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# The Potential of Ethanol Production from Sweet Sorghum in Sub-Saharan Africa as Affected by Variety and Sowing Time

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***Authors' contributions***

*This work was carried out in collaboration between both authors. Author MIM provided the plant materials, designed the study, performed the statistical analysis, wrote the protocol and the first draft of the manuscript. Author SIA conducted the field trials and laboratory analysis, collected the data, managed the analyses and literature searches. Both authors read and approved the final manuscript.*

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## ABSTRACT

Renewable bio-energy is receiving worldwide importance in view of depleting fossil energy. Research works on sorghum as bio-fuel crop in sub-Saharan Africa are meager. The study aimed to investigate the potential of sweet sorghum for ethanol production from stem-juice. The experiment was conducted in Sudan, Khartoum State, during 2016-2017. Forty local and exotic sweet sorghum varieties arranged in RCB Design were investigated under irrigated conditions across three sowing times. Yields of cane, juice, sugar, ethanol and related attributes were studied. Highly significant differences (P=.01) were detected among varieties and interaction with sowing time. Ethanol yield potentials for some varieties were comparable to those reported in India and USA (1162-1416 L ha-1). High brix values (20-22%) and cane yields (45-51 ha-1) were encountered. Juice yield was low (3673-13743 L ha-1) probably due to reduced milling efficiency. The exotic materials performed better than the local ones in theoretical ethanol productivity and related attributes other than cane yield. Eight exotic and five local varieties were recommended for ethanol production. None of the Ankolib materials appeared to have notable potential for ethanol

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production. Interaction of sowing time with variety has great impact on ethanol yield implying the importance of variety option for different sowing times. It was concluded that the study furnished basic data needed for assessing the economic feasibility of ethanol production from irrigated sweet sorghum in sub-Saharan Africa-Sudan.

*Keywords: Brix; stem-juice; cane yield; bagasse; Ankolib; Sudan.*

## 1. INTRODUCTION

Sorghum is the fifth most important cereal crop worldwide [1] and the Africa's second important crop in terms of tonnage [2]. It is the stable diet for the food-insecure people in the sub-Saharan Africa. In Sudan, sorghum leads other crops in both acreage and produce, occupying 50% of the total area cultivated and 75 % of the total cereals produced. Being a C4 species with greater photosynthetic efficiency employed to support multipurpose economic utility, sorghum offers great potential for a number of uses mainly food, feed, syrup and bio-ethanol production [3] with the latter two application merited by sweet sorghum which accumulates large quantities of sweet juice in the stem.

Invoked by the oil crisis of 1973 -76, bio-ethanol from sweet sorghum had been explored with worldwide interest as renewable resources [1]. The most prominent research efforts on this regard were done in India since early 1970s by the Nimbkar Agricultural Research Institute (NARI) [4]. Other efforts were initiated in China since 1974 [5] and Europe in mid 1980s [6] where sweet sorghum have become an attractive choice for biomass energy. Research works conducted worldwide during the last two decades indicated that sweet sorghum for bioethanol production offers good prospects as an additional feed stock for existing distillers [7]. Compared to other energy crops, sorghum is less input-demanding with very short production cycle. It also lends itself to concurrent production of food, feed or both along with bioenergy feedstock, supporting competitiveness of ethanol production from stem-juice feedstock [7-9]. Moreover, sweet sorghum juice is best suited for ethanol production owing to its higher total reducing sugar content relative to sugar cane juice [10]. The sugar content in the juice extracted from sweet sorghum varies from 16% to 23% brix with great potential for fuel alcohol production [11].

Being a possible center of origin and diversification [12] Sudan endowed with a wealth of genetic variability in sorghum [13,14] enabling selection for most of the economic traits. The sorghum germplasm of Sudan is well recognized and extensively utilized in the USA and other parts of the world [15]. More than 50% of the sweet stalk sorghums in the World Collection came from Sudan [16]. In spite of that, very little research work was done on sorghum as bio-fuel feedstock. Selection among local and exotic stocks of sweet sorghum started in 2001 [17] with some materials being identified for forage production [18]. Batoul [19] evaluated eight introduced sweet sorghum genotypes for ethanol production and some related traits. Abdalbagi and Mohammed [9] studied concurrent improvement of stem-sugar, stover and grain yield in Sudanese and exotic sorghums. Our approach is not to breed sorghum as a dedicated energy crop as did workers in the United States [20] and elsewhere. The potential for grain production should at least be maintained considering the impact of the crop on food security of the Sudanese people. This might be achievable since the developing grain is not a significant sink for whole–plant carbohydrates and sugar accumulation occurs before anthesis allowing for escaping competition with grain filling [20-22].

The effect of sowing time on attributes relating to ethanol production from sweet sorghum should be investigated since the weather in sub-Saharan Africa allows for 2-3 production cycles depending on maturity duration. On the other hand, the impact of sowing time on sweet sorghum performance is well documented [23-25], hence, assessing the magnitude of interaction between sowing time and genotype is vital to optimize the variety choice. The present study is aiming at investigating the performance of local and exotic sweet sorghums varieties for ethanol production and related traits across different sowing times. The ultimate objectives were to assess the potential of ethanol production from stem-juice of sweet sorghum in sub-Saharan Africa.

## 2. MATERIALS AND METHODS

**The experimental site:** The experiment was conducted in Alwaha Project, Khartoum State

(15°21'05.0"N, 32°57'57.1"E, elevation 395 m asl). The site is well located in the Sub-Saharan Sahelian zone where the climate is typically hot, sunny, dry and windy all year-round with nearly neutral day length. The temperature during the cool season (Nov-Feb) ranges 16-36°C while that of the hot season (May-September) ranges 25-42°C. Day length ranges from 11:12 (H:M) in December to 13:01 (H:M) in June. The mean annual precipitation ranges 100- 200 mm with average of 167 mm, ninety percent of which occurs during July, August and September. The soil is sandy clay loam with alkaline pH of 9.0 (8.2-9.2), low Cation Exchange Capacity (CEC) of 18 (11.1-24.6) and inherently low organic matter (nitrogen deficient).

