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Research Article

# Grain yield, nutritional, polyphenols and antioxidant capacity in accessions of sorghum (*Sorghum bicolor* L. Moench)

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## Abstract

Sorghum is an economically important crop in developing countries. The objective of this study was to compare the agronomic performance, and the chromatic, nutritional and nutraceutical properties of nineteen sorghum accessions cultivated in Tamaulipas, Mexico. Results showed that the grain yield (15.22 to 70.18 g per plant), days to flowering (73 to 92 days), panicle length (16.63 to 27.67 cm), luminosity (27.14 to 57.75), chromaticity (5.65 to 15.33) and hue angle (38.49 to 82.66) varied. The percentage of protein (7.33 to 3.43%), fiber (0.60 to 3.03%) and carbohydrates (70.17 to 78.39%) also varied. Grains had a high concentration of magnesium, phosphorus and potassium; the content of total phenols and total flavonoids (free + bound) was found in a range of 117.61 to 2367.01 mg GAE/100 g and 22.52 to 613.92 mg CE/100 g, respectively. The antioxidant capacities (free + bound) showed ranges from 65.09 to 2,017.58 µmol TE/100 g, 43.13 to 1,907.99 µmol TE/100 g and 107.20 to 3,523.20 µmol TE/100 g using the ABTS, DPPH and FRAP methods, respectively. A negative correlation (-0.36) was observed between grain yield and days to flowering. In addition, a positive correlation between phenolic compounds and antioxidant capacity. These results confirm an important genetic diversity among the studied accessions of sorghum.

***Keywords:*** antioxidant capacity; correlation; phenolic compounds; sorghum grain; yield

## Introduction

Sorghum (*Sorghum bicolor* L. Moench) is the fifth most important cereal after corn, rice, wheat, and barley because of its multipurpose (food, forage, bioethanol, and other industrial uses) and has an economic importance (Kanbar *et al.*, 2021). This crop has been used for a long time as a staple food in arid and semi-arid

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areas prone to drought (Ishikawa *et al.*, 2017) as it is resistant to biotic and abiotic stress (Emendack *et al.*, 2021). In addition, due to its high yield, it can contribute to the food supply for the growing world population, especially as an option to produce food for celiac patients (Pontieri *et al.*, 2013).

The United States Department of Agriculture (USDA) reports that on average, 100 g of grain have about 72.10 g of carbohydrates, 12.40 g of water, 10.60 g of protein, 6.70 g of fibers and 3.50 g of lipids, which provide approximately 1377 kJ of energy (USDA, 2019). It has been reported that sorghum grains and sorghum flours are rich sources of macronutrients, micronutrients and bioactive compounds, mainly phenolic acids, 3-deoxyantocyanidins and condensed tannins, which promote beneficial changes in parameters related to non-communicable diseases such as obesity, diabetes, dyslipidemia, cardiovascular disease, cancer and hypertension (Xiong *et al.*, 2019). Currently, attention has been paid to develop new ways of using sorghum for food, promoting its consumption in processed foods including gluten-free breads, cookies, tortillas and pasta (Rashwan *et al.*, 2021). However, in sorghum crop, the agronomic potential and the quality of the grain is determined by the genotype and the growing conditions (Espitia-Hernández *et al.*, 2020).

According to the United Nations Food and Agriculture Organization (FAOSTAT, 2020), Mexico has been placed within the top 10 producers of sorghum, the main production areas are in the states of Guanajuato, Michoacán, Sinaloa, Jalisco and Tamaulipas with 75% of the total, where different sorghum genotypes that produce grains pigmented with yellow, black, purple, brown, red and orange colors are grown (Alejandro Allende *et al.*, 2020).

However, there is a great interest in developing the commercial exploitation of this crop in the Northeast of Mexico, specifically in the Southeast of the state of Coahuila, since 49% its territory is dry and semi-dry, and 46% is very dry. With these adverse conditions, sorghum cultivation, due to its tolerance to drought, low input requirements and good adaptation to weather conditions (Regassa and Wortmann, 2014), represents a significant possibility for its commercial establishment and self-consumption by producers in the region. In view of the above, the objective of this study was to compare the agronomic performance, the chromatic, nutritional and nutraceutical properties of nineteen sorghum accessions cultivated in the northeast of Mexico.

## Materials and Methods

### *Sorghum accessions and experimental site*

The material used for this experiment comprised nineteen sorghum accessions with different pigmentations, from the Sorghum Improvement Program of the Seed Technology Training and Development Center (CCDTS) of the Universidad Autónoma Agraria Antonio Narro (UAAAN, Figure 1). Sorghum accessions were cultivated in the Municipality of Matamoros, Tamaulipas in the Ejido Sandoval locality (latitude 25°54'49"N and longitude 97°41'57" W), at an average height of 10 meters above sea level. Average temperature of the site is 7 °C in winter and in summer it can reach 40 °C. Sowing was carried out on February 21$^{st}$ during the spring-summer cycle of 2020, under open field conditions, in a loamy-clay soil with a pH of 8.29, organic matter of 1.55% and an electrical conductivity of 0.78 dS/m. Nitrogen (N) levels were high (14.70 ppm), while phosphorus (P) levels were moderately low (12.10 ppm) and potassium (K) levels were optimal at 666 ppm.

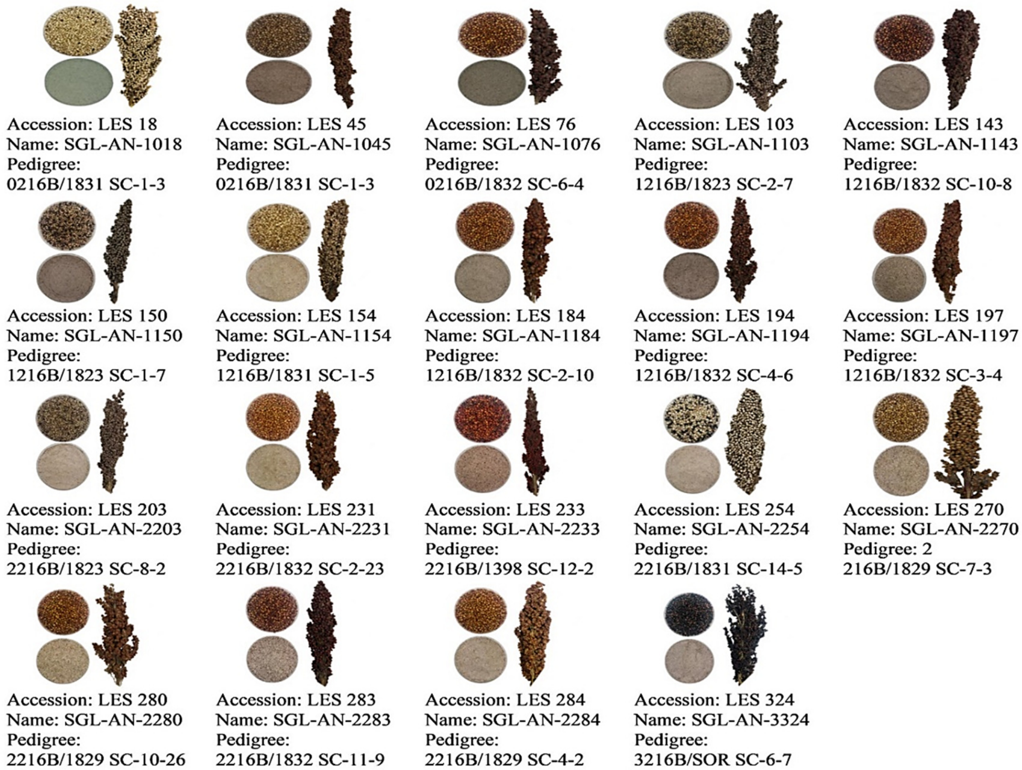


**Figure 1.** Sorghum accessions selected for the study
All lines were developed from experimental crosses and selected using the pedigree method of plant breeding. Crosses to generate parent populations were made at Guasave, Sinaloa. The crosses were grown in the agricultural spring-summer cycle (2018) at Buenavista, Saltillo, Coahuila, selecting F1 plants. F2 populations were grown and selected in a field in Matamoros, Tamaulipas. The visual selection of sorghum plants was made with the best agronomic characteristics, based on the duration of the vegetative cycle, plant height, days to 50% anthesis, health, panicle length, exertion length and grain yield.

*Growth conditions and experimental planting design*

Sowing was carried out under a randomized complete block design, with three repetitions and an arrangement of rows of 5 m long, 0.80 m between rows, and 1 m between lanes, having a population of 16 plants per linear meter. A pre-sowing irrigation and a first fertilization were performed by applying 100 kg of ammonium sulfate (N21-P00-K00-S24). Fifteen days after sowing, the first weeding and a second fertilization were carried out (liquid formulation, N32-P00-K00). The second weeding was done 44 days after sowing, and a week later the first auxiliary irrigation was done.

