RESEARCH ARTICLE

SABRAO Journal of Breeding and Genetics
56 (4) 1563-1573, 2024
http://doi.org/10.54910/sabrao2024.56.4.22
http://sabraojournal.org/
pISSN 1029-7073; eISSN 2224-8978

AGRONOMIC VARIABILITY OF SORGHUM (*SORGHUM BICOLOR*) GENOTYPES WITH DIFFERENT LIGNIN CONTENT ASSESSED FOR BIOMATERIAL PURPOSES

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SUMMARY

Sorghum (*Sorghum bicolor* L.) is a crop for potential development and cultivation in Indonesia because of its high tolerance for planting on marginal lands. The sorghum plant can serve as food, feed, bioenergy, and renewable materials. Sorghum exhibits numerous phenotypes; therefore, it is crucial to determine their suitability for various purposes. The ideotype of sorghum genotypes for biomaterial purposes is a recognized genotype with high lignin content and biomass. The Indonesian Agency for Research and Innovation has identified sorghum landraces with different lignin content in their germplasm. The agronomic parameters evaluation of these genotypes determined their biomaterial suitability purposes. The presented study showed that sorghum genotypes with different lignin content levels have variable biomass (plant height, stem diameter, leaf weight, and stem weight) and yield (panicle weight, length, and hundred-seed weight) attributing traits. The enhanced stem weight is the main contributor to total biomass in these sorghum genotypes. Stem weight positively correlated to a high lignin content and considerable broad sense heritability estimates. Therefore, these traits can become selection criteria for choosing sorghum genotypes for biomaterial purposes. The sorghum genotypes KS and G181 showed ideotype suitability for biomaterials.

Keywords: Sorghum (*Sorghum bicolor* L.), biomass, character, heritability, selection, yield

Communicating Editor: Dr. Quaid Hussain

Manuscript received: November 16, 2023; Accepted: April 18, 2024.

Citation: Astuti D, Widyajayantie D, Wiyono S, Hidayat SH, Nugroho S, Trikoesoemaningtyas (2024). Agronomic variability of sorghum (*Sorghum bicolor*) genotypes with different lignin content assessed for biomaterial purposes. *SABRAO J. Breed. Genet.* 56(4): 1563-1573. http://doi.org/10.54910/sabrao2024.56.4.22.

Key findings: The high lignin content with biomass is the ideotype of sorghum (*Sorghum bicolor* L.) genotypes for biomaterial purposes. Stem weight can be beneficial as a selection criterion for considering sorghum genotypes for biomaterial purposes. The sorghum genotype 'KS' showed ideotype suitability for particle board manufacturing, while the genotype G181 revealed an ideotype for biopellets.

INTRODUCTION

Sorghum (*Sorghum bicolor* [L.] Moench) is the fifth most valuable and potential cereal crop after rice, wheat, corn, and barley worldwide (Gladman *et al.*, 2019). According to FAO global data, since 2022, the top three countries producing the most sorghum are the United States, Sudan, and Nigeria. Globally, sorghum is mostly for animal feed, fodder, and high-value products, such as syrup and bioethanol. It is also a highly productive crop in environmental conditions restricting the cultivation of other cereals. Sorghum is a multipurpose crop that produces grainsand converts biomass into bioenergy and biomaterial.

Sorghum is a known producer of massive biomass, serving as feed and energy, such as biopellet and bioethanol. This plant can be a potential raw material for renewable energy because of its abundance, fast growth, and being inexpensive. Sorghum has several advantages compared with other biomass-producing crops that produce grain used as food, forage as animal feed, and biomass for bioenergy and biomaterial production, referring to it as a biomass crop because of producing a vast biomass amount at a lower cost than other crops due to a short growing season, mechanized management, and high adaptability. Sorghum growing can occur in dry and waterlogged conditions and produce better on nutrient-poor soil. With its high tolerance for planting on marginal lands and broad adaptation in arid areas and weather stress, sorghum has the potential to develop more and grow in Indonesia.

The sorghum utilization for biomaterials required both high biomass and high lignin content. However, investigating the lignin content in sorghum has not progressed and needs further exploration. Lignin is one of the primary components and vital parts of plant cell walls, essential for plant growth and environmental adaptation. Sorghum with high lignin content has several potentials, including fiber-making ingredients. Additionally, the high lignin has correlated positively with high biomass production (Koshiba *et al.*, 2017). Therefore, it is a prospective raw material for making biomaterials, such as biopellets and particle boards, to minimize the use of wood.