**The plant materials:** Forty sorghum varieties were studied (Table 1) comprising 13 exotic sweet sorghum varieties (group 1), and 27 sweet-stalk local varieties of which 12 were selected from local landraces (group 2) and 15 were developed by hybridization and selection among the local varieties (group 3). The exotic materials were obtained from USA, USDA-ARS University of Nebraska. The local varieties were developed by individual plant selection among the local land races of Ankolib, Abu Sabin, Abjaro and Garawi. Ankolib (Ank) is the general term used for sweet sorghums in Sudan characterized by sweet stalks just like sugarcane [26]. Abjaro (Abj) and Abu Sabin (Ab70) are traditional grain sorghums with the latter being widely used for forage production in Sudan. Garawi (SG) is the mother population of Sudangrass from which the first varieties had been developed in the USA [27].

**Sowing times:** The materials were tested across three sowing times viz., 21/June/2016, 30/Nov/2016 and 19/Feb/2017. The June and Nov sowings represent summer and winter sowings, respectively.

**Cultural practices and experimental design:** The materials were arranged in RCB design with 3 replicates in each sowing time. Seeds were sown in rows 60 cm apart at seeding rate of 20 kg ha$^{-1}$ using a seed-drill. Phosphorous (43 P2O5 kg ha$^{-1}$) and Nitrogen (55 N kg ha$^{-1}$) fertilizers were applied at sowing and 4 weeks after emergence, respectively. The trials were irrigated using pivot irrigation system. No pesticides were used to control insect pests or diseases. Weeds were kept to minimum by hand removal.

**Data collection:** The data recorded included: Days to flower, plant height, stover yield, millable cane yield, juice yield, brix (%) and bagasse yield. The yield attributes and related parameters were estimated from 10 meter-row randomly selected from each plot. Plant height and bagasse yield were studied in November and June sowings only. The cane cutting was practiced at physiological maturity of the grain with the intention of not sacrificing the grain as essential food or feed component. Stover yield was estimated after removing the panicles. The plants were cut at 5-7 cm above the ground level

**Table 1. Plant materials used in the study**

| S. No. | Group 1 | Group 2 | Group 3 |
|---|---|---|---|
| 1 | Waconia-L | ANK. S.18 | 1AbjSG51 |
| 2 | Red-x | ANK.LzmNrs | 2AbjSG51 |
| 3 | N98 | ANK. S.36 | 3AbjSG51 |
| 4 | Brawley | ANK. S.43 | 4AbjSG51 |
| 5 | KansasCollies | S.134 Ab70 | 5AbjSG51 |
| 6 | BlueRibbon | S.154 Ab70 | 6AbjS3Ab70 |
| 7 | SugarDrip | S.158 Ab70 | 7AbjS3Ab70 |
| 8 | Hastings | SG.33 | 8AbjS3Ab70 |
| 9 | N100 | SG.11 | 9AbjS3Ab70 |
| 10 | N110 | SG.12-1 | 10AbjS3Ab70 |
| 11 | N99 | SG.04 | 11AbjS3Ab70 |
| 12 | Colman | SG.34 | 12AbjS3Ab70 |
| 13 | Fremont | | 13AbjS3Ab70 |
| 14 | | | 14AbjS3Ab70 |
| 15 | | | 15AbjS3Ab70 |

and the weight of stover was immediately taken using spring balance. Millable cane yield was determined from the harvested stover after striping the leaves (blade + sheath) and removing the peduncles. The fresh cane in each plot was weighed in the field, labeled and immediately taken to the lab to determine the juice characteristics. The juice attributes were measured in the laboratory of the National Food Research Centre, Khartoum North. Juice yield was determined from the first press. The cane was washed, left to dry for a while and then passed through a two-roller hand operated sugarcane mill. The juice received was filtered. using muslin cloth. The volume of juice per plot was determined using measuring cylinder and transformed to L $ha^{-1}$. The brix value was determined from the entire volume of the extracted juice in each plot using hand refractometer. Bagasse yield was calculated by subtracting Juice yield from millabe cane yield and multiplying by 0.1. Sugar yield was worked out following Reddy et al. [7] where:

Sugar yield (t $ha^{-1}$) = ((Brix% x 0.8746) + 0.1516)/100) x Juice yield (L $ha^{-1}$). Theoretical ethanol yield (L $ha^{-1}$) was calculated following previous workers [28,29] by multiplying sugar yield by a conversion factor of 0.581.

**Statistical analysis:** The data were analyzed following the standard procedure of analyzing analysis of variance (ANOVA) for the RCB design [30]. Single ANOVA was first done for each sowing time before performing the combined analysis. Least Significant Difference (LSD) procedure was used to separate the means. The statistical package of GenStat [31] was used to run the data analysis.

## 3. RESULTS

### 3.1 Variations

Table 2 shows the mean squares of varieties, sowing times and interactions for the studied traits. Significant differences (P=.01) were detected among varieties for all traits. The variety x sowing time interaction was highly significant (P=.01) for nearly all traits indicating that the performance of varieties was not consistent across sowing time. The difference between sowing times were not significant for traits other than plant height and days to flowering.

### 3.2 Cane Yield

Table 3 indicated that the highest cane yield was shown by the exotic variety SugarDrip (45-61.2 averaging 51.0 t $ha^{-1}$). Among the local materials, the highest cane yield was shown by 3AbjSG51 (41.7-50.5 averaging 50.5 t $ha^{-1}$) and 15AbjS3Ab70 (40-50 averaging 45.0 t $ha^{-1}$). Most of the local varieties out-yielded the exotic ones in cane yield. Exotic varieties showing considerable cane yield other than SugarDrip included BlueRibbon (31.7-50 averaging 43.9 t $ha^{-1}$), N100 (30-53.3 averaging 39.4 t $ha^{-1}$) and Hastings (30-45 averaging 38.9 t $ha^{-1}$). The cane yield of the Ankolib materials was low with average yield ranging from 26.1 to 30 t $ha^{-1}$shown by ANK.LzmNrs and ANK. S.18, respectively.