*Evaluation of agronomic parameters*

The agronomic parameters that were evaluated were the following (Oliveira *et al.*, 2020): grain yield in grams per plant (GY) was determined at harvest, for this, five representative plants from each plot were selected, which were threshed individually, then the grain was weighed and the value was reported as average in grams per plant (g/plant); days to flowering (DF), considering the number of days elapsed from the moment of sowing until the population was in the beginning of anthesis; panicle length (PL), comprises the distance between the base of the panicle to its apex; exertion length (EL), was measured from the flag leaf to the base of the neck of the panicle; plant height (PH), considers the measure from the base of the plant to the tip of the panicle. These variables were evaluated in physiological maturity and the result was expressed in cm.

*Grain sample for physicochemical, nutritional and nutraceutical analysis*

During harvest, grain samples for each accession were obtained by taking ten panicles from each of the three replications established in the field. Panicles were threshed, then grouped and finally mixed in a paper bag (pool); each having an approximate weight of 200 to 300 g. Of the total weight of the pool, 50% of the grain was kept for reserve and the other 50% was used to perform the functional analyses.

*Determination of grain colour*

The colour characteristics were determined with a Konica Minolta reader (CR-10 Tokyo, Japan) on the pericarp of the grain by placing 100 g of grain from each accession in a Petri dish (4.73 cm × 1.50 cm). The chromatic parameters were obtained using the CIELCH colour systems ($L^*$, $C^*$, $h$) established by the International Commission Internationale De L'ecleirage (CIE, 2004). To graph the colour, the ColorHexa online software was used using the values obtained from $L^*$, $C^*$ and $h$ (ColorHexa, 2020).

*Chemical composition analysis*

Proximal analysis was done according to Association of Official Analytical Chemists (AOAC, 1998), for protein quantification (method 960.52), crude fiber (method 920.86), ash (method 923.03), fat (method 923.03) and moisture (method 925.09). The carbohydrate content was obtained based on the sum of the percentages of protein, crude fiber, ash, fat, and moisture minus 100 percent (Rodríguez-Salinas *et al.*, 2020).

*Determination of minerals by coupled plasma induction atomic emission spectrometry (ICP-AES)*

The grain sample from each accession was dried in a Yamato DX 602C oven (Yamato Scientific Co, Japan) at 60 °C for 72 h. The resulting material was subjected to acid digestion in a mixture of perchloric acid and nitric acid (Alcántar and Sandoval, 1999). Nitrogen (N) was quantified by the micro Kjendahl method according to the Bremner methodology (1965). The concentrations in mg/100 g of phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) were quantified using the acid digestion extract using a coupled plasma induction atomic emission spectrometer (ICP-AES Agilent 725-ES, Agilent Technologies, United States).

*Determination of total phenols and total flavonoids*

Free and bound phenolic compounds were extracted according to Rodríguez-Salinas et al. (2020). Determinations of total phenols and total flavonoids, whether free or bound, and the antioxidant capacity tests were carried out in a Thermo Spectronic BioMate3 spectrophotometer (Rochester, NY, USA), in accordance with the work by López-Contreras *et al.* (2015). The determination of the total phenol content was carried out using the Folin-Ciocalteu reagent, using gallic acid as a standard for the calibration curve (0 to 200 mg/L). The absorbance of the samples was measured at 750 nm, and the results were expressed as milligrams of gallic acid equivalent per one hundred grams of sample (mg GAE/100 g). The determination of the total flavonoid content was based on the reaction of the complex of aluminum chloride and sodium hydroxide, using as a reference standard (+)-catechin at a concentration of 0 to 200 mg/L. The absorbance of the samples was measured at 510 nm and the result was reported as equivalent milligrams of (+)-catechin per 100 grams of sample (mg CE/100 g).

*Antioxidant capacity tests*

The antioxidant capacity tests for ABTS (2,2'-azinobis (3-ethylbenzothiazoline-6-sulfonic acid)), DPPH (2,2-diphenyl-1-picrylhydrazyl) and FRAP (ferric reducing antioxidant power) were performed according to Camposeco-Montejo *et al.* (2021). The results were reported in micromoles of Trolox (6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid) equivalent per one hundred grams of sample (μmol TE/100 g), taking as reference the calibration curve of Trolox (0 to 500 μmol/L).

*Statistical analysis*

To evaluate the different accessions in the field (agronomic parameters), an experimental design of complete random blocks was used with three repetitions (57 experimental plots, total). The chemical analyses in grains were evaluated under a complete random design with three repetitions for each accession. The results were analysed using the SPSS version 21.0 statistical package (SPSS Inc., Chicago, IL, USA), with a Tukey mean comparison test ($P \leq 0.05$) and were reported as mean values of three repetitions ± standard deviation.

## Results

*Performance of agronomic parameters*

The agronomic parameters evaluated showed significant differences ($P \leq 0.05$) between the sorghum accessions (Table 1). For GY, values ranged between 15.22 to 70.18, the lowest yields were LES 280 and LES 184 with 15.22 and 15.39 g/plant, respectively, while those with the highest yield were LES 284 with 60.00 g/plant, followed by LES 254 with 70.18 g/plant. For DF, the range varied from 73 to 92 days, with a greater precocity in LES 254 and LES 45 with 73 and 76 days, respectively; genotypes LES 154, LES 197 and LES 231 needed more DF with 90 and 92 days. Table 7 shows a negative correlation coefficient (-0.36) between the GY and DF, which indicates that the precocious sorghums got the highest yields.

**Table 1.** Agronomic parameters of pigmented sorghum accessions

| Accession | Agronomic parameters | | | | |
|---|---|---|---|---|---|
| | GY (g/plant) | DF (Days) | PL (cm) | EL (cm) | PH (cm) |
| LES 254 | 70.18 ± 23.67 a | 73.00 j | 22.00 ± 1.73 a-d | 1.00 ± 0.06 f | 89.00 ± 3.46 ef |
| LES 284 | 60.00 ± 2.00 ab | 82.00 f | 18.67 ± 2.08 b-d | 8.00 ± 1.73 b-f | 114.67 ± 1.15 b-d |
| LES 143 | 49.96 ± 3.81 a-c | 80.00 g | 23.64 ± 3.88 a-d | 10.89 ± 0.77 b-e | 62.67 ± 0.58 gh |
| LES 18 | 42.00 ± 1.00 a-d | 78.00 h | 23.07 ± 1.01 a-d | 11.02 ± 0.05 b-e | 109.00 ± 0.00 b-d |
| LES 103 | 39.37 ± 4.93 b-d | 82.00 f | 25.00 ± 1.20 a-c | 11.25 ± 1.51 b-e | 99.33 ± 0.58 de |
| LES 324 | 39.00 ± 1.12 b-d | 82.00 f | 26.00 ± 0.00 ab | 16.00 ± 0.07 ab | 100.00 ± 2.10 ed |
| LES 203 | 37.05 ± 12.56 b-d | 88.00 c | 27.67 ± 0.58 a | 6.53 ± 1.33 c-f | 107.67 ± 0.58 b-d |
| LES 197 | 35.42 ± 2.10 b-d | 90.00 b | 19.67 ± 1.15 b-d | 4.53 ± 2.55 d-f | 123.3 ± 15.01 b |
| LES 270 | 34.99 ± 4.02 b-d | 82.00 f | 19.67 ± 0.58 b-d | 15.87 ± 0.23 ab | 104.33 ± 2.89 c-e |
| LES 150 | 28.19 ± 3.81 cd | 85.00 e | 22.41 ± 3.30 a-d | 10.66 ± 2.89 b-e | 58.33 ± 1.15 h |
| LES 233 | 27.06 ± 0.76 cd | 80.00 g | 27.67 ± 2.31 a | 7.33 ± 4.67 c-f | 97.67 ± 0.58 de |
| LES 283 | 27.02 ± 3.06 cd | 80.00 g | 20.33 ± 1.15 a-d | 4.07 ± 2.66 ef | 78.00 ± 5.20 fg |
| LES 45 | 23.75 ± 1.04 cd | 76.00 i | 20.91 ± 0.50 a-d | 12.53 ± 0.06 a-d | 104.67 ± 1.15 c-e |
| LES 76 | 23.33 ± 0.75 cd | 78.00 h | 21.00 ± 0.00 a-d | 12.70 ± 0.17 a-d | 144.00 ± 1.73 a |
| LES 194 | 18.74 ± 2.75 d | 86.00 d | 20.33 ± 6.66 a-d | 19.67 ± 4.04 a | 99.67 ± 16.17 de |
| LES 231 | 18.38 ± 1.61 d | 92.00 a | 19.33 ± 3.79 b-d | 11.31 ± 1.75 a-e | 118.67 ± 5.77 bc |
| LES 154 | 17.31 ± 1.04 d | 90.00 b | 21.67 ± 0.58 a-d | 10.50 ± 7.50 b-e | 113.00 ± 10.39 b-d |
| LES 184 | 15.39 ± 1.98 d | 85.00 e | 17.33 ± 1.15 cd | 12.67 ± 0.58 a-d | 120.33 ± 2.31 bc |
| LES 280 | 15.22 ± 1.03 d | 78.00 h | 16.63 ± 0.91 d | 14.10 ± 3.29 a-c | 121.67 ± 5.77 bc |

GY = Grain yield in grams per plant, DF = Days to flowering, PL = Panicle length, EL = Exsertion length, PH = Plant height. Values are the average of three repetitions. Means (n = 3) ± standard deviation. Different letters within each column means that the treatments were statistically different Tukey ($P \leq 0.05$).

