions. By juxtaposing these findings with global sorghum research, we aspire to unearth unique insights that could pave the way for innovative agricultural practices, ensuring food security and sustainable development in vulnerable ecosystems.

In essence, this study not only contributes to the existing body of knowledge on sorghum cultivation and its potential applications but also proposes a multifaceted approach that leverages the untapped potential of sorghum by-products, emphasizing the importance of sustainability and resource optimization in agricultural research.

Materials and Methods

The Plant Material

The tests conducted on sorghum populations originating from Algerian oases, have been locally named by farmers of the region based on the color of the seed coat. The "*Hamra*" denomination, which means "red", for those from Ksar Ouled Ali (33°24'11.4''N 3°43'27.2''W); and the "*Beïda*" denomination, which means white, for those from M'Raguen (28°04'12.0''N; 0°06'56.9''E). A second experimental trial, featuring the introduction of eight seed varieties from the ACSAD was carried out, thereby enriching the genetic diversity under study and offering new prospects for agricultural adaptation in these regions.

Table 1. Origin, color and weight of 1000 seed of the studied populations

Population	Color	Origin	Weight of 1000 seed (g)
Hamra	Red	Algeria	40.16
Beïda-Adrar	White	Algeria	31.13
Biofuel	White	ACSAD	40.40
Beïda_In-Salah	White	Algeria	39.30
Ezra	White	ACSAD	36.80
Touggourt	Black	Algeria	31.40
Masser17	White	ACSAD	34.60
El-Ménéa	Black	Algeria	42.40
Dorado9	White	ACSAD	37.50
Kharssi	Red	Algeria	47.00
Soudane	Black	Algeria	24.37


(A) (B)

Figure 1. Experimental plot indicating the complete random block device type with three repetitions (A) and grown sorghum stalks at milky pasty physiological stage (B).

Table 2. Climatic data of the period of the formal experimental trial.

Period	Precipitation (mm)	Average temperature (°C)	Average humidity (%)
Mai	14.0	19.9	69.30
June	14.4	23.0	70.00
July	13.2	27.2	70.40
August	07.2	27.3	70.90
September	12.4	24.0	67.80
October	91.6	20.6	74.50
November	92.4	14.7	82.00
	245.20[a]	22.39[b]	72.13[b]

Source: Data provided from Mehdi Boualem meteorological station of Algeria's National Institute of Agronomic Research (INRAA), Algiers; [a]: Total precipitations, [b]: average value.

The Site and Experimental Device

The experimental setup was designed as a completely randomized block with three replications, covering an area of 640.5 m^2. The seeding occurred in open fields within a greenhouse that was covered by a net, located at the Mehdi Boualem experimental station of Algeria's National Institute of Agronomic Research (INRAA), situated in Algiers. The geographical coordinates of the location are 36°41'4.35'' North and 3°06'24.84'' East, with an elevation of 18.5 meters (Figure 1). In each block the population was represented by four lines spaced 30 cm apart. Between each population, 60 cm was left and between each block, 1 m was left. This small spacing is used in irrigated cultivation. The seeding rate used was 3 grams per bag, four bags per meter. Fifteen days post-germination, seedlings were thinned to leave one plant per bag.

To fertilize, 6.65 g of urea per linear meter were applied 50 days after sowing, i.e. at the milky stage for seed filling. The control of aphids was carried out using a broad-spectrum systemic insecticide containing 700 g Kg^{-1} of Imidacloripides. The applied dose was 100 g ha^{-1} of the insecticide.

A line of one linear meter of the middle is mowed for each stage and the two of the peripheries were kept for seed production.

The parameters noted in green were: the height of the stems using a tape measure, the diameter of the stem using a caliper, the leaves were separated from the stems before weighing to determine the leaf to stem ratio. The number of tillers was determined over the entire square meter. The green and dry yields were subsequently determined. The first harvest occurred 52 days after planting, during the vegetative stage, with the plants reaching an average height of 40 cm.

The climate and irrigation

The climate of the region is Mediterranean, situated within the subhumid bioclimatic stage. It is distinguished by a rainy season that typically spans from September to May, complemented by a sunny summer period. During the initial week of the first experimental trial, the mean and maximum temperatures recorded were 15 °C and 23.3 °C, respectively. The highest rainfall observed during the experimental timeframe amounted to 16mm in October.

For the first month of the second experimental trial, which started on Mai, the mean temperature was 19.9 °C. The total rainfall recorded at the climatic station throughout the duration of the experiment was 245.2 mm. The maximum rainfall within the experimental period occurred in the last two months, October and November, with 91.6 mm and 92.4 mm, respectively, as detailed in Table 2. The average temperature over the seven months of the experiment was 22.39 °C, with the highest temperature of 27.3 °C recorded in August and the lowest at 14.7 °C in November. Air humidity remained high throughout the experimental period, averaging 72.13%. To compensate for the water deficit, irrigation was applied twice a week at the onset of the vegetation period and reduced to once a week towards the end of the vegetation cycle.

Table 3. Some parameters of the three local sorghum populations – preliminary experimental trial

Population	Cycle of the plant[a] (days)	Height (cm)	Squeezed sap		
			Volume (mL 100 g^{-1})	Brix index	Sugar (%)
Hamra	119	162	23.10	1.349	11.0
Beïda-Adrar	119	207	14.23	1.355	14.5
Soudane	119	269	01.55	1.359	17.0

[a] Plant cycle duration in days.