**Table 2. Mean squares from combined analysis for sweet sorghum varieties grown at different sowing times**

| Source of variation | d.f. | Ethanol yield (L $ha^{-1}$) | Brix (%) | Cane yield (t $ha^{-1}$) | Juice yield (L $ha^{-1}$) | Sugar yield (t $ha^{-1}$) | Plant height (cm) | Days to flowering |
|---|---|---|---|---|---|---|---|---|
| Sowing time (SD) | 2 | 1652216 | 26.470 | 2410.7 | 157200000 | 4.8946 | 254624** | 6877** |
| Residual | 6 | 440082. | 6.028 | 1067.7 | 50460000 | 1.3037 | 2706 | 38.69 |
| Variety (G) | 39 | 574465** | 55.756** | 413.7** | 41830000** | 1.7018** | 2617** | 669.76** |
| G x SD | 77 | 158547** | 5.594** | 145.1* | 14940000** | 0.4697** | 971** | 350.40** |
| Residual | 231 | 54518. | 1.929 | 101.6 | 6248000 | 0.1615 | 322 | 11.49 |

**,** = significant at .05 and .01 probability level, respectivel*

**Table 3. Cane yield (t $ha^{-1}$) of sweet sorghum varieties grown at different sowing times**

| Sowing time Variety | June 2016 | Nov 2016 | Feb 2017 | Mean |
|---|---|---|---|---|
| SugarDrip | 45.0 | 61.2 | 46.7 | 51.0 |
| 3AbjSG51 | 41.7 | 50.0 | 60.0 | 50.5 |
| 15AbjS3Ab70 | 40.0 | * | 50.0 | 45.0 |
| 5AbjSG51 | 33.3 | 45.0 | 55.0 | 44.4 |
| BlueRibbon | 31.7 | 50.0 | 50.0 | 43.9 |
| 8AbjS3Ab70 | 40.0 | 36.7 | 51.7 | 42.8 |
| 1AbjSG51 | 30.0 | 41.7 | 55.0 | 42.2 |
| 6AbjS3Ab70 | 41.7 | 33.3 | 46.7 | 40.5 |
| N100 | 30.0 | 53.3 | 35.0 | 39.4 |
| Hastings | 41.7 | 30.0 | 45.0 | 38.9 |
| 12AbjS3Ab70 | 48.3 | 25.0 | 43.3 | 38.9 |
| 9AbjS3Ab70 | 38.3 | 30.0 | 48.3 | 38.9 |
| 10AbjS3Ab70 | 41.7 | 31.7 | 41.7 | 38.3 |
| 14AbjS3Ab70 | 41.7 | 28.3 | 45.0 | 38.3 |
| 4AbjSG51 | 26.7 | 48.3 | 40.0 | 38.3 |
| S.154 Ab70 | 30.0 | 31.7 | 51.7 | 37.8 |
| 7AbjS3Ab70 | 31.7 | 31.7 | 50.0 | 37.8 |
| 11AbjS3Ab70 | 31.7 | 40.0 | 40.0 | 37.2 |
| 2AbjSG51 | 28.3 | 40.0 | 38.3 | 35.5 |
| N99 | 33.3 | 25.0 | 43.3 | 33.9 |
| Brawley | 23.3 | 36.7 | 40.0 | 33.3 |
| KansasCollies | 28.3 | 28.3 | 43.3 | 33.3 |
| 13AbjS3Ab70 | 33.3 | 30.0 | 31.7 | 31.7 |
| Waconia-L | 30.0 | 26.7 | 36.7 | 31.1 |
| N110 | 25.0 | 23.3 | 43.3 | 30.5 |
| N98 | 31.7 | 26.7 | 33.3 | 30.5 |
| SG.12-1 | 30.0 | 28.3 | 33.3 | 30.5 |
| ANK. S.18 | 38.3 | 16.7 | 35.0 | 30.0 |
| Red-x | 25.0 | 30.0 | 33.3 | 29.4 |
| S.158 Ab70 | 25.0 | 21.7 | 41.7 | 29.4 |
| SG.33 | 30.0 | 26.7 | 31.7 | 29.4 |
| ANK. S.36 | 35.0 | 26.7 | 25.0 | 28.9 |
| Colman | 28.3 | 26.7 | 31.7 | 28.9 |
| S.134 Ab70 | 33.3 | 18.3 | 33.3 | 28.3 |
| Fremont | 25.0 | 23.3 | 40.0 | 28.1 |
| ANK. S.43 | 33.3 | 23.3 | 25.0 | 27.2 |
| SG.04 | 28.3 | 21.7 | 30.0 | 26.7 |
| ANK.LzmNrs | 31.7 | 20.0 | 26.7 | 26.1 |
| SG.11 | 28.3 | 21.7 | 26.7 | 25.6 |
| SG.34 | 26.7 | 20.0 | 23.3 | 23.3 |
| Mean | 32.9 | 31.5 | 40.0 | 34.8 |
| SE± | 5.56 | 5.47 | 6.39 | 3.36 |
| LSD (0.05) | 15.65 | 15.41 | 17.98 | 9.36 |
| CV(%) | 29.3 | 30.1 | 27.6 | 28.9 |