For PL, values were in a range from 16.63 to 27.67 cm. The smallest size was observed in LES 280 (16.63 cm) and LES 184 (17.33 cm), in comparison with LES 203 and LES 233, both with 27.67 cm, which had the longest values. For EL, the values ranged between 1.00 and 19.67 cm. The highest EL was observed in LES 194 (19.67 cm), followed by LES 324 (16.00 cm), while LES 254 and LES 283 had the lowest EL (1.00 and 4.07 cm, respectively). In PH, the values observed ranged between 58.33 and 144.00 cm. LES 150 and LES 143

(58.33 and 62.67 cm, respectively) show less growth compared to the values obtained in LES 197 and LES 76 (123.33 and 144.00 cm, respectively).

*Grain colour characteristics*

The colour characteristics ($L^*$, $C^*$ and $h$) of sorghum accessions showed significant differences (P ≤ 0.05) (Table 2). The $L^*$ values of LES 254 and LES 18 indicated a high tendency to white with values of 54.49 and 57.75, respectively, while the lowest values were observed in LES 324 and LES 283 (27.14 and 29.08, respectively). Results show a negative correlation coefficient between the values of $L^*$ (-0.56) and $h$ (-0.53) with the concentration of free phenols in the grain, suggesting that the grains with less luminosity and saturation of colour have a higher concentration of antioxidant compounds (Table 7). Regarding $C^*$, LES 231 and LES 280 showed the highest values (14.80 and 15.33, respectively) which indicates a higher colour saturation, while the lowest values (5.65 and 9.12) were observed in LES 324 and LES 150, respectively. The hue angle ($h$) values varied from 38.49 to 82.66, which correspond to the red-yellow quadrant of the hue circle, which indicates that yellow is the chromatic characteristic of the sorghum grain analysed.

**Table 2.** Colour parameters of pigmented sorghum grain accessions

| Accession | Colour parameter | | | |
|---|---|---|---|---|
| | $L^*$ | $C^*$ | $h$ | Appearance |
| LES 18 | 57.75 ± 2.40 a | 14.22 ± 0.18 ab | 82.66 ± 1.24 a | |
| LES 154 | 55.36 ± 0.05 a | 13.66 ± 4.28 ab | 69.34 ± 11.08 bc | |
| LES 254 | 54.49 ± 3.09 a | 12.47 ± 1.29 a-c | 78.64 ± 1.50 ab | |
| LES 203 | 43.07 ± 1.13 b | 11.61 ± 1.37 a-c | 65.11 ± 2.80 c-e | |
| LES 103 | 41.90 ± 0.53 bc | 11.28 ± 0.54 a-c | 67.83 ± 1.04 b-d | |
| LES 270 | 39.14 ± 1.04 b-d | 13.66 ± 0.91 ab | 61.92 ± 3.72 c-f | |
| LES 231 | 37.95 ± 1.52 b-d | 14.80 ± 0.70 ab | 59.22 ± 3.34 c-h | |
| LES 150 | 37.69 ± 4.39 b-d | 9.12 ± 1.80 cd | 59.85 ± 6.41 c-g | |
| LES 197 | 37.34 ± 0.05 c-e | 14.47 ± 0.17 ab | 61.10 ± 2.05 c-g | |
| LES 280 | 36.94 ± 1.43 c-f | 15.33 ± 0.17 a | 58.69 ± 5.19 c-h | |
| LES 284 | 35.61 ± 5.06 d-g | 13.27 ± 2.02 a-c | 52.19 ± 10.04 e-i | |
| LES 45 | 35.54 ± 1.32 d-g | 11.56 ± 0.31 a-c | 55.31 ± 3.72 d-i | |
| LES 76 | 34.39 ± 1.51 d-g | 13.50 ± 0.61 ab | 50.93 ± 1.05 f-k | |
| LES 184 | 33.74 ± 1.02 d-h | 14.40 ± 0.82 ab | 51.24 ± 3.16 f-j | |
| LES 194 | 31.90 ± 0.52 e-i | 12.43 ± 1.14 a-c | 46.27 ± 2.68 h-k | |
| LES 233 | 31.72 ± 0.71 f-i | 13.03 ± 3.11 a-c | 38.49 ± 2.90 k | |
| LES 143 | 31.16 ± 2.91 g-i | 11.28 ± 0.43 a-c | 45.27 ± 5.14 i-k | |
| LES 283 | 29.08 ± 0.78 hi | 10.55 ± 1.45 bc | 39.83 ± 4.13 jk | |
| LES 324 | 27.14 ± 1.31 i | 5.65 ± 2.40 d | 48.02 ± 8.39 g-k | |

$L^*$: luminosity; $C^*$: chromaticity; $h$: hue angle. Values are the average of three repetitions. Means (n = 3) ± standard deviation. Different letters within each column means that the treatments were statistically different (P ≤ 0.05).

*Chemical composition evaluation*

Results of the chemical composition of the sorghum accessions show significant differences (P ≤ 0.05) (Table 3). The protein concentration ranged from 7.33% to 13.43%. The lowest concentration was observed in LES 18 and LES 203 (7.33% and 8.66%, respectively), while LES 254 and LES 283 showed the highest values with 12.44% and 13.43%, respectively. Fiber content ranged from 0.60% to 3.03%, the lowest content was for LES 18 (0.60%) and LES 45 (1.02%), while LES 203 and LES 197 obtained the highest content with 2.95%

and 3.03%, respectively. For ash, a range of 1.15% to 1.90% was found, the minimum values were in LES 254 and LES 194 (1.15% and 1.20%, respectively), while the highest values were observed in LES 284 and LES 197 (1.85% and 1.90%, respectively).

The fat content ranged from 1.93% to 3.23%, where LES 103 and LES 203 had the lowest values with 1.93% and 2.10%, respectively, while LES 18 and LES 283 had the highest content (3.18% and 3.23%). Accessions with a lower moisture content were LES 184 and LES 324 with 8.70% and 9.05%, respectively, while in LES 103 and LES 194, a higher moisture content was detected (10.65% and 10.90%, respectively). The minimum values of carbohydrates were presented in LES 283 (70.17%) and LES 231 (71.88%), while the maximum values were for LES 324 and LES 18 with 75.50% and 78.39%, respectively.