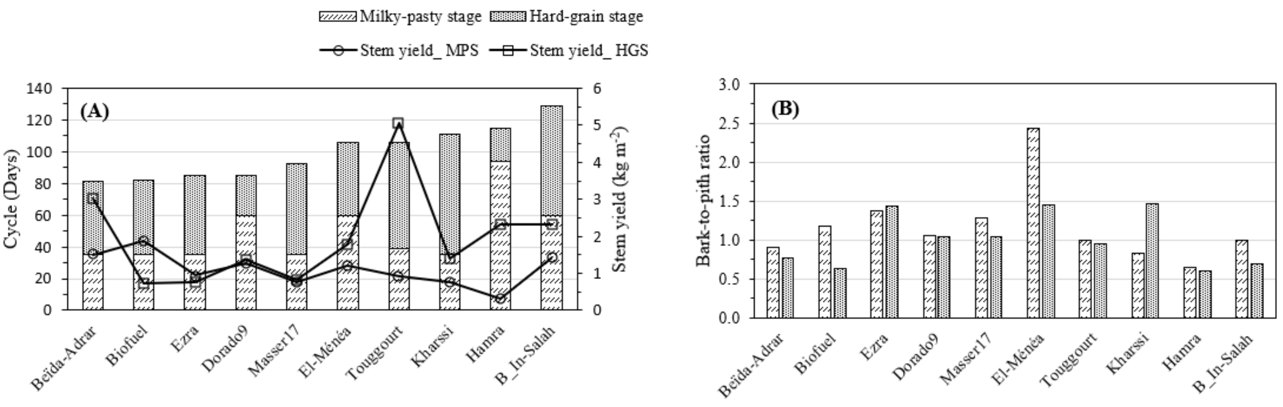

Figure 2. Stems yield across physiological growth cycle of sorghum populations and varieties at milky-pasty (MPS) and hard-grain stages (HGS) (A) and their in green bark-to-pith ratio (B) through formal experimental trial.

The Soil

The physico-chemical analysis of the soil reveals a loamy clay texture, as indicated by the soil structure triangle. The soil has a slightly basic pH of 7.87 and an electrical conductivity of 0.28 dS m^{-1}, indicating that it is only mildly saline. The nitrogen content in the soil is relatively low for sorghum 340 ppm and would likely require fertilization to ensure optimal growth, the phosphorus content is adequate to high at 53.15 ppm, and the potassium level is also high, measuring 670 ppm.

Sap Extraction Procedure

After collecting and weighing the sorghum stems, the pith was separated from the bark with a knife. For the sap extraction about 500 g of pith cut into small pieces then underwent extraction using an endless vice grinder to recover the sap and the residue (pressed pith). The sap volume was determined using a graduated measuring cylinder. Sugar rate of the sap was measured by means of a temperature-adjusted professional refractometer (Krüss, Germany) at 20°C, the device provides a reading of the refractive index and the rate of soluble organic matter in the sap, i.e. rate of sugar.

Statistical Analysis

All the statistics were performed by means of the XLSTAT 2014.5.03 software for Windows. Mean values obtained for the variables studied in the different groups were compared by one-way ANOVA, assuming that there were significant differences among them when the statistical comparison gives $p<0.05$. Factor analysis, using principal components as the method of factor extraction was employed to summarize information in a reduced number of factors.

Results and Discussion

In the preliminary experimental trial, the growth cycle of the three sorghum populations was identical, with each reaching the milky-pasty stage by the 119th day post-sowing (Table 3). However, in the second experimental trial, the growth cycle experienced significant variations; the *Hamra* population's cycle was shortened to 94 days, and the *Beïda-Adrar* population's cycle was drastically reduced to just 35 days, as illustrated in Figure 2. The average stem height also showed a decrease compared to the previous trial. Specifically, the *Hamra*'s height, which was 2.69 m, fell to 0.99 m. Similarly, the *Beïda*'s height decreased from 2.07 m to 1.35 m, as recorded in Tables 3 and 4. The observed variations in the growth cycle and stem height of cultivated sorghum are influenced by both varietal and environmental factors, aligning with findings reported in the literature.

Plant height is a crucial trait; affecting susceptibility to lodging, overall plant productivity, and the feasibility of intercropping practices. Grain sorghum varieties used for silage, which involve utilizing the whole plant for animal feed or for generating energy through anaerobic digestion, are typically larger.

This underscores the importance of selecting appropriate sorghum varieties based on intended use and environmental conditions to optimize yield and quality. The stem diameter also showed considerable variation across the varieties, measuring 22.2 mm in the *Dorado9* variety and narrowing down to 10.38 mm for *Ezra* (Table 4).

This variation significantly affected the bark-to-pith ratio, which ranged from 0.65 for *Hamra* to 2.43 for El-Ménéa, suggesting that the most substantial pith portion, which houses the sap, was predominantly found in the *Hamra, Kharssi*, and *Beïda-Adrar* varieties, with respective ratios of 0.65, 0.83, and 0.91, as detailed in Figure 2.

Table 4. Biometric parameters of sorghum populations and varieties at milky-pasty stage

Variety / population	Sap color	Stem diameter (mm)	Average height (cm)
Masser17	Green	11.27	122
Kharssi	Green	12.35	130
Ezra	Green	10.38	126
Beïda-Adrar	Green	17.20	135
Biofuel	Yellow	18.63	071
Touggourt	Green	17.70	143
Dorado9	Yellow	22.20	096
B_In-Salah	Yellow	17.20	147
El-Ménéa	Green	15.30	154
Hamra	Yellow	17.50	099