**Table 4. Juice yield (L $ha^{-1}$) of sweet sorghum varieties grown at different sowing times**

| Sowing time Variety | June 2016 | Nov 2016 | Feb 2017 | Mean |
|---|---|---|---|---|
| SugarDrip | 10729 | 20504 | 9994 | 13743 |
| BlueRibbon | 6717 | 13523 | 11825 | 10689 |
| N100 | 7977 | 15084 | 7298 | 10119 |
| 15AbjS3Ab70 | 8537 | * | 11300 | 9919 |
| 8AbjS3Ab70 | 8210 | 8317 | 12163 | 9564 |
| 5AbjSG51 | 6484 | 7323 | 13367 | 9058 |
| 1AbjSG51 | 6251 | 7734 | 12749 | 8911 |
| Hastings | 9050 | 6100 | 10389 | 8513 |
| S.154 Ab70 | 5271 | 6444 | 12768 | 8161 |
| 3AbjSG51 | 6461 | 9146 | 8637 | 8081 |
| N110 | 7510 | 4741 | 10955 | 7736 |
| 11AbjS3Ab70 | 6577 | 7293 | 8758 | 7543 |
| 9AbjS3Ab70 | 5831 | 6300 | 10260 | 7464 |
| 14AbjS3Ab70 | 6997 | 5581 | 9731 | 7436 |
| Waconia-L | 6484 | 7005 | 8751 | 7413 |
| Red-x | 6577 | 7528 | 7650 | 7252 |
| 6AbjS3Ab70 | 7090 | 5735 | 8907 | 7244 |
| KansasCollies | 6484 | 5226 | 9868 | 7193 |
| Brawley | 4711 | 8095 | 8742 | 7183 |
| 4AbjSG51 | 5691 | 8494 | 6871 | 7019 |
| 13AbjS3Ab70 | 6857 | 5948 | 8021 | 6942 |
| 7AbjS3Ab70 | 6204 | 5805 | 8574 | 6861 |
| 12AbjS3Ab70 | 6624 | 4983 | 8303 | 6637 |
| 10AbjS3Ab70 | 6951 | 5003 | 7891 | 6615 |
| 2AbjSG51 | 5598 | 6232 | 7939 | 6590 |
| N99 | 6857 | 3472 | 9087 | 6472 |
| S.158 Ab70 | 5458 | 3217 | 10717 | 6464 |
| Colman | 6811 | 4816 | 6776 | 6134 |
| ANK. S.18 | 8070 | 1958 | 7800 | 5942 |
| SG.12-1 | 5924 | 4127 | 7480 | 5844 |
| Fremont | 4105 | 3791 | 10776 | 5655 |
| ANK. S.36 | 7090 | 6150 | 3429 | 5556 |
| N98 | 4945 | 4956 | 5612 | 5171 |
| SG.33 | 5784 | 3989 | 4744 | 4839 |
| ANK.LzmNrs | 7137 | 2158 | 3769 | 4355 |
| S.134 Ab70 | 5784 | 2136 | 4933 | 4284 |
| SG.11 | 5318 | 2029 | 4320 | 3889 |
| ANK. S.43 | 4851 | 2221 | 3946 | 3673 |
| SG.34 | 3592 | 2273 | 2745 | 2870 |
| SG.04 | 3592 | 2018 | 2594 | 2734 |
| Mean | 6430 | 6089 | 8240 | 6923 |
| SE± | 1056.3 | 1387.2 | 1793.9 | 833.2 |
| LSD (0.05) | 2974.0 | 3907.2 | 5051.7 | 2321.5 |
| CV(%) | 28.5 | 39.5 | 37.6 | 36.0 |

**Table 5. Brix reading (%) of sweet sorghum varieties grown at different sowing times**

| Sowing time Variety | June 2016 | Nov 2016 | Feb 2017 | Mean |
|---|---|---|---|---|
| BlueRibbon | 21.7 | 22.7 | 22.7 | 22.3 |
| N100 | 22.7 | 22.7 | 21.7 | 22.3 |
| KansasCollies | 23.7 | 19.7 | 23.3 | 22.2 |
| Brawley | 23.0 | 22.0 | 21.0 | 22.0 |
| Waconia-L | 21.7 | 21.0 | 22.7 | 21.8 |
| N110 | 19.0 | 21.3 | 22.3 | 20.9 |
| Hastings | 19.7 | 21.3 | 20.7 | 20.6 |
| SugarDrip | 21.3 | 19.7 | 20.0 | 20.3 |
| Red-x | 18.3 | 19.7 | 21.7 | 19.9 |
| Colman | 19.3 | 20.7 | 19.3 | 19.8 |
| 14AbjS3Ab70 | 19.7 | 19.3 | 20.3 | 19.8 |
| Fremont | 18.7 | 19.3 | 18.3 | 18.8 |
| 11AbjS3Ab70 | 17.3 | 19.3 | 19.3 | 18.7 |
| N99 | 19.0 | 16.3 | 20.0 | 18.4 |
| 13AbjS3Ab70 | 17.0 | 18.0 | 20.0 | 18.3 |
| ANK. S.18 | 20.0 | 15.7 | 19.0 | 18.2 |
| N98 | 20.0 | 15.7 | 19.0 | 18.2 |
| ANK. S.36 | 19.0 | 18.7 | 16.3 | 18.0 |
| 10AbjS3Ab70 | 17.0 | 16.3 | 20.3 | 17.9 |
| 15AbjS3Ab70 | 17.3 | * | 17.7 | 17.5 |
| SG.33 | 17.3 | 17.0 | 16.7 | 17.0 |
| 2AbjSG51 | 18.3 | 16.0 | 15.7 | 16.7 |
| 9AbjS3Ab70 | 14.7 | 17.0 | 18.3 | 16.7 |
| 3AbjSG51 | 18.0 | 15.0 | 16.3 | 16.4 |
| ANK.LzmNrs | 18.0 | 15.0 | 16.0 | 16.3 |
| 7AbjS3Ab70 | 17.3 | 16.7 | 15.0 | 16.3 |
| 4AbjSG51 | 18.0 | 15.3 | 15.3 | 16.2 |
| 8AbjS3Ab70 | 15.7 | 14.7 | 17.7 | 16.0 |
| 5AbjSG51 | 16.7 | 15.0 | 16.0 | 15.9 |
| SG.04 | 16.3 | 14.7 | 16.0 | 15.7 |
| 1AbjSG51 | 15.3 | 15.7 | 15.7 | 15.6 |
| S.154 Ab70 | 15.0 | 13.7 | 17.7 | 15.4 |
| SG.12-1 | 14.0 | 15.7 | 16.7 | 15.4 |
| S.158 Ab70 | 13.7 | 14.0 | 18.3 | 15.3 |
| ANK. S.43 | 13.0 | 16.0 | 16.3 | 15.1 |
| SG.11 | 16.3 | 13.3 | 15.7 | 15.1 |
| 12AbjS3Ab70 | 15.0 | 16.0 | 14.3 | 15.1 |
| 6AbjS3Ab70 | 15.0 | 14.3 | 13.7 | 14.3 |
| SG.34 | 13.0 | 15.0 | 14.3 | 14.1 |
| S.134 Ab70 | 13.0 | 13.0 | 15.3 | 13.8 |
| Mean | 17.7 | 17.2 | 18.2 | 17.7 |
| SE± | 0.858 | 0.773 | 0.771 | 0.4629 |
| LSD (0.05) | 2.415 | 2.178 | 2.169 | 1.2898 |
| CV(%) | 8.4 | 7.8 | 7.3 | 7.8 |

### 3.3 Juice Yield

Table 4 shows that the highest juice yield was shown by exotic varieties: SugarDrip (9994-20504 averaging 13743L ha$^{-1}$), BlueRibbon (6717-13523 averaging 10689 L ha$^{-1}$) and N100 (7298-15084 averaging 10119 L ha$^{-1}$). The exotic materials were generally juicier than the local ones. Among the local materials, considerable averages of juice yields (8161 to 9919 L ha$^{-1}$) were shown by: 15AbjS3Ab70, 8AbjS3Ab70, 5AbjSG51, 1AbjSG5 and S.154 Ab70. Their juice yield in Feb sowing exceeded that of the exotic ones ranging from 11300 to 13367 L ha$^{-1}$. The average juice yields of the Ankolib materials were low ranging from 3673 to 5942 L ha$^{-1}$.