Biomass, as a renewable energy source, has drawn a lot of attention because biomass has a relatively high energy content that is abundant in nature. One of the many benefits of using biomass energy sources is the renewability of these sustainable energy sources. Biopellet is one type of bioenergy produced from sorghum biomass. The high lignin content in sorghum is the main factor functioning as a natural adhesive in manufacturing biomass briquetting and pellets, which results in a relatively high calorific value (more than 6.100 kcal/kg) (Wiloso *et al*., 2020). In addition to making biopellets, past studies showed successful particle board production from sorghum biomass, and its cultivation can yield better biomass of around 20–30 t/ha in three months, depending on the variety (Khazaeian *et al.,* 2015). Sorghum bagasse still has sufficient lignin content and can benefit as a natural fiber source and a raw material to make boards instead of wood particles. A high lignin content in sorghum and high biomass is necessary for biomaterial applications. The plant composition also depends upon the plant taxa, tissue type, developmental stage, and environmental factors (Hoch *et al*., 2021). Hence, biomass values also differ among the sorghum genotypes, which are genetically determined.

Sorghum displays a wide range of phenotypes, with an unknown genotype that is best for the target purpose (Yang *et al*., 2021). Therefore, using lignin found in sorghum is crucial to know the genotype agronomic characteristics. Goswami *et al.* (2020) also pointed out that grown sorghum varies a lot, and raising sorghum productivity requires knowing the type and extent of genetic variability in germplasm collections. Additionally, such analysis is also necessary to determine sorghum genotypes with the highest biomass and lignin content needed to be used as an economically and ecologically viable biomaterial.

The presented study evaluated the nine sorghum genotypes with known total lignin content. The latest research also aimed to determine the information on sorghum germplasm suitable for cultivation and use as biomaterial, appropriate for breeding, and genetically modifying the development of sorghum as a biomaterial. These research results can be applicable to optimize sorghum biomass as a biomaterial product through breeding. Therefore, breeders can utilize the information for selecting existing sorghum genotypes for cultivation and parental lines for breeding leading to improved sorghum yield with high lignin content and biomass.

MATERIALS AND METHODS

Plant material and experimental site

In this study, the genetic material comprised nine sorghum (*Sorghum bicolor* L.) genotypes with known lignin contents procured from the Research Center for Genetic Engineering, Agency for Research and Innovation (BRIN) (Wahyuni *et al.*, 2019). Categorizing the sorghum genotypes revealed high- (Konawe Selatan/KS, 4183A and Sorgum Malai Mekar/SMM), medium- (Super-1, Kawali, and 181.73.1.1), and low-containing (Jagung Rote, JP, and Pahat) lignin content. The sorghum research commenced at the Dramaga, Bogor Regency, West Java Province, Indonesia, which is 215.7 masl (6° 35′ 07″ S, 106° 45′ 11″).

Experimental design and cultural practices

Conducting the sorghum experiment employed a randomized complete block design (RCBD) with three replications. The block size was 5 m × 6 m, with 2 m between the blocks containing nine genotypes each. The planting distances were 75 cm × 25 cm using 20 plants per genotype. Planting began from October 2021 until March 2022. Fertilizer applications ensued twice, two weeks after planting (80 kg/ha NPK) and eight weeks after planting (160 kg/ha Urea). A weeding activity in the sixth week after planting continued at a three-week interval to prevent it from interfering with plant growth and observation activities.

Observations on agronomic traits

The recorded observations on seven different agronomic traits included plant height (cm), stem diameter (cm), leaf weight (g), stem weight (g), panicle weight (g), panicle length (cm), and hundred seeds weight (g). The scrutiny continued on 10 randomly selected plants in each genotype and replication using the appropriate procedure. Plant height (PH) measurement occurred at the fruit ripening stage (the generative phase) from the soil surface (base of the plant) to the top of the panicle (highest point attained at a natural position above the soil level). For stem diameter (SD) measurement, the study used a digital caliper at the third internode (from the bottom). Leaf weight (LW) measuring ensued postharvest, assuming no leaves had fallen. Stem weight (SW) acquisition was by weighing the stems immediately after harvest. Panicle weight (PW) had all the weight of panicles measured immediately after harvest. Panicle length (PL) measurement began from the bottom of the neck to the tip of the panicle. Hundred seed weight (HSW) included weighing 100 dried seeds of the sorghum genotypes.