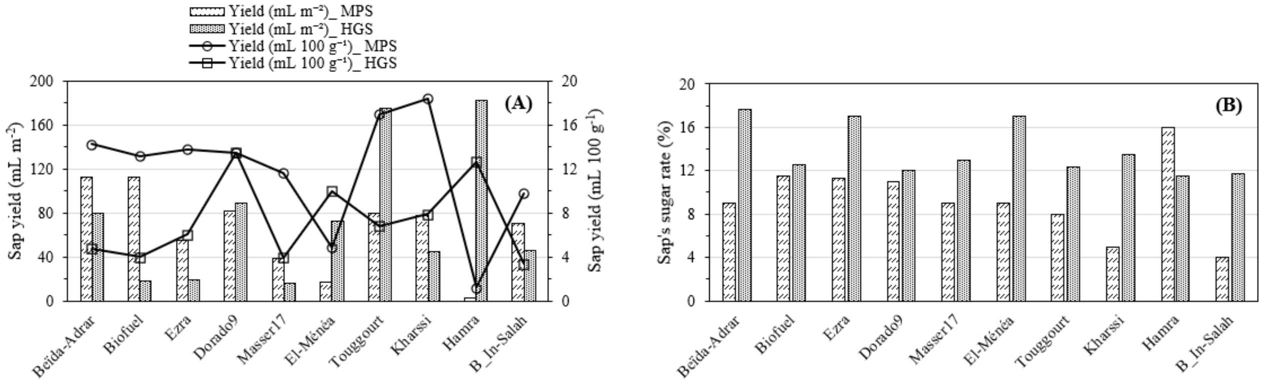

Figure 3. Yielded sap volume (A) and sap's sugar rate (B) of the studied sorghum populations and varieties at two physiological stages (MPS: Milky-pasty stage and HGS: Hard-grain stage).

When analyzing the average height of these varieties at this particular stage, they can be categorized into three distinct groups based on their stature. The tallest varieties, ranging from 143 to 154 cm (*Touggourt, El-Ménéa, B_In-Salah*), the varieties of medium height, spanning from 122 to 135 cm (*Kharssi, Ezra, Beïda-Adrar, Masser17*), and the shorter varieties, measuring between 0.71 and 0.99 cm (*Biofuel, Dorado9, Hamra*).

The highest observed average stalk height among these varieties was 154 cm, as detailed in Table 4. The plant height is deemed a critical attribute, as it influences the plant's vulnerability to lodging, its overall productivity, and the feasibility of intercropping practices. The varieties under discussion include *Beïda_In-Salah* (*B_In-Salah*), *Beïda-Adrar*, *Touggourt*, and *El-Ménéa* (Table 4), highlighting the diverse morphological traits that characterize sorghum cultivation.

The *Biofuel* variety achieved the highest stem yield per square meter at the milky-pasty stage, producing an impressive 1.867 kg m^{-2}, whereas the *Hamra* population recorded the lowest yield with only 0.312 kg m^{-2} (Figure 2A). Varieties characterized by medium stem diameter ranging from (15.3 ~ 22.2 mm), for instance *El-Ménéa, B_In-Salah, Beïda-Adrar*, and *Dorado9*, demonstrated moderate production levels, yielding 1.200 ~ 1.508 kg m^{-2} (Figure 2A).

On the other hand, the couple of verities "*Masser17, Kharsi*" and "*Touggourt, Ezra*" produced yields that were relatively near to each other, with (0.753; 0.771) and (0.936; 0.939) kg m^{-2}, respectively (Figure 2A).

The sap volume extracted per 100 g of green stems from the *Beïda-Adrar* sorghum population maintained a consistent level across the two experimental trials, producing 14.23 mL in the first one and 14.22 mL in the second. Conversely, the *Hamra* population experienced a significant decrease, from 23.1 mL in the first experimental trial to only 1.22 mL in the second one (Table 3, Figure 3A). Notably, the change in sap volume in the *Hamra* population was accompanied by an increase in its sugar rate, which rose from 11% in the preliminary experimental trial to 16% in the formal one. On the other hand, the *Beïda-Adrar* population saw a decrease in sap's sugar rate, from 14.5% to 9% across the two experimental trials, as reported in Table 3 and Figure 3B.

These variations in sap production and sugar rate can be attributed to several environmental factors beyond just the genetic makeup of the sorghum populations. Factors such as climate conditions, soil quality, and fertilization practices play crucial roles in influencing both the quantity of sap produced and the synthesis of sugar within the plant. This highlights the complex interplay between environmental conditions and plant physiology in determining the productivity and quality of sorghum crops.

At the milky-pasty stage within the formal experimental trial, the tested varieties exhibited a diverse range of sap yield, with outputs fluctuating between 2.31 mL m^{-2} and reaching up to 112.66 mL m^{-2}, as depicted in Figure 3A. Furthermore, the sap displayed a notable variability in color, ranging from green to yellow (Table 4). According to classical works, sorghum stem juiciness being governed by a dominant single locus gene labeled as 'D' (Zhang et al., 2018). The latter authors confirmed that the dry gene encodes a plant-specific NAC transcription factor and that stem juiciness results from loss of function of the dry gene. The extracted sap could be valorized using maceration and double distillation to produce bioethanol (Nenciu et al., 2022).