## 3.4 Brix

Table 5 indicated that many of the exotic varieties averaged brix values above 20%. Of these: BlueRibbon, N100, KansasCollies Brawley and Wacconia L; averaged the highest brix value (around 22%). SugarDrip showed brix value of 20.3%. The lowest brix reading among the exotic materials (18.2%) was shown by N98. For the local materials, the top brix readings ranged from 18% to 20% shown by 14AbjS3Ab70, 11AbjS3Ab70, 13AbjS3Ab70, ANK. S.18, ANK. S.36 and 10AbjS3Ab70. The lowest brix among the local materials was shown by S.134 Ab70 (13.8%).

## 3.5 Sugar Yield

Table 6 shows that the best sugar yield was shown by the exotic varieties SugarDrip (1.76 - 3.55 averaging 2.44 t ha$^{-1}$), BlueRibbon (1.29 - 2.70 averaging 2.11 t ha$^{-1}$) and N100 (1.39 - 3.02 averaging 2.00 t ha$^{-1}$). The best performing local materials in sugar yields were 15AbjS3Ab70 (1.32-1.78 averaging 1.55 t ha$^{-1}$) and 8AbjS3Ab70 (1.12-1.91 averaging 1.39 t ha$^{-1}$). The local variety S.154Ab70 gave 2.0 t ha$^{-1}$ in Feb sowing but showed low yield of less than 1.0 t ha$^{-1}$ in other sowing times. Among Ankolib materials, ANK. S.18 was the best, showing sugar yield of 1.0 t ha$^{-1}$.

## 3.6 Ethanol Yield

Table 7 indicated that the best overall-average ethanol yield in the whole materials tested was shown by the exotic varieties SugarDrip (1416 L ha$^{-1}$), BlueRibbon (1226 L ha$^{-1}$) and N100 (1162 L ha$^{-1}$). The ethanol yield of SugarDrip in Nov, June and Feb sowings were 2065, 1159 and 1025 L ha$^{-1}$, respectively. The ethanol yield of N100 in Nov sowing was 1752 L ha$^{-1}$ whereas that of BlueRibbon was 1566 L ha$^{-1}$. Other exotic varieties with good average performance included Hastings, N110, Waconia-L, KansasCollies and Brawley; their ethanol yield in Feb sowing ranged from 1016 to 1253 L ha$^{-1}$ with overall average ranging 804-897 L ha$^{-1}$.

Among the local materials, the best average performance in ethanol yield was shown by: 15AbjS3Ab70 (901 L ha$^{-1}$), 8AbjS3Ab70 (805 L ha$^{-1}$), 14AbjS3Ab70 (756 L ha$^{-1}$), 5AbjSG51 (734 L ha$^{-1}$) and S.154 Ab70 (675 L ha$^{-1}$); their ethanol yield in Feb sowing ranged from 1016 to 1163 L ha$^{-1}$. With regard to the Ankolib materials, ANK. S.18 was the best in average performance (583 L ha$^{-1}$) with 820 and 770 L ha$^{-1}$ ethanol yield in June and Feb sowings, respectively.

## 3.7 Bagasse Yield

Table 8 indicated that bagasse yield of SugarDrip (44.4 t ha$^{-1}$) was significantly the highest in Nov sowing followed by BlueRibbon (28.1 t ha$^{-1}$) and N100 (27.5 t ha$^{-1}$). In Feb sowing, the highest bagasse yields were shown by: 3AbjSG51 (29.1 t ha$^{-1}$), BlueRibbon (28.8 t ha$^{-1}$), 15AbjS3Ab70 (27.5 t ha$^{-1}$), SugarDrip (27.5 t ha$^{-1}$) and S.154 Ab70 (27.2 t ha$^{-1}$). Bagasse yields of lower than 15 t ha$^{-1}$ were encountered in both sowings specially by Ankolib materials.

## 3.8 Days to Flowering

Table 9 shows that apart from Fremont that averaged 62 days to flower, most of the local materials flowered earlier (66-83 days) than the exotic ones (72-158 days). SugarDrip and N100 in Nov sowing took more than 150 days to flower while taking less than 70 days to flower in June sowing. Similar trend was also observed in some exotic (Colman and Red-x) and local (4AbjSG51) materials.

## 3.9 Plant Height

Table 10 shows that all varieties were significantly taller in Feb than Nov sowing, averaging 229 and 164 cm, respectively. SugarDrip was significantly the tallest (214 cm) in Nov sowing and was also among the tallest in Feb sowing (240 cm). BlueRibbon was the tallest (251 cm) among the exotic varieties in Feb sowing. Most of the local materials were taller than the exotic ones with plant height ranging from 200 cm to 278 cm in Feb sowing.