Statistical analysis

Using Microsoft Excel Office 2019 helped compile and tabulate all the recorded data. The analysis of variance (ANOVA) ran the SAS version 9.4. The association between the lignin content and the related agronomic traits reached assessment using simple Pearson’s correlation analysis post hoc test at $p < 0.05$, by an online tool Metabo Analyst 5.0 (https://www.metaboanalyst.ca). Computing estimates of genotypic and phenotypic variances depended on the partition of variances of expected mean squares from the analysis of variance. The genetic variability and the genotypic coefficient of variation (GCV) also received calculations. Broad sense heritability (h^2_{bs}) formulation comprised the genotypic to the phenotypic variance ratio.

RESULTS AND DISCUSSION

The sorghum genotypes with different origins were specimens in the study, and these collections comprised national varieties, landraces from the Eastern part of Indonesia, breeding lines, and germplasm of the National Agency for Research and Innovation (BRIN), Indonesia (Table 1). Selecting these nine sorghum genotypes was due to varied levels of lignin content ranging from 14.4% to 22.9%. The genotypes with high lignin content will serve for biomaterial development. Grossman and Vermeris (2019) stated numerous prospects for using lignin-based plant biomass, i.e., pellets, boards, and adhesive raw materials (Jamaluddin *et al.*, 2018; Wiloso *et al.*, 2020).

Several studies emerged on lignin modification in sorghum genotypes for producing lignin-based plant biomass, employing a transgenic technique (Umezawa, 2018). The transgenic strategy was a means to enhance the lignin content in sorghum genotypes for plant raw material enhancement. The other approach to obtaining sorghum with high-lignin content for biomaterial production is by conducting the selection of existing genotypes (either local or introduction). Information on the agronomic performance of these genotypes is necessary to develop into a commercial variety.

Previous studies reported no significant differences among the sorghum genotypes for the composition of chemical compounds that are vital in making particle board; however, three sorghum genotypes, i.e., 4183, Super-1, and Pahat, varied in their total biomass (Jajang *et al.,* 2022). The study also reported that the synthesis of biomaterials requires a significantly large biomass. Besides high lignin content, the sorghum genotype with high biomass also qualifies for biomaterials. In the sorghum growth phase, the highest biomass is at the end of the generative phase because growth stops after that phase, and the highest lignin content is also in the same phase, with lignin accumulated constitutively during the growth period (Lee *et al*., 2019). The different quantitative traits, i.e., plant height, stem diameter, leaf weight, stem weight, panicle length and weight, and hundred-seed weight, all appeared connected with biomass.

Analysis of variance for agronomic characteristics revealed significant differences among the sorghum genotypes for plant height, stem diameter, stem weight, panicle length, and seed weight (Table 2). This variability in agronomic traits showed a considerable genetic variability in the nine sorghum genotypes. The available genetic variability of these genotypes enables the breeders to select sorghum genotype that suits various purposes, such as food, feed, and

Table 1. Origin and lignin content of sorghum genotypes.

Genotypes	Origin	Lignin content (%)
KS	N/A (collection of BRIN)	22.9
G4183	breeding lines	20.5
SMM	Landraces	19.7
Kawali	National variety (2001)	18.4
Super1	National variety (2013)	18.4
G181.73.1.1	Breeding lines	18.0
Jagung Rote	Landraces	16.5
JP	N/A (Collection of BRIN)	14.6
Pahat	National variety	14.4

N/A: data not available.

Table 2. Analysis of variance for agronomic characteristics in sorghum genotypes.

Characteristics	MS genotipe	MS error	Pr > F genotype	F value genotype	CV (%)
Plant height	7792.67	335.411	0.0129*	23.23	6.2972
Stem diameter	7.09470	1.9620	0.0154*	3.62	7.0370
Leaf weight	67.1731	43.5383	0.3914	1.54	16.1147
Stem weight	23050.3	1239.28	0.0177*	18.60	10.2358
Panicle weight	0.00788	0.0176	0.8277	0.45	7.2032
Panicle length	30.2113	2.9958	0.0420*	10.08	6.1252
Hundred seed weight	0.59687	0.0029	0.0005**	205.69	1.6725

Note: *Significant at 5%; **Significant at 1%.