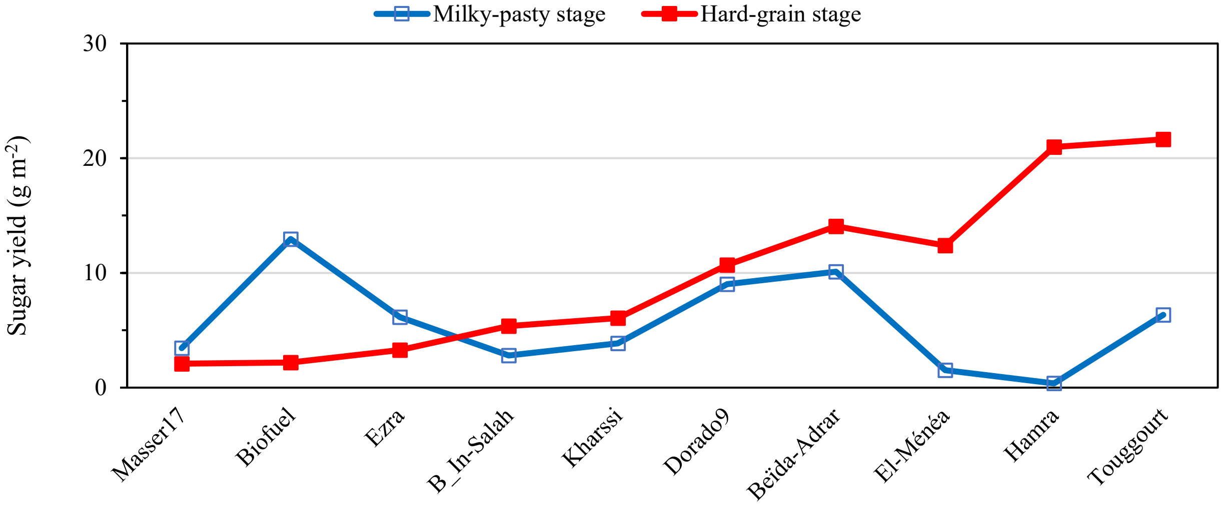

Figure 4. Comparative analysis of total sugar yield across sorghum populations during milky-pasty and hard-grain stages. Yields were expressed as sugar weight (g m^{-2}).

The local population *B_In-Salah* yielded 70.36 mL m^{-2} of sap with the least sugar rate (4%) of the experimental trial, while *Masser17* yielded 38.23 mL m^{-2} of sap with 9% of sugar concentration. Moreover, for *Hamra*, the highest sap's sugar rate (16%) with the lowest volume of produced sap (2.31 mL m^{-2}) were observed (Figure 3A and B).

This data suggests that selecting a variety for bioethanol production requires balancing sap volume and sugar concentration. The *Biofuel* variety, for instance, offers a sap volume of 112.66 mL m^{-2} and a sugar rate of 11.5%, a balance echoed by the *Beïda-Adrar* variety, which provides a similar yielded volume of 112.23 mL m^{-2} with a slightly lower sugar rate 9% (Figure 3A and B). Hence, sap volume and sugar concentration are variable traits across varieties and are influenced by the environmental conditions of the experiment. According to Miège (1940), sugar does not degrade during storage; in a study, sorghum stems stored from September 20 to January 7 retained a sugar concentration of 19.56%. Despite observing stem pith blackening and sap degradation in our samples stored in a cold room, the sugar content remained unaffected.

Comparing the fine-stemmed populations of *Soudane, Touggourt*, and *El-Ménéa* over two experimental trials revealed significant differences in their bark-to-pith ratios: 4 in *Soudane*, 2.43 in *El-Ménéa*, and 1 in *Touggourt* (Figure 2B). *Touggourt*'s population, with a sap volume of 16.94 mL 100 g^{-1} stem, is juicier compared to *El-Ménéa* and *Soudane*, which offer 4.85 and 1.55 mL 100 g^{-1}, respectively (Table 3, Figure 3A), which makes them easier for tedding. Based on the bark-to-pith ratio, *Touggourt*'s population is more suitable as ruminants forage due to its higher digestibility and palatability. Moreover, it encloses a higher juice volume too (Figure 3). Notably, the late-maturing local variety *B_In-Salah* displayed a robust stem yield of 1.44 kg m^{-2}. This variety also generates an average sap volume of 70.36 mL m^{-2} of stem and boasts a balanced bark-to-pith ratio of 1, as indicated in Figures 2A, B and 3A. Aimed at seed production, the *B_In-Salah* population is characterized by its large stems, long panicles, and weighty panicles, positioning it as a prime candidate for such purposes.

The analysis contrasting the milky-pasty and hard-grain growth cycles of sorghum revealed distinct rankings among the populations studied, as depicted in Figure 2A. Specifically, within the span of 81-85.33 days, the varieties *Beïda-Adrar, Biofuel, Ezra, Dorado9*, and *Masser17* were observed. Meanwhile, a longer cycle ranging from 105.67 to 128.676 days encompassed *El-Ménéa, Kharsi, Hamra*, and *B_In-Salah* varieties. Traditionally, "early" or recession sorghum, strictly speaking, is cultivated during the dry season from October to December in loam-clay soils capable of flooding.

This category exclusively comprises dura sorghum varieties. In contrast, "late" sorghum is planted towards the end of the dry season (February to May) and harvested in the rainy season (September-October), typically involving guinea sorghum varieties. The earliness of these varieties, defined by the seedling-to-maturity cycle, ranges between 90~100 days. Furthermore, when assessing the yield of the plant's aerial part, excluding panicles, measured in kilograms per square meter, *Touggourt* population emerged as the leading variety with a yield of 5.052 kg m^{-2}. Conversely, *Biofuel* ranked at the bottom with a significantly lower yield of 0.723 kg m^{-2}, as illustrated in Figure 2A. This variation underscores the significant impact of genetic and environmental factors on the growth cycles and productivity of different sorghum varieties.

The sap production dynamics of sorghum stems displayed notable variations between the milky-pasty stage and the hard grain stage across different populations. Notably, an increase in sap volume is observed in certain populations, such as El-Ménéa, where sap production escalated from 4.75 mL to 10 mL per 100 g of stem. Similarly, the *Hamra* population witnesses a significant rise from 1.22 mL to 12.58 ml per 100 g of stem. The *Dorado9* variety shows a marginal increase from 13.33 mL to 13.43 mL per 100 g of stem. Conversely, other populations exhibit a decrease in sap volume at the hard grain stage, as detailed in Figure 3A. Additionally, at this stage, certain populations (*El-Ménéa, Hamra, B_In-Salah*) produced sap containing red pigments, indicating varietal differences in sap characteristics.