**Table 6. Sugar yield (t ha$^{-1}$) of sweet sorghum varieties grown at different sowing times**

| Sowing time Variety | June 2016 | Nov 2016 | Feb 2017 | Mean |
|---|---|---|---|---|
| SugarDrip | 1.99 | 3.55 | 1.76 | 2.44 |
| BlueRibbon | 1.29 | 2.70 | 2.35 | 2.11 |
| N100 | 1.59 | 3.02 | 1.39 | 2.00 |
| 15AbjS3Ab70 | 1.32 | * | 1.78 | 1.55 |
| Hastings | 1.58 | 1.16 | 1.89 | 1.54 |
| N110 | 1.26 | 0.91 | 2.16 | 1.44 |
| Waconia-L | 1.23 | 1.31 | 1.75 | 1.43 |
| KansasCollies | 1.36 | 0.91 | 2.03 | 1.43 |
| 8AbjS3Ab70 | 1.12 | 1.14 | 1.91 | 1.39 |
| Brawley | 0.96 | 1.58 | 1.62 | 1.38 |
| 14AbjS3Ab70 | 1.20 | 0.95 | 1.75 | 1.30 |
| Red-x | 1.08 | 1.30 | 1.47 | 1.28 |
| 5AbjSG51 | 0.95 | 0.96 | 1.88 | 1.26 |
| 11AbjS3Ab70 | 1.01 | 1.23 | 1.47 | 1.24 |
| 1AbjSG51 | 0.84 | 1.05 | 1.71 | 1.20 |
| 3AbjSG51 | 1.03 | 1.22 | 1.26 | 1.17 |
| S.154 Ab70 | 0.71 | 0.77 | 2.00 | 1.16 |
| 13AbjS3Ab70 | 1.02 | 0.93 | 1.42 | 1.12 |
| 9AbjS3Ab70 | 0.76 | 0.94 | 1.66 | 1.12 |
| N99 | 1.17 | 0.51 | 1.61 | 1.10 |
| 10AbjS3Ab70 | 1.05 | 0.72 | 1.41 | 1.06 |
| Colman | 1.14 | 0.89 | 1.16 | 1.06 |
| ANK. S.18 | 1.41 | 0.27 | 1.33 | 1.00 |
| 4AbjSG51 | 0.91 | 1.12 | 0.95 | 0.99 |
| 7AbjS3Ab70 | 0.96 | 0.88 | 1.14 | 0.99 |
| 2AbjSG51 | 0.90 | 0.88 | 1.11 | 0.97 |
| Fremont | 0.68 | 0.63 | 1.77 | 0.93 |
| 6AbjS3Ab70 | 0.94 | 0.75 | 1.08 | 0.93 |
| S.158 Ab70 | 0.66 | 0.38 | 1.70 | 0.91 |
| ANK. S.36 | 1.16 | 1.05 | 0.50 | 0.90 |
| 12AbjS3Ab70 | 0.89 | 0.71 | 1.06 | 0.88 |
| N98 | 0.87 | 0.68 | 0.94 | 0.83 |
| SG.12-1 | 0.74 | 0.57 | 1.11 | 0.81 |
| SG.33 | 0.89 | 0.60 | 0.71 | 0.73 |
| ANK.LzmNrs | 1.13 | 0.28 | 0.53 | 0.65 |
| S.134 Ab70 | 0.68 | 0.24 | 0.70 | 0.54 |
| SG.11 | 0.77 | 0.24 | 0.60 | 0.54 |
| ANK. S.43 | 0.57 | 0.32 | 0.58 | 0.49 |
| SG.04 | 0.51 | 0.26 | 0.37 | 0.38 |
| SG.34 | 0.41 | 0.31 | 0.36 | 0.36 |
| Mean | 1.02 | 0.97 | 1.35 | 1.11 |
| SE± | 0.171 | 0.236 | 0.277 | 0.134 |
| LSD (0.05) | 0.480 | 0.666 | 0.781 | 0.373 |
| CV(%) | 29.0 | 42.1 | 35.6 | 36.0 |

**Table 7. Ethanol yield (L $ha^{-1}$) of sweet sorghum varieties grown at different sowing times**

| Sowing time Variety | June 2016 | Nov 2016 | Feb 2017 | Mean |
|---|---|---|---|---|
| SugarDrip | 1159 | 2065 | 1025 | 1416 |
| BlueRibbon | 747 | 1566 | 1365 | 1226 |
| N100 | 926 | 1752 | 807 | 1162 |
| 15AbjS3Ab70 | 767 | * | 1035 | 901 |
| Hastings | 917 | 674 | 1100 | 897 |
| N110 | 731 | 529 | 1253 | 838 |
| Waconia-L | 717 | 762 | 1016 | 832 |
| KansasCollies | 788 | 527 | 1179 | 831 |
| 8AbjS3Ab70 | 648 | 660 | 1109 | 805 |
| Brawley | 555 | 918 | 940 | 804 |
| 14AbjS3Ab70 | 698 | 553 | 1016 | 756 |
| Red-x | 625 | 757 | 851 | 745 |
| 5AbjSG51 | 553 | 558 | 1089 | 734 |
| 11AbjS3Ab70 | 584 | 714 | 855 | 718 |
| 1AbjSG51 | 489 | 607 | 993 | 697 |
| 3AbjSG51 | 599 | 706 | 732 | 679 |
| S.154 Ab70 | 414 | 448 | 1163 | 675 |
| 13AbjS3Ab70 | 593 | 539 | 822 | 651 |
| 9AbjS3Ab70 | 443 | 545 | 964 | 651 |
| N99 | 678 | 297 | 934 | 636 |
| 10AbjS3Ab70 | 611 | 419 | 819 | 617 |
| Colman | 660 | 517 | 671 | 616 |
| ANK. S.18 | 820 | 158 | 770 | 583 |
| 4AbjSG51 | 528 | 652 | 549 | 577 |
| 7AbjS3Ab70 | 557 | 509 | 661 | 576 |
| 2AbjSG51 | 525 | 512 | 646 | 561 |
| Fremont | 392 | 365 | 1026 | 540 |
| 6AbjS3Ab70 | 547 | 435 | 630 | 537 |
| S.158 Ab70 | 381 | 222 | 988 | 530 |
| ANK. S.36 | 676 | 609 | 290 | 525 |
| 12AbjS3Ab70 | 514 | 410 | 617 | 514 |
| N98 | 508 | 395 | 548 | 484 |
| SG.12-1 | 430 | 333 | 647 | 470 |
| SG.33 | 515 | 350 | 414 | 427 |
| ANK.LzmNrs | 659 | 164 | 307 | 377 |
| S.134 Ab70 | 392 | 138 | 406 | 312 |
| SG.11 | 447 | 139 | 346 | 311 |
| ANK. S.43 | 334 | 183 | 339 | 285 |
| SG.04 | 294 | 152 | 213 | 220 |
| SG.34 | 237 | 180 | 207 | 208 |
| Mean | 591 | 565 | 782 | 646 |
| SE± | 99.1 | 137.4 | 161.1 | 77.8 |
| LSD (0.05) | 279.1 | 386.9 | 453.6 | 216.9 |
| CV(%) | 29.0 | 42.1 | 35.6 | 36.0 |