**Table 3.** Chemical composition of pigmented sorghum accessions

| Accession | Component % | | | | | |
|---|---|---|---|---|---|---|
| | Protein | Fiber | Ash | Fat | Humidity | Carbohydrates |
| LES 283 | 13.43 ± 0.19 a | 1.23 ± 0.22 e-g | 1.50 ± 0.20 a-e | 3.23 ± 0.08 a | 10.45 ± 0.15 a-c | 70.17 ± 1.02 h |
| LES 254 | 12.44 ± 0.05 b | 1.19 ± 0.17 fg | 1.15 ± 0.15 e | 12.44 ± 0.05 b | 9.75 ± 0.05 d-f | 72.57 ± 2.12 fg |
| LES 231 | 12.01 ± 0.19 b | 2.23 ± 0.07 bc | 1.70 ± 0.10 a-d | 2.38 ± 0.13 d-g | 9.80 ± 0.10 e-f | 71.88 ± 1.59 g |
| LES 284 | 11.49 ± 0.05 c | 1.69 ± 0.20 c-f | 1.85 ± 0.05 ab | 2.75 ± 0.21 a-e | 9.45 ± 0.15 e-g | 72.76 ± 0.15 fg |
| LES 154 | 11.42 ± 0.09 c | 2.35 ± 0.02 b | 1.50 ± 0.10 a-e | 2.48 ± 0.23 b-f | 9.10 ± 0.10 gh | 73.15 ± 1.13 d-f |
| LES 233 | 11.42 ± 0.17 c | 1.14 ± 0.21 f-h | 1.70 ± 0.11 a-d | 2.43 ± 0.03 e-f | 9.25 ± 0.25 f-h | 74.06 ± 1.09 cd |
| LES 270 | 11.29 ± 0.22 cd | 1.79 ± 0.20 b-d | 1.45 ± 0.05 a-e | 3.05 ± 0.05 a | 9.85 ± 0.05 de | 72.57 ± 2.27 fg |
| LES 184 | 10.98 ± 0.28 de | 1.82 ± 0.18 b-d | 1.60 ± 0.13 a-e | 2.23 ± 0.08 e-g | 8.70 ± 0.20 h | 74.68 ± 1.13 bc |
| LES 197 | 10.90 ± 0.26 de | 3.03 ± 0.11 a | 1.90 ± 0.16 a | 2.33 ± 0.03 d-g | 9.90 ± 0.30 c-e | 71.95 ± 2.09 g |
| LES 194 | 10.73 ± 0.09 ef | 1.64 ± 0.23 d-f | 1.20 ± 0.20 de | 2.73 ± 0.08 a-e | 10.90 ± 0.30 a | 72.80 ± 0.89 e-g |
| LES 143 | 10.60 ± 0.04 ef | 1.58 ± 0.31 d-g | 1.55 ± 0.25 a-e | 3.00 ± 0.03 ab | 10.10 ± 0.10 b-d | 73.17 ± 3.37 d-f |
| LES 280 | 10.34 ± 0.04 fg | 1.66 ± 0.02 d-f | 1.55 ± 0.05 a-e | 2.45 ± 0.05 c-g | 10.10 ± 0.20 b-d | 73.89 ± 2.12 c-e |
| LES 150 | 9.94 ± 0.19 gh | 1.56 ± 0.14 d-g | 1.60 ± 0.20 a-d | 2.38 ± 0.38 d-g | 9.90 ± 0.1 7 c-e | 74.62 ± 1.53 bc |
| LES 76 | 9.77 ± 0.09 h | 1.04 ± 0.17 gh | 1.50 ± 0.10 a-e | 2.98 ± 0.33 a-c | 10.20 ± 0.20 b-d | 74.51 ± 3.07 bc |
| LES 324 | 9.56 ± 0.21 h | 1.42 ± 0.06 d-g | 1.75 ± 0.15 a-c | 2.73 ± 0.03 a-e | 9.05 ± 0.25 gh | 75.50 ± 2.37 b |
| LES 103 | 9.52 ± 0.09 gh | 1.65 ± 0.01 d-f | 1.45 ± 0.25 a-e | 1.93 ± 0.08 g | 10.65 ± 0.05 ab | 74.37 ± 3.35 bc |
| LES 45 | 9.52 ± 0.09 h | 1.02 ± 0.01 gh | 1.30 ± 0.13 c-e | 3.08 ± 0.03 a | 10.20 ± 0.40 b-d | 74.89 ± 1.28 bc |
| LES 203 | 8.66 ± 0.14 i | 2.95 ± 0.19 a | 1.35 ± 0.05 c-e | 2.10 ± 0.15 fg | 9.95 ± 0.15 c-e | 74.99 ± 3.54 bc |
| LES 18 | 7.33 ± 0.04 j | 0.60 ± 0.08 h | 1.25 ± 0.25 c-e | 3.18 ± 0.13 a | 9.25 ± 0.05 f-h | 78.39 ± 2.43 a |

Values are the average of three repetitions. Means (n = 3) ± standard deviation. Different letters within each column means that the treatments were statistically different ($P \leq 0.05$).

*Macroelement concentration*

The macroelements content of the different sorghum accessions show significant differences ($P \leq 0.05$) in Mg, Ca, N, K and P (Table 4). The Mg content among the sorghum accessions ranged from 80.44 to 135.67 mg/100 g. The lowest value was observed in LES 283 (80.44 mg/100 g), followed by LES 203 with 86.03 mg/100 g, respectively. The highest values were observed in LES 154 and LES 18 (112.64 and 135.67 mg/100 g, respectively). For Ca content, values ranging from 74.79 to 110.99 mg/100 g were observed. The minimum Ca values were found in LES 254 and LES 231 (74.79 and 75.52 mg/100 g, respectively), while the highest values range from 104.07 to 110.99 mg/100 g and were for LES 324 and LES 18, respectively. Nitrogen ranged from 1.93 to 2.89%. The minimum values were found in LES 18 and LES 324 with 1.93 and 1.94%, respectively, while the maximum concentrations were found in LES 194 and LES 184 with 2.80 and 2.89%. There was a negative correlation (-0.25) between N and GY (Table 7). For P, the values obtained were found in a range from 154.04 to 278.15 mg/100 g. The minimum values of the P content ranged from 154.04 (LES 203) to 157.75 mg/100 g (LES 150), while the maximum values were found in LES 154 and LES 18 with 247.78 and 278.15 mg/100 g, respectively. The concentration of K in the sorghum accessions ranged from 110.55 to 331.06 mg/100 g. The lowest values were in LES 283 and LES 280 with 110.53 and 115.36 mg/100 g, respectively. LES 45 and LES 18 were the accessions with the highest K content, with 263.90 and 331.06 mg/100 g, respectively.

**Table 4.** Macro-elements of pigmented sorghum accessions

| Accession | Macro-elements (mg/100 g) | | | | |
|---|---|---|---|---|---|
| | Mg | Ca | N (%) | P | K |
| LES 18 | 135.67 ± 5.19 a | 110.99 ± 4.27 a | 1.93 ± 0.12 c | 278.15 ± 14.56 a | 331.06 ± 25.15 a |
| LES 154 | 112.64 ± 3.78 b | 82.91 ± 4.20 bc | 2.63 ± 0.06 a-c | 247.78 ± 11.23 ab | 178.03 ± 11.15 b-d |
| LES 231 | 108.82 ± 4.70 bc | 75.52 ± 2.12 c | 2.76 ± 0.10 ab | 223.69 ± 13.69 b-e | 225.45 ± 15.63 bc |
| LES 143 | 108.64 ± 4.82 bc | 96.30 ± 5.64 a-c | 2.58 ± 0.12 a-c | 203.24 ± 19.60 c-h | 183.39 ± 13.51 b-e |
| LES 197 | 108.43 ± 4.87 bc | 89.02 ± 1.05 a-c | 2.54 ± 0.31 a-c | 209.19 ± 11.25 c-g | 201.62 ± 11.25 b-d |
| LES 270 | 106.08 ± 3.51 bd | 83.05 ± 3.11 bc | 2.54 ± 0.19 a-c | 198.91 ± 10.08 d-i | 203.04 ± 14.93 b-d |
| LES 233 | 105.82 ± 2.38 bd | 82.00 ± 2.58 bc | 2.45 ± 0.06 a-c | 232.74 ± 14.86 b-d | 229.34 ± 13.68 bc |
| LES 45 | 105.30 ± 1.41 b-e | 90.62 ± 5.80 a-c | 2.12 ± 0.09 bc | 171.40 ± 10.55 h-j | 263.90 ± 17.37 ab |
| LES 254 | 104.02 ± 2.07 b-e | 74.79 ± 4.26 c | 2.36 ± 0.19 a-c | 212.87 ± 11.36 c-f | 235.33 ± 13.54 bc |
| LES 324 | 100.39 ± 2.74 b-e | 104.07 ± 6.51 ab | 1.94 ± 0.22 c | 237.54 ± 10.40 bc | 132.88 ± 12.44 de |
| LES 194 | 99.35 ± 4.26 b-f | 89.89 ± 6.26 a-c | 2.80 ± 0.40 ab | 198.04 ± 20.04 e-i | 178.44 ± 13.55 b-d |
| LES 76 | 96.85 ± 3.35 b-f | 82.76 ± 5.30 bc | 2.14 ± 0.33 bc | 174.34 ± 11.14 h-j | 186.92 ± 17.23 b-e |
| LES 184 | 95.07 ± 3.41 b-f | 79.74 ± 3.22 bc | 2.89 ± 0.31 a | 193.55 ± 13.50 e-i | 188.64 ± 16.21 b-e |
| LES 103 | 94.00 ± 4.35 b-f | 98.57 ± 4.17 a-c | 2.47 ± 0.15 a-c | 175.30 ± 17.48 g-j | 204.32 ± 13.78 bc |
| LES 284 | 90.42 ± 5.10 c-f | 98.50 ± 2.85 a-c | 2.08 ± 0.09 bc | 203.30 ± 12.51 b-h | 157.08 ± 15.76 c-e |
| LES 150 | 88.59 ± 6.88 d-f | 89.23 ± 3.54 a-c | 2.28 ± 0.06 a-c | 157.75 ± 15.35 j | 191.52 ± 14.27 b-e |
| LES 280 | 86.13 ± 4.20 ef | 92.10 ± 5.73 a-c | 2.41 ± 0.29 a-c | 179.23 ± 9.48 f-j | 115.36 ± 11.42 e |
| LES 203 | 86.03 ± 2.58 ef | 76.53 ± 4.45 c | 2.19 ± 0.19 a-c | 159.04 ± 10.98 j | 227.30 ± 15.63 bc |
| LES 283 | 80.44 ± 3.35 f | 88.05 ± 5.20 a-c | 1.97 ± 0.22 c | 168.29 ± 11.96 ij | 110.55 ± 10.21 e |

Mg = Magnesium, Ca = Calcium, N = Nitrogen, P = Phosphorus and K = Potassium. Values are the average of three repetitions. Means (n = 3) ± standard deviation. Different letters within each column means that the treatments were statistically different ($P \leq 0.05$).