The bark-to-pith ratio (B/P) also undergoes changes from the milky-pasty stage to the hard grain stage across various populations. This ratio diminished in several populations, including *Masser17, Beïda-Adrar, Biofuel, Touggourt, B_In-Salah*, and *El-Ménéa*, highlighting a shift in the structural composition of the stem. Conversely, an increase in the B/P ratio was noted in the *Kharssi* and *Ezra* populations, whereas it remained constant in *Dorado9* and *Hamra*. These observations, depicted in Figure 2B, underlined the complexity of growth stage effects on the physiological and structural attributes of sorghum stems, influencing both sap production and stem composition.

The variation in sugar concentration from the milky-pasty stage to the hard grain stage across different sorghum populations presents intriguing insights, particularly noting an exception in the *Hamra* population where a decrease from 16% to 11.5% was observed. This reduction is attributed to an increase in sap volume, as illustrated in Figure 3B, underscoring the dynamic interplay between sap volume and sugar concentration during sorghum maturation.

In terms of comparison of yields per exploited surface area, at the pasty-milky-stage, we noted that the *Beïda-Adrar* population had generated a sap volume (112.23 mL m^{-2}) comparable to that of the "*Biofuel*" variety (112.65 mL m^{-2}). *Kharssi* and *Touggourt* populations generated a sap yield (77.42 and 79.25 mL m^{-2}, respectively) very close if not identical to that of the *Dorado9* variety [79.25 mL m^{-2}, (Figure 3A)]. Furthermore, in terms of sugar yield, *Biofuel* stands out as the best performing variety at this stage with a yield of 12.95 g m^{-2}, followed by the *Beïda-Adrar* population, which recorded a yield of 10.10 g m^{-2}. In third place is the *Dorado9* variety with a yield of 8.71 g m^{-2}. The *Touggourt* population displayed a yield (6.34 g m^{-2}) comparable to that of Ezra with 6.14 g m^{-2} (Figure 4). The sugar content of the extracted sap is as important because based on it; it is possible to determine the total amount of bioethanol that could be provided by the culture. Nenciu et al., (2022) calculated the potential for bioethanol production for two cultures considering an average sugar content in the sap of 110 g L^{-1} and a theoretical yield of ethanol from sweet sorghum sap sugars of 0.51 g ethanol per g sugar, with an expected conversion ratio of 90%. They evaluated bioethanol potential obtained exclusively by fermentation of the sap to be 0.45 t ha^{-1} for crops established on marginal soils and 0.61 t ha^{-1} for those established on regular soils.

At the hard-grain stage, it was noted that the *Hamra* and *Touggourt* populations recorded the highest sap production value with 182.48 and 174.83 mL m^{-2}, respectively (Figure 3A). Indeed, the highest sugar production is categorized first by the *Touggourt* and *Hamra* populations with 21.64 and 20.98 g m^{-2}, respectively.

In second place is the *Bieda-Adrar* population with 14.07 g m^{-2}, and in third place is the *El-Ménéa* population with 12.37 g m^{-2} (Figure 4).

Historical data support the notion that as sorghum approaches maturity, both its weight and sugar content typically increase, with juice composition across various varieties ranging between 10.21% and 17.15%. The endeavors of Failyer and Willard in 1884 at the Kansas Agricultural Station serve as a testament to the potential for enhancing sugar content through selective breeding, successfully increasing the sugar concentration in a common sorghum variety from 11.62% to 16.10% over a decade. Similarly, Penny and Neal's work at the Delaware Farm Station between 1889 and 1897 yielded a variety with a sugar content of 19.15% (Miège, 1940). These historical achievements highlight the significant impact of targeted breeding efforts on improving the sugar content in sorghum, further emphasized by the noted effect of castration on both dry matter content and sugar concentration.

This evolving understanding of sorghum's biochemical properties underscores the crop's potential for varied applications, including bioethanol production and as a sweetener source, dependent on the optimization of sugar content through both agronomic practices and genetic improvement (Dalla Marta et al., 2014).

The variance analysis, as detailed in Table 5, reveals a highly significant variation across most of the parameters under examination, with the exception of the bark-to-pith ratio (in green), which averages 1.05 across the ten populations studied. This ratio, however, increases to 2.24 after the steaming process, indicating a notable change in the structural composition of the stem post-treatment. A critical observation from the analysis is the average moisture percentage remaining in the pith after sap extraction, which stands at 71.87%. This high percentage suggests that a considerable amount of sap was left within the pith post-extraction, pointing towards inefficiencies in the current extraction methodology that necessitates further refinement for optimal sap yield. Furthermore, the descriptive analysis concerning the percentage of sugar yield and the corresponding sap volume reveals a positive skewness, indicating a peak distribution. This means that a majority of the values cluster around the mean 5.66 g m^{-2} for sugar and 64.61 mL m^{-2} for sap volume, suggesting a relatively uniform distribution of sugar concentrations and sap volumes across the populations studied, albeit with room for optimization in sap extraction techniques to enhance yield and efficiency.

This analysis underscores the need for improved methodologies in sap extraction to minimize waste and maximize the potential uses of sorghum sap, particularly in applications requiring high sugar content. Further research and development in this area could lead to more efficient agricultural practices and better utilization of sorghum as a valuable crop.

The Pearson (n) correlation matrix detailed in Table 6, presents interesting insights into the relationships between various parameters related to sorghum crop performance. Key observations from the matrix include:

There is a significant correlation between the stems yield and the sap and sugar yields. Indeed, in sweet sorghums, sugar accumulates within the stems; the higher the yield of stems is the greater is the sweetie sap yield. We also observe a significantly positive correlation between stem diameter and stem yield as well as between stem diameter and sap and sugar yields. Indeed, the stem is made up of a bark that surrounds the pith containing the sweet sap, the larger the stem diameter, the larger the portion of the pith sozzled with sweet sap. Prior research identified a positive correlation between height, which directly influences stem yield, and sugar accumulation.