**Table 8. Bagasse yield (t ha$^{-1}$) of sweet sorghum varieties grown at two sowing times**

| Sowing time Variety | Nov 2016 | Feb 2017 | Mean |
|---|---|---|---|
| SugarDrip | 44.4 | 27.5 | 36.0 |
| BlueRibbon | 28.1 | 28.8 | 28.4 |
| 15AbjS3Ab70 | * | 27.5 | 27.5 |
| 3AbjSG51 | 18.1 | 29.1 | 23.6 |
| N100 | 27.5 | 19.2 | 23.4 |
| S.154 Ab70 | 17.8 | 27.2 | 22.5 |
| Hastings | 17.2 | 24.8 | 21.0 |
| 11AbjS3Ab70 | 20.6 | 20.8 | 20.7 |
| Brawley | 18.6 | 22.1 | 20.4 |
| 8AbjS3Ab70 | 15.8 | 24.8 | 20.3 |
| 10AbjS3Ab70 | 14.4 | 25.1 | 19.8 |
| 7AbjS3Ab70 | 13.6 | 24.8 | 19.2 |
| 12AbjS3Ab70 | 14.2 | 24.0 | 19.1 |
| 14AbjS3Ab70 | 15.0 | 22.9 | 19.0 |
| Waconia-L | 16.9 | 20.3 | 18.6 |
| KansasCollies | 13.1 | 24.0 | 18.5 |
| 6AbjS3Ab70 | 13.3 | 23.7 | 18.5 |
| 1AbjSG51 | 15.0 | 21.9 | 18.4 |
| 5AbjSG51 | 15.8 | 20.3 | 18.1 |
| N110 | 13.1 | 22.7 | 17.9 |
| 4AbjSG51 | 16.4 | 18.1 | 17.3 |
| 13AbjS3Ab70 | 17.8 | 16.5 | 17.2 |
| 9AbjS3Ab70 | 11.4 | 22.9 | 17.2 |
| N99 | 12.5 | 20.5 | 16.5 |
| S.158 Ab70 | 13.3 | 18.9 | 16.1 |
| Colman | 13.9 | 17.9 | 15.9 |
| Red-x | 14.2 | 17.6 | 15.9 |
| SG.12-1 | 14.7 | 16.8 | 15.8 |
| N98 | 14.4 | 16.0 | 15.2 |
| SG.33 | 12.8 | 16.0 | 14.4 |
| S.134 Ab70 | 11.7 | 16.5 | 14.1 |
| Fremont | 10.6 | 16.0 | 12.7 |
| 2AbjSG51 | 11.3 | 13.3 | 12.3 |
| SG.04 | 10.6 | 13.9 | 12.2 |
| ANK. S.43 | 10.6 | 13.3 | 11.9 |
| ANK. S.36 | 13.1 | 10.4 | 11.7 |
| ANK.LzmNrs | 9.7 | 11.7 | 10.7 |
| ANK. S.18 | 7.2 | 14.1 | 10.7 |
| SG.34 | 8.9 | 12.0 | 10.4 |
| SG.11 | 8.9 | 10.7 | 9.8 |
| Mean | 15.3 | 19.9 | 17.6 |
| SE± | 2.25 | 3.05 | 1.55 |
| LSD (0.05) | 6.35 | 8.59 | 4.33 |
| CV(%) | 25.5 | 26.6 | 26.3 |

**Table 9. Days to flowering of sweet sorghum varieties grown at different sowing times**

| Sowing time Variety | June 2016 | Nov 2016 | Feb 2017 | Mean |
|---|---|---|---|---|
| Fremont | 51 | 69 | 65 | 62 |
| S.158 Ab70 | 61 | 72 | 64 | 66 |
| SG.11 | 59 | 73 | 65 | 66 |
| N98 | 60 | 69 | 73 | 68 |
| S.154 Ab70 | 65 | 64 | 75 | 68 |
| SG.12-1 | 68 | 75 | 65 | 70 |
| SG.04 | 66 | 78 | 66 | 70 |
| SG.34 | 65 | 72 | 73 | 70 |
| N99 | 60 | 77 | 74 | 70 |
| 5AbjSG51 | 63 | 81 | 68 | 70 |
| ANK. S.18 | 82 | 65 | 68 | 72 |
| ANK. S.43 | 79 | 70 | 66 | 72 |
| Hastings | 64 | 80 | 72 | 72 |
| S.134 Ab70 | 67 | 75 | 74 | 72 |
| SG.33 | 63 | 81 | 74 | 73 |
| 13AbjS3Ab70 | 70 | 74 | 75 | 73 |
| Waconia-L | 60 | 87 | 74 | 74 |
| ANK. S.36 | 75 | 72 | 75 | 74 |
| KansasCollies | 63 | 83 | 77 | 74 |
| N110 | 60 | 88 | 77 | 75 |
| 15AbjS3Ab70 | 73 | * | 79 | 76 |
| ANK.LzmNrs | 72 | 82 | 73 | 76 |
| Brawley | 62 | 87 | 78 | 76 |
| 8AbjS3Ab70 | 79 | 74 | 78 | 77 |
| Red-x | 62 | 91 | 77 | 77 |
| 4AbjSG51 | 71 | 90 | 76 | 79 |
| 14AbjS3Ab70 | 78 | 80 | 80 | 79 |
| 3AbjSG51 | 69 | 93 | 76 | 79 |
| Colman | 65 | 95 | 79 | 80 |
| 10AbjS3Ab70 | 79 | 81 | 80 | 80 |
| 12AbjS3Ab70 | 81 | 81 | 79 | 80 |
| 7AbjS3Ab70 | 76 | 90 | 77 | 81 |
| 11AbjS3Ab70 | 79 | 89 | 79 | 82 |
| 2AbjSG51 | 80 | 89 | 77 | 82 |
| 6AbjS3Ab70 | 81 | 88 | 79 | 82 |
| 1AbjSG51 | 81 | 89 | 78 | 83 |
| 9AbjS3Ab70 | 86 | 83 | 81 | 83 |
| BlueRibbon | 75 | 97 | 86 | 86 |
| N100 | 67 | 155 | 89 | 104 |
| SugarDrip | 69 | 158 | 90 | 106 |
| Mean | 70 | 85 | 75 | 76 |
| SE± | 2.301 | 2.311 | 0.943 | 1.130 |
| LSD (0.05) | 6.479 | 6.509 | 2.656 | 3.148 |
| CV(%) | 5.7 | 4.7 | 2.2 | 4.4 |

## 4. DISCUSSION

**Ethanol yield potential and related attributes:** The ethanol yield in this study was estimated from sugar yield which was consequently based on juice yield and brix's reading. The level of ethanol yield achieved by some varieties in this study (1500 - 2000 L $ha^{-1}$) was above of that reported in USA (532-1544 L $ha^{-1}$) [29] and India (1000-1134 L $ha^{-1}$) [32]. Both workers studied the ethanol yield potential of the major sweet sorghum or commercially released cultivars in their countries, i.e. in USA: M81E, SugarDrip, Keller, Dale and Della; in India: SSV 84, CSV19 SS and CSH 22 SS. The brix values encountered in this study for many varieties (19%-22%) were higher than the best performing ones in the above studies (18.7%). Similarly, Stalk (cane) yield shown by many varieties in this study (Table 3) was higher than those reported [29,32]. However, with few exceptions, juice yields depicted in Table 4 were somewhat lower than those reported in the above studies (12000-23400 t $ha^{-1}$). Low juice yield could be attributed to the low efficiency of the miller used (Two-roller hand operated). Using such type of millers will result in less than 50% of juice being collected [33]. Thus, higher juice yield (hence, ethanol yield) might have been expected if a machine with improved milling efficiency was used.