### *Content of total phenols and total flavonoids*

For the content of total phenols and total flavonoids, significant differences were found between accessions ($P \leq 0.05$) (Table 5). Free phenols concentration ranged from 103.50 to 2177.10 mg GAE/100 g, from 12.31 to 189.91 mg GAE/100 g in bound extracts, and 117.61 to 2367.01 mg GAE/100 g in the total extract. For soluble phenols, the lowest values were for LES 18 and LES 254 with 103.50 and 105.30 mg GAE/100 g, respectively, while the accessions with the highest content of free phenols were LES 197 and LES 233 (1664.40 and 2177.10 mg GAE/100 g, respectively). For bound phenols, LES 254 and LES 103 had the lowest concentrations (12.31 and 10.84 mg GAE/100 g, respectively), while LES 280 and LES 233 were the accessions with the highest concentration with values of 150.50 and 189.91 mg GAE/100 g, respectively. The negative correlation coefficient (-0.32) between GY and bound phenols (Table 7) shows that sorghum grains with a higher content of bound phenolic compounds presented a lower yield. The quantification of free and bound phenols allowed to identify that LES 254 and LES 18 are the accessions with the lowest content of total phenols (117.61 and 125.45 mg GAE/100 g, respectively), on the other hand, those with the highest concentration were LES 197 and LES 233 with 1787.73 and 2367.01 mg GAE/100 g, respectively.

The content of total flavonoids in the evaluated accessions was found in a range from 16.92 to 542.39 mg CE/100 g in free extracts, 2.93 to 11.98 mg CE/100 g in bound extracts and 22.52 to 613.92 mg CE/100 g in total extracts (Table 5). In free extracts, the lowest values correspond to LES 18 (16.92 mg CE/100 g) and LES 254 (32.18 mg CE/100 g), on the contrary, LES 194 and LES 197 (532.48 and 542.39 mg CE/100 g, respectively) had the highest values. In bound extracts, LES 154 and LES 18 showed the lowest values with 2.93 and 5.60 mg CE/100 g, respectively, while LES 197 and LES 233 reported the highest values of 71.53 and 111.98 mg CE/100 g, respectively. The results of free and bound flavonoids identify LES 18 and LES 254 as the accessions with the lowest concentration (22.52 and 42.42 mg CE/100 g, respectively), while those with the highest concentration were LES 280 and LES 197 with 601.13 and 613.92 mg CE/100 g. The content of flavonoids showed significant positive correlations with the antioxidant capacity tests for DPPH (0.76 and 0.65), ABTS (0.77 and 0.69) and FRAP (0.71) (Table 7), which suggests that higher flavonoids values are related to a higher antioxidant capacity.

**Table 5.** Content of total phenols and total flavonoids in pigmented sorghum accessions

| Accession | Total phenols (mg GAE/100 g) | | | Total flavonoids (mg CE/100 g) | | |
|---|---|---|---|---|---|---|
| | Free | Bound | Total | Free | Bound | Total |
| LES 233 | 2177.10 ± 70.35 a | 189.91 ± 7.07 a | 2367.01 | 77.99 ± 8.38 fg | 111.98 ± 9.11 a | 189.97 |
| LES 197 | 1664.40 ± 67.82 ab | 123.33 ± 11.77 cd | 1787.73 | 542.39 ± 34.04 a | 71.53 ± 4.00 bc | 613.92 |
| LES 280 | 1585.40 ± 38.78 ab | 150.50 ± 8.00 b | 1735.90 | 519.71 ± 25.51 a | 81.42 ± 5.04 b | 601.13 |
| LES 231 | 1539.10 ± 11.41 ab | 134.79 ± 10.65 bc | 1673.89 | 460.14 ± 36.90 ab | 71.49 ± 4.07 bc | 531.63 |
| LES 150 | 1498.50 ± 55.52 ab | 130.60 ± 6.94 c | 1629.10 | 69.36 ± 4.54 fg | 22.86 ± 3.06 fg | 92.22 |
| LES 194 | 1402.30 ± 28.13 a-c | 116.53 ± 6.21c d | 1518.83 | 532.48 ± 34.34 a | 58.80 ± 6.03 cd | 591.28 |
| LES 284 | 1379.60 ± 18.19 a-d | 106.10 ± 7.28 de | 1485.70 | 459.58 ± 16.33 ab | 59.51 ± 5.95 cd | 519.09 |
| LES 283 | 1205.70 ± 70.63 a-d | 92.18 ± 4.15 ef | 1297.88 | 383.64 ± 27.30 bc | 47.44 ± 5.28 de | 431.08 |
| LES 184 | 1163.30 ± 14.28 a-d | 104.00 ± 12.33 ed | 1267.30 | 309.73 ± 26.21 cd | 36.86 ± 6.04 ef | 346.59 |
| LES 143 | 1111.40 ± 50.91 a-d | 104.14 ± 9.43 ed | 1215.54 | 372.08 ± 51.52 bc | 43.58 ± 4.00 ed | 415.66 |
| LES 76 | 813.70 ± 52.64 b-d | 72.93 ± 10.66 fg | 886.63 | 231.21 ± 29.88 de | 12.91 ± 4.18 gh | 244.12 |
| LES 270 | 756.80 ± 80.45 b-d | 65.44 ± 4.85 gh | 822.24 | 198.26 ± 31.30 e | 10.23 ± 5.02 gh | 208.49 |
| LES 45 | 707.90 ± 67.18 b-d | 70.88 ± 7.93 g | 778.78 | 195.97 ± 36.75 e | 15.57 ± 4.02 gh | 211.54 |
| LES 324 | 674.50 ± 22.94 b-d | 46.43 ± 2.98 h | 720.93 | 139.87 ± 12.39 fe | 85.29 ± 7.34 b | 225.16 |
| LES 103 | 175.70 ± 8.25 b-d | 10.84 ± 1.86 i | 186.54 | 46.85 ± 8.34 fg | 6.92 ± 4.16 gh | 53.79 |
| LES 203 | 133.80 ± 10.05 cd | 22.22 ± 3.59 i | 156.02 | 41.51 ± 2.01 fg | 8.25 ± 1.14 gh | 49.76 |
| LES 154 | 127.80 ± 16.35 cd | 17.05 ± 2.62 i | 144.85 | 40.20 ± 3.04 fg | 2.93 ± 1.16 h | 43.13 |
| LES 18 | 103.50 ± 9.53 d | 21.95 ± 2.47 i | 125.45 | 16.92 ± 3.04 g | 5.60 ± 2.00 h | 22.52 |
| LES 254 | 105.30 ± 7.31 d | 12.31 ± 2.52 i | 117.61 | 32.18 ± 4.08 fg | 10.24 ± 1.18 gh | 42.42 |

Values are the average of three repetitions. Means (n = 3) ± standard deviation. Different letters within each column means that the treatments were statistically different (P ≤ 0.05).

### *Evaluation of antioxidant capacity*

The results showed significant differences (P ≤ 0.05) for antioxidant capacity in the ABTS, DPPH and FRAP tests (Table 6).

### *ABTS*

For ABTS, values between 55.55 to 1,925.57 µmol TE/100 g were found in free extracts, 9.54 to 182.02 µmol TE/100 g for bound extracts, and 65.09 to 2,107.58 µmol TE/100 g for total extracts (Table 6). The minimum values in free extracts were found in LES 254 and LES 18 with 55.55 and 63.97 µmol TE/100 g, respectively, while the maximum values were found in LES 280 and LES 233 with 1,631.88 and 1,925.57 µmol TE/100 g, respectively. For bound extracts, LES 254 and LES 203 (9.54 and 11.73 µmol TE/100 g, respectively) were the accessions with the lowest values, while the highest values were found in LES 231 and LES 233 (155.07 and 182.01 µmol TE/100 g, respectively). For total antioxidant capacity, LES 254 and LES 203 were the ones who obtained the lowest results (65.09 and 77.51 µmol TE/100 g, respectively), while LES 280 and LES 233 were the accessions with the highest antioxidant capacity with values of 1,783.85 and 2,107.58 µmol TE/100 g, respectively. Table 7 shows a negative correlation between GY and antioxidant capacity, which indicates that the accessions with the highest antioxidant capacity are the ones with the lowest performance (Tables 1 and 6).