Table 5. Analysis of the variance of the studied parameters

Settings	Average	Standard deviation	Variance	DF	Chi-square	p	95%inf	95%Sup
Cycle (days)	95.96	21.29	453.39	25	11334.96	<0.0001	301.042	775.76
Stem yield (g m^{-2})	1918.46	1534.09	2353444.98	26	61189569.62	<0.0001	1573597.81	3978733.76
B/P in green	1.17	0.520	0.269	26	6.980	0.001	0.180	0.454
B/P in Dry	2.243	0.98	0.966	26	25.125	0.9761	0.646	1.634
Volume of sap (mL m^{-2})	64.61	36.972	1359.569	24	12236.123	<0.001	723.219	3679.912
Sugar yield (g m^{-2})	5.66	4.03	16.25	22	146.28	<0.0001	0.370	12.96

DF: Degree of freedom

Table 6. Correlation matrix Pearson (n) of studied parameters at Milky-Pasty stage

Variables	Cycle (Days)	Height (cm)	Diameter (mm)	Stem yield (g m^{-2})	B/P (in green)	B/P (in dry)	Sap yield (mL m^{-2})	Sugar yield (g m^{-2})
Cycle (Days)	1.0							
Height (cm)	-0.1168	1.0						
Diameter (mm)	-0.4402	0.0327	1.0					
Stem yield (g m^{-2})	-0.4023	-0.1447	**0.8015**	1.0				
B/P (in green)	-0.0814	0.3556	0.1806	0.2145	1.0			
B/P (in dry)	-0.3852	0.5977	0.3532	0.1949	**0.8585**	1.0		
Sap yield (mL m^{-2})	**-0.6493**	-0.2140	**0.7253**	**0.7364**	-0.3357	-0.1274	1.0	
Sugar yield (g m^{-2})	-0.5613	-0.5067	**0.6529**	**0.7329**	-0.1749	-0.0818	**0.8756**	1.0

Values in bold are different from 0 at a significance level alpha=0.05

However, Shukla et al. (2017) concluded from their experiments that high sugar concentration in sweet sorghum is not conditional on the plants being tall. Moreover, it have been observed a negative correlation between the duration of growth cycle and the yield of sap and sugar. Which means that high-yielding varieties are those with a short growth-cycle.

Thus, varieties with longer growth cycles tend to have a lower ratio of dry bark to pith, indicating these varieties may be richer in pith content, which could be beneficial for certain uses such as forage or biofuel production (Nenciu et al., 2022).

These correlations shed light on the complex interplay between structural characteristics of the sorghum plant and its productivity, sugar content, and growth cycle. Understanding these relationships is crucial for breeding and cultivation strategies aimed at optimizing yield, sugar content, and overall plant utility, especially in contexts like biofuel production or nutritional value in forage crops. Further research and targeted breeding programs could leverage these insights to develop sorghum varieties that balance these traits according to specific agricultural and industrial needs.

The Principal Component Analysis (PCA) of sorghum populations at both the milky-pasty and hard grain stages (Figure 5) offers a deep dive into the intricate dynamics that define the growth, structure, and productivity of these crops. By capturing 77.86% of the variability in the early stage and 78.86% at maturity, the PCA underscores the dominant factors and relationships among various sorghum characteristics, paving the way for a nuanced understanding of their development. At the milky-pasty stage, the PCA reveals significant insights with the first two components encompassing a considerable chunk of the dataset's complexity.

It groups together *Biofuel, Beïda Adrar,* and *Dorado9*, highlighting their robust growth and promising productivity potential based on stem diameter, yield, sap quantity, and sugar content. Meanwhile, *El-Ménéa* population, emerge with unique structural compositions, as indicated by its height and B/P ratio in both green and dry states. The *Hamra* population was distinguished by its longer growth cycle and poorer sap and sugar yields, suggesting specific genetic traits or adaptations that set it apart. Transitioning to the hard grain stage, the analysis shifts, reflecting the dynamic changes as the sorghum matures. The grouping of *El-Ménéa, Kharssi*, and *Ezra,* around structural ratios points to their advantageous qualities for structural integrity.

B_In-Salah distinctive growth cycle highlights its unique position, potentially affecting its cultivation strategy and utility. *Touggourt, Hamra,* and *Beïda-Adrar* stand out for their high sugar content, marking them as prime candidates for sugar production; Furthermore*, this grouping with B_In-Salah* population are noted for their high stem yields, indicating their suitability for biomass production.

Thus, sweet sorghum is exploited not only for bioethanol production through alcoholic fermentation but also for the recovery of vegetable waste, which can be used in the pyrolysis process to generate valuable chemical components (bio-oil) and serve as a soil amendment (biochar), yielding both economic and environmental benefits (Nenciu et al., 2020).

Conclusion

Throughout this research, we embarked on a comprehensive exploration of sorghum populations (*Sorghum bicolor* L.) within Algerian oases and introduced ACSAD varieties, yielding fascinating insights over two consecutive experimental trials. Our findings lighten up the dynamic nature of sorghum cultivation, revealing significant variances in growth cycles, stem heights, and productivity, which are influenced by a complex interplay of environmental factors such as climate, soil quality, and agricultural practices.