**Table 10. Plant height (cm) of sweet sorghum varieties grown at two sowing times**

| Sowing time Variety | Nov 2016 | Feb 2017 | Mean |
|---|---|---|---|
| 11AbjS3Ab70 | 192 | 270 | 231 |
| SugarDrip | 214 | 240 | 227 |
| 12AbjS3Ab70 | 184 | 265 | 225 |
| 15AbjS3Ab70 | * | 223 | 223 |
| 10AbjS3Ab70 | 180 | 255 | 218 |
| 7AbjS3Ab70 | 167 | 268 | 218 |
| BlueRibbon | 175 | 251 | 213 |
| 14AbjS3Ab70 | 161 | 264 | 212 |
| 5AbjSG51 | 166 | 259 | 212 |
| 8AbjS3Ab70 | 160 | 263 | 212 |
| 6AbjS3Ab70 | 144 | 278 | 211 |
| 13AbjS3Ab70 | 187 | 231 | 209 |
| Hastings | 172 | 239 | 206 |
| 3AbjSG51 | 168 | 244 | 206 |
| N100 | 199 | 210 | 205 |
| ANK.LzmNrs | 182 | 219 | 201 |
| 4AbjSG51 | 155 | 244 | 199 |
| N110 | 160 | 237 | 199 |
| Brawley | 170 | 226 | 198 |
| 1AbjSG51 | 161 | 235 | 198 |
| KansasCollies | 142 | 248 | 195 |
| ANK. S.36 | 172 | 217 | 195 |
| ANK. S.43 | 159 | 230 | 195 |
| S.154 Ab70 | 157 | 231 | 194 |
| 9AbjS3Ab70 | 161 | 226 | 194 |
| 2AbjSG51 | 166 | 220 | 193 |
| Colman | 143 | 235 | 189 |
| SG.34 | 162 | 212 | 187 |
| Waconia-L | 161 | 212 | 187 |
| S.134 Ab70 | 155 | 217 | 186 |
| SG.33 | 159 | 211 | 185 |
| N99 | 164 | 202 | 183 |
| Red-x | 160 | 203 | 182 |
| SG.12-1 | 158 | 199 | 179 |
| SG.04 | 158 | 198 | 178 |
| N98 | 145 | 204 | 175 |
| S.158 Ab70 | 155 | 191 | 173 |
| ANK. S.18 | 133 | 200 | 167 |
| Fremont | 141 | 185 | 163 |
| SG.11 | 137 | 186 | 162 |
| Mean | 164 | 229 | 197 |
| SE± | 8.14 | 12.13 | 5.980 |
| LSD (0.05) | 22.93 | 34.17 | 16.707 |
| CV(%) | 8.6 | 9.2 | 9.1 |

**Variety choice and effect of sowing time:** Some exotic and local varieties showing good potential for ethanol production in Sudan have been identified. These included the exotic varieties: SugarDrip, BlueRibbon, N100, Hastings, N110, Waconia-L, KansasCollies, Brawley and the local varieties: 15AbjS3Ab70, 8AbjS3Ab70, 14AbjS3Ab70, 5AbjSG51 and S.154 Ab70. However, the performance of these varieties is inconsistent across sowing time as indicated by the significant interaction for ethanol yield. Moreover, the interaction between the main effects for other traits attributing to ethanol yield indicated further the influence of sowing time on variety option. Thus, the exotic varieties: SugarDrip, N100 and Hastings can be suggested for growing in June (summer) sowing; SugarDrip, BlueRibbon, N100 and Brawley for late Nov (winter) sowing; BlueRibbon, N110, KansasCollies and Hastings can be suggested for February sowing. However, taking into account the maturity duration (time from sowing to harvest) the choice of SugarDrip and N100 for winter sowing should be reconsidered. Both varieties took more than 150 days to flower during winter implying higher costs of production in spite of their high ethanol yield. The inconsistency in performance of varieties across sowing times is expected since the development of sorghum is known to be influenced by photoperiod [34-36] with some variability among cultivars. While temperature was reported to control the life cycle of plants [36], photoperiod influences the vegetative stage from emergence to panicle initiation [36].

The local varieties suggested for ethanol production in this study are mostly suitable for growing in February sowing. This is specially true for S.154Ab70 and 8AbjS3Ab70. None of the studied Ankolib materials seemed to be promising for ethanol production. The best performing Ankolib variety (ANK. S.18) gave below average ethanol yield in the overall average performance. This could be attributed to the low juice yield probably resulting from poor cane yield. These results substantiate our previous findings [9]. It worth mentioning that most of the local varieties excel the exotic ones in grain yield as evident from our previous studies [9]. Moreover, the grains of the local varieties being bold and white colored are more valued by consumers. Sorghum grains are important starch-feedstock for ethanol production in USA [20] and other countries.

## 5. CONCLUSION

The present study revealed some exotic and locally developed sweet sorghum materials with relatively high potential for ethanol production in in sub-Saharan Africa at different growing seasons. The study furnished basic and reliable data that can be used to further assessing the economic feasibility of ethanol production from sweet sorghum in Sudan. The levels of ethanol yield reported here could be increased by improving milling efficiency and optimizing husbandry practices. Special care should be given to the variety option. There is no one variety choice for all growing seasons but different varieties matching different growing times. To embark on commercial ethanol production without determining the appropriate variety is not advisable. Likewise, we don’t recommend using the present land races of Ankolib for commercial ethanol production in Sudan.

## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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