### *DPPH*

DPPH results for sorghum accessions ranged from 33.87 to 1,780.37 µmol TE/100 g in free extracts, 9.27 to 127.62 µmol TE/100 g in bound extracts, and 107.20 to 1907.99 µmol TE/100 g in total extracts (Table 6). The lowest values for the free extracts were LES 254 and LES 203, with 33.87 and 56.11 µmol TE/100 g, respectively. LES 280 and LES 233 were the accessions with the highest antioxidant capacity values (1,532.72 and 1,780.37 µmol TE/100g, respectively). The lowest antioxidant capacity in bound extracts was observed in LES 254 (9.27 µmol TE/100 g) and LES 154 (9.50 µmol TE/100 g), while LES 280 (120.23 µmol TE/100 g) and LES 233 (127.62 µmol TE/100 g) obtained the highest values. In total antioxidant capacity, LES 18 (107.20 µmol TE/100 g) and LES 254 (153.10 µmol TE/100 g) obtained the lowest values, while LES 280 and LES 233 had the highest values (1652.95 and 1907.99 µmol TE/100 g, respectively).

*FRAP*

Table 6 shows the results of antioxidant capacity for the FRAP test, with ranges from 81.70 to 3,197.10, 16.91 to 326.04, and 107.20 to 3,523.20 µmol TE/100 g for free, bound, and total extracts, respectively. The minimum values for free extracts were found in LES 18 and LES 254, with 81.70 and 134.30 µmol TE/100 g, respectively, while the maximum values were found in LES 231 (2,839.20 µmol TE/100 g) and LES 233 (3,197.10 µmol TE/100 g). LES 154 and LES 254 (16.91 and 18.82 µmol TE/100 g, respectively) are the accessions with the lowest values in antioxidant capacity of bound extracts, on the contrary, LES 231 (283.24 µmol TE/100 g) and LES 233 (326.04 µmol TE/100 g) are those who got the highest values. LES 18 (107.20 µmol TE/100 g) was the accession with the lowest total antioxidant capacity, followed by LES 254 (153.10 µmol TE/100 g). LES 231 and LES 233 were the accessions with the highest antioxidant capacity, with values of 3,122.50 and 3,523.20 µmol TE/100 g, respectively.

**Table 6.** Antioxidant capacity in pigmented sorghum accessions

| Accession | ABTS (µmol TE/100 g) | | | DPPH (µmol TE/100 g) | | | FRAP (µmol TE/100 g) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Free | Bound | Total | Free | Bound | Total | Free | Bound | Total |
| LES 233 | 1925.57 ± 39.95 a | 182.01 ± 3.57 a | 2107.58 | 1780.37 ± 27.51 a | 127.62 ± 3.23 a | 1907.99 | 3197.10 ± 118.26 c | 326.04 ± 11.80 a | 3523.20 |
| LES 280 | 1631.88 ± 65.39 b | 151.97 ± 2.74 bc | 1783.85 | 1532.72 ± 61.21 b | 120.23 ± 1.54 ab | 1652.95 | 2036.10 ± 89.00 ef | 258.67 ± 8.99 bc | 2294.80 |
| LES 231 | 1510.31 ± 65.84bc | 155.08 ± 2.50 b | 1665.38 | 1203.06 ± 51.33 c | 101.12 ± 2.68 d-f | 1304.18 | 2839.20 ± 86.99 c | 283.24 ± 14.15 b | 3122.50 |
| LES 197 | 1493.77 ± 21.18bc | 153.17 ± 2.30 bc | 1646.95 | 1179.49 ± 27.26 c | 119.95 ± 4.50 ab | 1299.43 | 2438.50 ± 116.26 d | 238.22 ± 3.61 c-e | 2676.70 |
| LES 194 | 1381.56 ± 69.66cd | 142.86 ± 2.35 de | 1524.43 | 1168.11 ± 33.24 c | 118.25 ± 1.68 ab | 1286.35 | 2231.30 ± 56.10 de | 221.43 ± 9.54 ef | 2452.73 |
| LES 284 | 1359.83 ± 63.42ce | 144.03 ± 2.46 d | 1503.85 | 1163.38 ± 33.97 c | 112.79 ± 1.75 bc | 1276.16 | 1871.50 ± 77.22 e-g | 235.41 ± 4.04 c-e | 2106.90 |
| LES 283 | 1300.10 ± 62.52de | 135.58 ± 3.43 e-g | 1435.68 | 1197.79 ± 22.58 c | 109.37 ± 3.38 b-e | 1307.16 | 1777.90 ± 111.70 fh | 218.89 ± 6.45 ef | 1996.80 |
| LES 150 | 1241.39 ± 60.42df | 146.08 ± 1.97 cd | 1387.47 | 1056.22 ± 28.79de | 112.94 ± 4.35 bc | 1169.16 | 1657.70 ± 104.04 fh | 248.68 ± 6.79 cd | 1906.30 |
| LES 184 | 1202.35 ± 78.77dg | 139.42 ± 3.24 d-f | 1341.77 | 1123.12 ± 58.46cd | 112.19 ± 2.26 bd | 1235.31 | 1761.40 ± 107.81f h | 227.99 ± 10.49de | 1989.40 |
| LES 143 | 1194.60 ± 92.21eg | 133.61 ± 1.81 f-h | 1328.21 | 1024.60 ± 64.03de | 102.02 ± 4.80 c-f | 1126.62 | 1928.60 ± 128.77 eg | 223.80 ± 6.25 de | 2152.40 |
| LES 76 | 1079.75 ± 75.53 fg | 127.43 ± 3.96 h | 1207.19 | 968.59 ± 22.45 e | 104.97 ± 8.48 c-e | 1073.56 | 1284.43 ± 94.06 b | 186.54 ± 13.17 g | 1303.08 |
| LES 45 | 1058.51 ± 66.16gh | 140.82 ± 3.75 d-f | 1199.33 | 958.95 ± 33.81 e | 100.88 ± 4.82 ef | 1059.82 | 1361.88 ± 93.68 a | 221.64 ± 9.35 ef | 1384.05 |
| LES 270 | 1039.61 ± 96.35gh | 141.22 ± 2.10 de | 1180.82 | 950.66 ± 29.66 e | 112.56 ± 2.48 bc | 1063.22 | 1550.80 ± 95.35 gh | 235.58 ± 9.87 c-e | 1786.40 |
| LES 324 | 888.40 ± 46.80 h | 129.41 ± 4.74 gh | 1017.81 | 745.69 ± 24.21 f | 93.25 ± 4.89 f | 838.94 | 1401.30 ± 41.96 h | 197.31 ± 4.62 fg | 1598.60 |
| LES 103 | 103.58 ± 5.97 i | 15.26 ± 2.39 i | 118.84 | 66.49 ± 2.60 g | 11.82 ± 2.60 g | 78.32 | 176.20 ± 13.89 i | 19.31 ± 2.99 h | 195.50 |
| LES 154 | 72.17 ± 2.24 i | 12.61 ± 1.59 i | 84.78 | 60.57 ± 3.38 g | 9.50 ± 1.85 g | 70.06 | 193.30 ± 9.04 i | 16.91 ± 4.39 h | 210.20 |
| LES 18 | 63.97 ± 2.65 i | 15.28 ± 2.66 i | 79.25 | 59.51 ± 5.23 g | 12.94 ± 1.70 g | 72.46 | 81.70 ± 6.29 i | 25.50 ± 2.16 h | 107.20 |
| LES 203 | 65.77 ± 3.42 i | 11.73 ± 1.61 i | 77.51 | 56.11 ± 3.91 g | 11.27 ± 1.85 g | 67.38 | 147.20 ± 12.75 i | 22.92 ± 4.88 h | 170.10 |
| LES 254 | 55.55 ± 2.27 i | 9.54 ± 0.89 i | 65.09 | 33.87 ± 1.94 g | 9.27 ± 1.49 g | 43.13 | 134.30 ± 14.72 i | 18.82 ± 6.53 h | 153.10 |

Values are the average of three repetitions. Means (n = 3) ± standard deviation. Different letters within each column mean that the treatments were statistically different ($P \leq 0.05$).