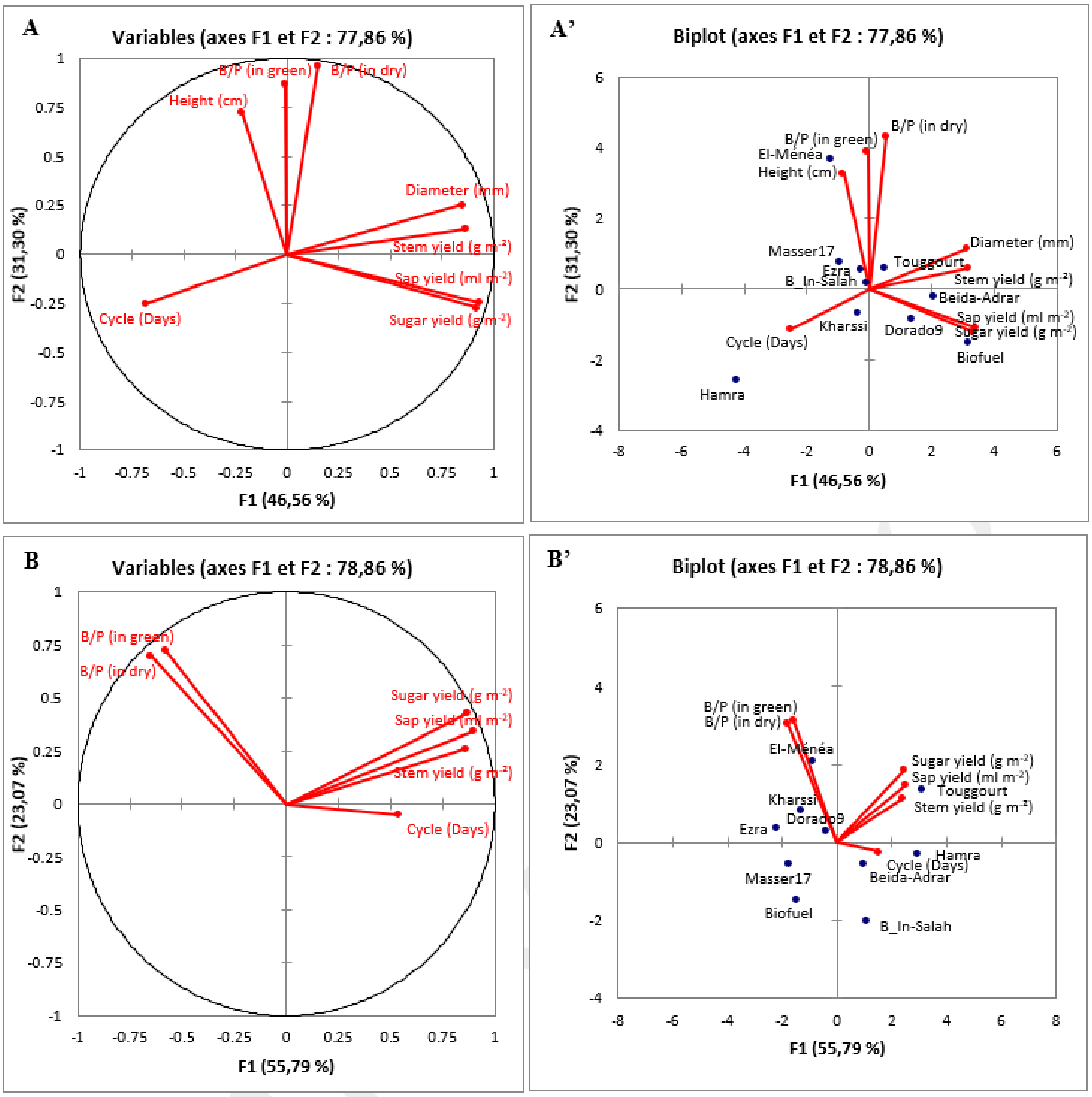

Figure 5. Analysis of the principal components at the milky-pasty (A, A') and at the hard grain stages (B, B').

We observed a notable shortening of the growth cycle in specific populations, with *Hamra* and *Beïda* showing remarkable reductions. This was accompanied by a decrease in stem heights, indicating a possible trend towards more compact, but potentially less productive, sorghum varieties under the prevailing conditions. The study further delved into the structural aspects of sorghum, highlighting the variability in stem diameters and the consequential impact on the bark-to-pith ratio. This ratio is a critical factor in assessing the structural composition and potential utility of the sorghum stem, with certain populations showcasing a higher pith content, indicative of a juicy or fleshy interior, which is desirable for certain applications. At the milky-pasty stage of development, we categorized the populations into three distinct groups based on average stem heights, which showcased a diverse range of growth habits from tall to short statures. Interestingly, the yield potential varied significantly across different stages of maturity and among the various populations, with some varieties like *Biofuel* showing exceptional productivity at the milky-pasty stage. Our investigation into the sap and sugar content revealed intriguing patterns of increase and decrease across different populations and stages of maturity, underscoring the intricate balance between sap volume and sugar concentration in determining the sweetness and utility of the sorghum crop. Through advanced statistical analyses, including variance analysis and Principal Component Analysis (PCA), we unraveled the complex relationships between various parameters such as stem yield, sugar content, and physiological growth cycles. These analyses highlighted the significant differences and correlations among the studied variables, offering a deep dive into the genetic and environmental factors shaping sorghum cultivation.

In conclusion, our study sheds light on the adaptive strategies and genetic potential of sorghum populations in Algerian oases, revealing the critical influence of environmental conditions and cultivation practices on their growth dynamics and productivity. The findings underscored the need for continued research and improvement in cultivation techniques to optimize the yield and quality of sorghum, a vital crop with wide-ranging applications in agriculture and industry.

Declarations

Ethical Approval Certificate

This article does not contain any studies with human or animal subjects.

Author Contribution Statement

F.A.: Conceptualization, data curation, formal analysis, investigation, methodology, resources, writing - original draft.

H.B.: Investigation, methodology, supervision, validation, writing - review & editing.

A.M.: Formal analysis, investigation, visualization, writing - review & editing.

Fund Statement

No particular funding to disclose.

Conflict of Interest

"The authors declare no conflict of interest."

Acknowledgments

The authors would like to conclude this article by paying a special tribute to their late colleague and friend, Rahale-Bouziane Hafida, in recognition of her contribution and in memory of her precious support.

References

Atlin, G. N., Cairns, J. E., & Das, B. (2017). Rapid breeding and varietal replacement are critical to adaptation of cropping systems in the developing world to climate change. Global food Security, 12, 31-37. https://doi.org/10.1016/j.gfs.2017.01.008

Baameur, M., Abelguerfi, A., Daddi Bouhoun, M., Saadi, H., & Ould El Hadj, M. (2015). Distribution study of some species of spontaneous Flora in two Saharan Regions of the North-East of Algeria (Ouargla and Ghardaa). International Journal of Biodiversity and Conservation, 7 (1), 41-49. Doi : 10.5897/IJBC2014.0725

Çakmakçı, R., Salık, M. A., & Çakmakçı, S. (2023). Assessment and Principles of Environmentally Sustainable Food and Agriculture Systems. Agriculture, 13(5), 1073. https://doi.org/10.3390/agriculture13051073

Dalla Marta, A., Mancini, M., Orlando, F., Natali, F., Capecchi, L., & Orlandini, S. (2014). Sweet sorghum for bioethanol production: Crop responses to different water stress levels. Biomass and Bioenergy, 64, 211-219. https://doi.org/10.1016/j.biombioe.2014.03.033

Dalton, T. J., & Hodjo, M. (2020). Trends in global production, consumption, and utilization of Sorghum. Sorghum in the 21st Century: Food–Fodder–Feed–Fuel for a Rapidly Changing World, 3-15. https://doi.org/10.1007/978-981-15-8249-3_1

Deribe, Y., & Kassa, E. (2020). Value creation and sorghum-based products: what synergetic actions are needed? Cogent Food & Agriculture, 6(1), 1722352. https://doi.org/10.1080/23311932.2020.1722352

FAO, 2016. La culture du sorgho de décrue en Afrique de l´Ouest et du Centre: Situation actuelle et définition d´un plan d´action régional. Edited by Jordi Comas and Helena Gómez Mac Pherson, Published by the Spanish agency for international cooperation with the collaboration of FAO .243p ftp://ftp.fao.org/TC/TCA/ESP/pdf/sorgho.pdf

Fritsche, U.R., Sims, R.E.H., & Monti, A. (2010). Direct and indirect land-use competition issues for energy crops and their sustainable production–an overview. Biofuels, Bioproducts and Biorefining, 4(6), 692-704. https://doi.org/10.1002/bbb.258

Hariprasanna, K., & Rakshit, S. (2016). Economic importance of sorghum. In: Rakshit, S., Wang, YH. (eds). The sorghum genome, Compendium of Plant Genomes (pp.1-25). Springer, Cham. https://doi.org/10.1007/978-3-319-47789-3_1

Miège, É. (1940). L'utilisation du Maïs et du Sorgho sucrés comme plantes saccharifères et alcooligènes. Journal d'agriculture traditionnelle et de botanique appliquée, 20 (226), 419-435. https://www.persee.fr/doc/jatba_0370-3681_1940_num_20_226_1552

Nenciu, F., Paraschiv, M., Kuncser, R., Stan, C., Cocarta, D., & Vladut, V. N. (2022). High-grade chemicals and biofuels produced from marginal lands using an integrated approach of alcoholic fermentation and pyrolysis of sweet sorghum biomass residues. Sustainability, 14(1), 402. https://doi.org/10.3390/su14010402

Ouedraogo, I., Runge, J., Eisenberg, J., Barron, J., & Sawadogo-Kaboré, S. (2014). The re-greening of the Sahel: natural cyclicity or human-induced change?. Land, 3(3), 1075-1090. https://doi.org/10.3390/land3031075

Popescu, A., & Condei, R. (2014). Some considerations on the prospects of Sorghum crop. Scientific papers series management, economic engineering in agriculture and rural development, 14(3), 295-304. https://managementjournal.usamv.ro/pdf/vol_14/art43.pdf

Reddy B.V.S., Rao P., Deb U.K., Stenhouse J.W., Ramaiah B. & Ortiz R. (2004). Global sorghum genetic enhancement processes at ICRISAT. Pages 65-102 in Sorghum genetic enhancement: research process, dissemination and impacts (Bantilan M.C.S., Deb U.K., Gowda C.L.L., Reddy B.V.S., Obilana A.B. and Evenson R.E., eds.). Patancheru 502 324, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics. https://core.ac.uk/download/211012972.pdf

Shukla S., Felderhoff T.J., Saballos A., & Vermerris W. (2017). The relationship between plant height and sugar accumulation in the stems of sweet sorghum (Sorghum bicolor (L.) Moench). Field Crops Research, 203, 181-191. https://doi.org/10.1016/j.fcr.2016.12.004

Swarup S., Cargill E.J., Crosby K., Flagel L., Kniskern J., & Glenn K.C. (2021). Genetic diversity is indispensable for plant breeding to improve crops. Crop Science, 61(2), 839–852. https://doi.org/10.1002/csc2.20377

Zegada-Lizarazu, W., & Monti, A. (2011). Energy crops in rotation. A review. Biomass and bioenergy, 35(1), 12-25. https://doi.org/10.1016/j.biombioe.2010.08.001

Zhang L.-M., Leng C.-Y., Luo H., Wu X.-Y., Liu Z.-Q., Zhang Y.-M., Zhang H., Xia Y., Shang L., Liu C.-M., Hao D.-Y., Zhou Y.-H., Chu C.-C., Cai H.-W., & Jing H.-C. (2018). Sweet sorghum originated through selection of dry, a plant-specific NAC transcription factor gene. The Plant Cell, 30(10), 2286–2307, https://doi.org/10.1105/tpc.18.00313