**Table 7.** Pearson's correlation coefficient between yield and content of nutritional and nutraceutical compounds of pigmented sorghum accessions

| | DF | PL | *L** | *C** | *h* | PRO | FIB | N | P | K | PHE F | PHE B | FLA F | FLA B | DPPH F | DPPH B | ABTS F | ABTS B | FRAP F | FRAP B |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GY | -0.36 ** | 0.29 * | 0.23 | -0.16 | 0.30* | 0.01 | -0.09 | -0.25 | 0.17 | 0.16 | -0.25 | -0.32 * | 0.30 * | -0.16 | -0.35 ** | -0.31 | -0.34 * | -0.31 * | -0.25 | -0. 31 * |
| DF | | -0.05 | -0.07 | 0.12 | -0.07 | 0.07 | 0.78** | 0.41 ** | 0.05 | -0.11 | 0.17 | 0.15 | -0.02 | -0.12 | 0.03 | 0.05 | 0.10 | 0.07 | -0.26 | 0.09 |
| PL | | | 0.01 | -0.48 ** | -0.04 | -0.31 * | -0.01 | -0.1 | 0.09 | 0.23 | -0.24 | -0.23 | -0.11 | -0.04 | -0.31 * | -0.35 ** | -0.31 * | -0.31 * | -0.13 | -0.29 * |
| *L** | | | | 0.32 * | 0.87 ** | -0.21 | 0.01 | -0.03 | 0.41 | 0.48 ** | -0.56 ** | -0.61 ** | -0.14 | -0.50 ** | -0.74 ** | -0.79 ** | -0.74 ** | -0.79 ** | -0.31 * | -0.76 ** |
| *C** | | | | | 0.28 ** | 0.08 | 0.16 | 0.27 | 0.11 | 0.16 | 0.15 | 0.16 | -0.07 | -0.04 | 0.12 | 0.06 | 0.12 | 0.03 | 0.06 | 0.06 |
| *h* | | | | | | -0.33 * | 0.06 | -0.06 | 0.29 * | 0.48 ** | -0.53 ** | 0.60 ** | -0.11 | -0.58 ** | -0.71 ** | -0.71 ** | -0.70 ** | -0.72 ** | -0.31 * | -0.69 ** |
| PRO | | | | | | | 0.12 | 0.30 * | -0.09 | -0.45 ** | 0.32 * | 0.31 * | 0.05 | 0.29 * | 0.36 ** | 0.31 * | 0.37 ** | 0.31 * | -0.14 | 0.33 * |
| FIB | | | | | | | | 0.37 ** | -0.14 | -0.15 | 0.09 | 0.03 | 0.01 | 0.06 | -0.07 | -0.06 | -0.01 | -0.06 | -0.03 * | -0.05 |
| N | | | | | | | | | 0.08 | -0.01 | 0.19 | 0.27 * | -0.27 * | 0.10 | 0.17 | 0.14 | 0.19 | 0.14 | -0.17 | 0.16 |
| P | | | | | | | | | | 0.36 ** | -0.10 | 0.12 | 0.16 | 0.16 | -0.19 | -0.24 | -0.18 | -0.19 | -0.31 * | -0.17 |
| K | | | | | | | | | | | -0.28 * | -0.26 * | -0.26 | -0.37 ** | -0.38 ** | -0.40 ** | -0.37** | -0.35** | 0.11 | -0.33 * |
| PHE F | | | | | | | | | | | | 0.85 * | 0.08 | 0.69 ** | 0.83 ** | 0.76 ** | 0.84 ** | 0.79 ** | 0.11 | 0.81 ** |
| PHE B | | | | | | | | | | | | | 0.04 | 0.76 ** | 0.94 ** | 0.85 ** | 0.94 ** | 0.87 ** | 0.15 | 0.90 ** |
| FLA F | | | | | | | | | | | | | | 0.25 | 0.11 | 0.15 | 0.13 | 0.16 | -0.07 | 0.14 |
| FLA B | | | | | | | | | | | | | | | 0.76 * | 0.65 ** | 0.77 ** | 0.69 ** | -0.07 | 0.71 ** |
| DPPH F | | | | | | | | | | | | | | | | 0.95 ** | 0.99** | 0.96 ** | 0.30 * | 0.97 ** |
| DPPH B | | | | | | | | | | | | | | | | | 0.96** | 0.99 ** | 0.36 ** | 0.97 ** |
| ABTS F | | | | | | | | | | | | | | | | | | 0.97 ** | 0.29 * | 0.97 ** |
| ABTS B | | | | | | | | | | | | | | | | | | | 0.37 ** | 0.99 ** |
| FRAP F | | | | | | | | | | | | | | | | | | | | 0.32 * |

GY = grain yield in grams per plant, DF = days to flowering, PL = panicle length, *L** = luminosity, *C** = chromaticity, *h* = hue angle, PRO = protein, FIB = fiber, N = nitrogen, P = phosphorus, K = potassium, PHE F = free phenols, PHE B = bound phenols, FLA F = free flavonoids, FLA B = bound flavonoids, DPPH F = DPPH free, DPPH B = DPPH bound, ABTS F = ABTS free, ABTS B = ABTS bound, FRAP F = FRAP free, FRAP B = FRAP bound, * Significant ($P \leq 0.05$); ** Highly significant ($P \leq 0.01$).

## Discussion

### *Agronomic parameters*

The determination of agronomic parameters is of utmost importance, since it allows us to understand the relationship that exists between a plant's growth and the final grain yield. In the case of GY, the results of this work are similar to those reported by Jabereldar *et al.* (2017), who reported sorghum grain yields of 25.10 to 61.50 g/plant in sorghum genotypes grown in two seasons. At present, sorghum genetic improvement programs are aimed at the development of genotypes with good yields, in addition to a high concentration of nutritional compounds in the grain (Flores-Naveda *et al.*, 2021). The results for DF differ from those obtained by Galicia-Juárez et al. (2020), who reported early genotypes with a flowering range of 51 to 71 days, and late genotypes with a range of 72 to 79 days. Early cycle sorghums are tolerant of drought and high temperatures, they can also have higher yields compared to late flowering varieties (Menezes *et al.*, 2021), because early maturing sorghums can evade the stress of a late drought through earlier grain filling, as this becomes a limitation for sorghum production worldwide (Wang *et al.*, 2020). However, late sorghums are characterized by reaching a greater length and diameter of the stem and number of internodes, which are used to produce ethanol because of their high content of juice and sugar (Naoura *et al.*, 2020).

The PL values are similar to those obtained by Mengistu et al. (2020), who reported values of 15.70 to 35.70 cm for PL in sorghum genotypes grown in Ethiopia. It has been reported that PL influences crop yield, since shorter panicles have fewer spikelets and grains, affecting the yield (de Souza *et al.*, 2021). For example, Belay and Meresa (2017) when evaluating sorghum genotypes, found that the highest yields were obtained in the genotypes with the highest development in PL. In this study, the accessions with the lowest yield (LES 280 and LES 184) were those with the lowest PL development. In addition, a positive correlation coefficient (0.29) was found between GY and PL (Table 7), which confirms that the greater the panicle length, the greater the grain yield, which, according to Mwamahonje et al. (2021) is closely related to genotypes that are resistant to drought. The EL results of the evaluated sorghum accessions are similar to the reported by Wondimu et al. (2020), who observed values from 1.00 to 21.00 cm. Having a good development in EL helps the grains to remain outside the flag leaf, reducing the damage by pests and diseases in the lower part of the panicle (Martínez *et al.*, 2016). The results for PH are similar to those reported by dos Santos et al. (2018), who reported plant heights for different sorghum genotypes in a range of 87.50 to 142.50 cm. The PH values obtained in this study are in an acceptable range, since plants with lower height are associated with greater stem resistance, being less susceptible to lodging (Batista *et al.*, 2019). Sorghums with a PH in a range of 98.33 to 136.63 cm are destined for grain production, and from 228 to 233 cm for forage (Li *et al.*, 2015; Guimarães *et al.*, 2019).

### *Grain colour*

Colour variations in sorghum grains help classify them for the food product for which they will be destined. The results for grain colour ($L^*$) were similar to those reported by de Oliveira et al. (2017), who reported $L^*$values in a range from 23.40 to 52.30 in pigmented sorghum genotypes. $L^*$values may decrease due to the anthocyanin concentration in the grain (Dia *et al.*, 2016), since it is a characteristic that is closely related to the concentration of polyphenolic compounds in the external structures (pericarp and aleurone layer) of sorghum grain (Xiong *et al.*, 2019). The colour saturation ($C^*$) of the samples had low values ranging from 5.65 to 15.33 and are in the gray area of the circle of shades (Flores-Naveda *et al.*, 2021). The $C^*$results differ from those reported by Afify *et al.* (2015), who reported values from 24.27 to 27.79 in sorghum varieties that were chosen for their high production in Egyptian areas. Likewise, the $L^*$ values reported by these authors differ from those found in this study, since they are in a range from 62.27 to 63.53, these results indicate that the evaluated accessions are darker than those reported in the literature. Determining grain color is important because the information obtained helps to anticipate the color quality of the final product (Galassi *et al.*, 2019). According to the *h* results, the color of the sorghum grain has a red-yellow tendency, a hue that is associated with a h value of 90 degrees in the circle of shades (Rodríguez-Salinas *et al.*, 2020). Sorghum with white grain (greater luminosity) is commonly used in the kitchen, while sorghum with pigmented pericarp (red and brown grain) with a higher content of bioactive compounds, such as polyphenolic compounds, are used to produce functional beverages (Punia *et al.*, 2021).

*Chemical composition*

For cereals intended for human consumption, such as sorghum grains, it is of utmost importance to determine the concentration of chemical compounds that are part of the grain. The protein values obtained in this study are similar to the average concentrations of 10.15% to 16.57% in sorghum varieties (Itagi and Hemalatha, 2017). The protein content is important because it defines the quality of the grain in terms of digestibility and nutritional value (Kimani *et al.*, 2020). For fiber, similar results were found to those obtained by Kaufman *et al.* (2018), who reported a fiber content that ranged between 1.60% and 2.00%. However, Mohapatra *et al.* (2019) observed that the average fiber content in sorghum is 2.76%. The ash values were similar to the average content (1.42%) reported by Isticioaia *et al.* (2018). However, the genetic variability of sorghum accessions is a factor that influences the chemical composition of the grain (Espitia-Hernández *et al.*, 2020). Fat results were similar to those reported by Rhodes *et al.* (2017) and Abah *et al.* (2020), who, evaluated the chemical composition of different sorghum genotypes with different origin and found fat values in a range from 1.05% to 4.40%. Humidity results agree with those obtained by Wang *et al.* (2019), who when analyzing sorghum flours, found an average of 10% humidity. According to Gely and Pagano (2017), most of the evaluated accessions have an adequate moisture content to avoid deterioration in storage conditions. The carbohydrate content was found to be similar to the values reported by Ratnavathi and Komala (2016) and Younis *et al.* (2019) who reported mean values from 71.30% to 77.28%. The concentration of carbohydrates in staple cereals is of utmost importance, as they provide the majority of the daily caloric intake in the human diet (Bird and Regina, 2018).

*Macroelements*

Cereals are considered an important source of minerals for the human diet, and the germ is the part that contains the highest concentration. The results obtained for Mg exceed the values reported by Elnasikh *et al.* (2020), who reported concentrations between 41.50 to 68.10 mg/100 g when evaluating sweet sorghum genotypes. Sorghum is considered a very important cereal, since it is one of the foods that provides the highest Mg in human intake (Rosanoff and Kumssa, 2020). Ca values are below those reported by Keyata et al. (2021) and Mohapatra *et al.* (2021), who found a Ca concentration in a range of 34.02 to 122.00 mg/100 g when evaluating the essential minerals in sorghum grain. Ca deficiency in the human diet is related to delays in growth, cognitive impairment and loss of bone mass (Rebellato *et al.*, 2020).

Phosphorus results are lower when compared with those obtained by Patekar *et al.* (2017) and Tasie and Gebreyes (2020), who found P concentrations in a range of 367.96 to 515.00 mg/100 g in different sorghum genotypes. Nitrogen values are similar to those reported by Appiah-Nkansah *et al.* (2018), who reported average values of 2.09% in sorghum grain samples. There is a negative correlation (-0.25) between N and GY (Table 7), which may be due to an excessive concentration of nitrogen in the soil that generates acidification and physiological disorders in the plant, like decreasing $CO_2$ assimilation and biosynthesis of photosynthetic pigments, since this mineral is required at optimal levels for the activation of soluble proteins and thylakoids responsible for photosynthesis, thus reducing growth and crop yield (Makino and Ueno, 2018). In sorghum grains, K is the most abundant mineral, concentrations ranging from 278.50 to 1,283.20 mg/100 g have been reported in local Turkish sorghum varieties (Kaplan, 2019). However, the difference in mineral concentration is determined by the influence of the genetic constitution, as well as by the environment and the interaction between both (Paiva *et al.*, 2017).

*Total phenols and total flavonoids*

Phenolic compounds are a large group of chemical substances that are secondary metabolites of plants and one of the biological properties of these compounds is their high antioxidant activity. The concentration of total phenols was similar to the reported by Shen *et al.* (2018) and Farida *et al.* (2020), who reported values of 174.40 to 3,214.46 mg GAE/100 g when evaluating the phenolic composition of the sorghum grain. Phenols are important because of their antibacterial, anticancer, and anti-inflammatory properties (Shahidi and Ambigaipalan, 2015; Ghimire *et al.*, 2021). The negative correlation coefficient (-0.32) between GY and bound phenols (Table 7) indicates that sorghum grains with a higher content of bound phenolic compounds had a lower yield, although the concentration of phenolic compounds in the grains increases in the antioxidant properties but can also negatively affect the absorption of essential nutrients (Fe, Mn and P) in the plant tissues, limiting the development of important physiological processes, and therefore reducing yield (Mohamed *et al.*, 2016; Kazemi *et al.*, 2021).

The values obtained for total flavonoids are higher than those reported by Khoddami *et al.* (2017), who found an average value of 124.00 mg CE/100 g when studying classes of phenols and anthocyanins in sorghum grain, but it coincides with the average values (490 mg CE/100 g) reported by Lyu *et al.* (2019). In sorghum with black and brown pericarp, the proportion of flavonoids is approximately 80%, while sorghum with red and white pericarp, the proportion of free flavonoids is 26-41% (Wu *et al.*, 2017), which is important since flavonoids have a great physiological, pharmacological, and health benefits (Eggleston *et al.*, 2020).

*Antioxidant capacity*

Phenolic compounds in cereals help to protect lipids from the cell membrane against reactive oxygen species, suggesting their use as antioxidants. The results of antioxidant capacity in ABTS are higher than those reported by Hou *et al.* (2016), who when evaluating the antioxidant capacity in sorghum genotypes, found values of 582.70 μmol TE/100 g, but similar to the average value (3,579.69 μmol TE/100 g) reported for pigmented sorghum genotypes (Flores-Naveda *et al.*, 2021). In this study, the antioxidant activity was higher in free phenol extracts than in bound phenol extracts. Some authors report that in sorghum grains the highest proportion of total phenolics correspond to the free form (Shen *et al.*, 2018). Table 7 shows a negative correlation between GY and antioxidant capacity, which shows that the accessions with the highest antioxidant capacity are those with the lowest performance. Consequently, it can be concluded that the content of antioxidant capacity is not related to a high crop yield (Martínez *et al.*, 2017).

The antioxidant capacity by DPPH agrees with the results reported by Ortiz-Cruz *et al.* (2020), who reported values in a range from 913 to 1,591 μmol TE/100 g for DPPH. There are different foods (pasta and chinese bread) to which whole sorghum flour has been incorporated to improve their antioxidant capacity (Khan *et al.*, 2015; Wu *et al.*, 2018). The concentration of phenolic compounds is related to a greater antioxidant capacity, which inhibits or delays the oxidation of a substrate in a chain reaction that is important to prevent various physiological and pathological abnormalities such as inflammation, cardiovascular diseases and cancer (Van Hung, 2016).

FRAP results were similar to those reported by López-Contreras *et al.* (2015), who reported an average antioxidant capacity of 1,693.20 μmol TE/100 g when evaluating the antioxidant properties of Sorghum bicolor genotypes cultivated in Nuevo León, Mexico. The concentration of polyphenols shows a high correlation with the antioxidant activity (Table 7) (Punia *et al.*, 2021). Therefore, accessions with high antioxidant capacity can be used in breeding programs to develop genotypes that can be used to process functional foods derived from sorghum (Aruna *et al.*, 2019).

## Conclusions

The results of this work help to identify the most precocious sorghum accessions with the highest panicle length and yield. Sorghum accessions with darker grain color had lower values in color parameters ($L^*$, $C^*$and *h*), and a negative correlation was found between the chromatic parameters, the concentration of phenolic compounds and the antioxidant capacity. The chemical and mineral composition analyzes confirm that there is a wide variability between sorghum accessions, which shows the genetic diversity of the evaluated materials in relation to the concentration of protein, carbohydrates, Mg, Ca, P and K. The content of total phenols and total flavonoids varied among sorghum accessions; however, the highest concentrations were detected in sorghums with lower yields and dark grain color (negative correlation). The antioxidant activity was detected in free and bound extracts; however, the highest activity was presented in free extracts in the ABTS, DPPH and FRAP tests, and it was positively correlated with the content of phenolic compounds.

## Authors' Contributions

Conceptualization: J.I.G.-L and A.F.-N; Data curation: J.I.G.-L, S.U.-F and N.R.-T; Funding acquisition: J.I.G.-L and A.F.-N; Investigation; S.U.-F, J.I.G.-L and A.F.-N; Methodology: J.I.G.-L, A.F.-N, S.R.-B and A.H.-J; Project administration: J.I.G.-L and A.F.-N; Supervision: J.I.G.-L and A.F.-N; Writing - original draft: J.I.G.-L and S.U.-F; Review and editing: J.I.G.-L, J.C.T.-A and A.L.-R. All authors read and approved the final manuscript.

## Ethical approval (for researches involving animals or humans)

Not applicable.

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## Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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