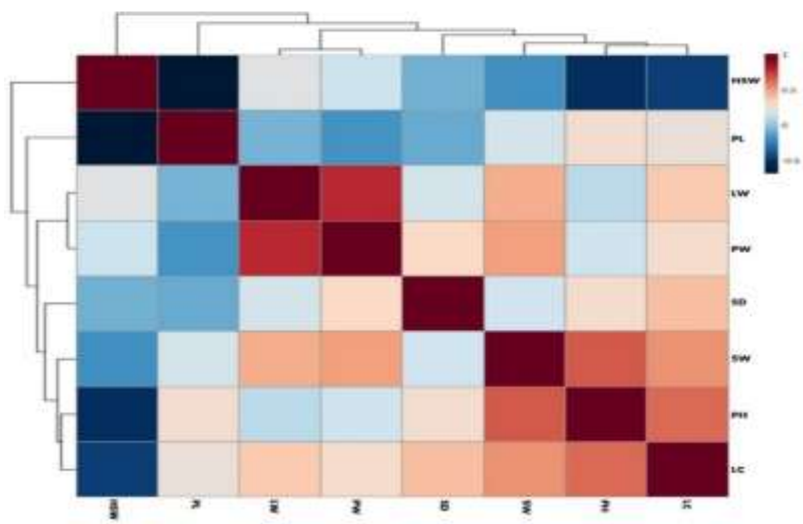

Figure 1. Correlation between agronomic characteristics and biomass and lignin contents.
LC: lignin content; PH: plant height; SW: stem weight; SD: stem diameter; PW: panicle weight; LW: leaf weight; PL: panicle length; HSW: 100-seed weight.

biomaterial. The analysis of variance for agronomic features also indicated a difference among the genotypes for stem weight, which plays a vital role in better biomass production. These results are often helpful in selecting sorghum genotypes for biomaterial because stem weight is the main trait associated with biomass.

Correlation analysis of agronomic characteristics and lignin content exhibited that hundred-seed weight appeared significantly associated with the lignin content (Figure 1). Chen *et al.* (2013) also mentioned that lignin content negatively affects the seed weight in *Arabidopsis* and *Cactaceae* plants, which supports the latest results in the sorghum genotypes. Hussain *et al.* (2019) explained that shade reduces the lignin content and seed production in soybean genotypes. The study also showed aside from environmental influences, plant species and genotypes influence lignin content and seed production. The study revealed that the lignin content had a substantial negative correlation with the hundred-seed weight. The negative correlation suggested that the seed production decreases as and when the lignin content increases. Through various mechanisms, lignin metabolism significantly influences plant growth and development (Bonawitz *et al.*, 2014.)

For biomaterial production requiring high biomass (final stage of the growth period), yield components (panicle weight, panicle length, and hundred-seed weight) are not under consideration (Table 3). Yield

Table 3. Yield components of sorghum genotypes differing in lignin content.

Genotypes	Panicle weight (g)	Panicle length (cm)	100-seed weight (g)	Harvest Index
KS	65.83[a]	38.08[a]	2.51[f]	0.11
G4183	84.67[a]	25.65[cd]	3.25[e]	0.17
SMM	67.50[a]	28.73[bc]	2.10[g]	0.14
Kawali	87.33[a]	25.93[cd]	3.67[bc]	0.21
Super1	62.33[a]	27.37[cd]	3.30[de]	0.14
G181	80.67[a]	19.90[e]	4.62[a]	0.14
Jagung Rote	71.67[a]	26.57[cd]	3.49[cd]	0.19
JP	83.33[a]	25.45[d]	3.72[b]	0.16
Pahat	47.17[a]	30.50[b]	3.73[b]	0.25

*Means followed by the same letters are not significantly different in Duncan's Multiple Range Test (α = 5%), Harvest index = panicle weight/total biomass.

components become a consideration for sorghum development for food and feed, and for this purpose, the high-yield component with low-lignin content is more suitable. A yield-component comparison analysis among the sorghum genotypes with differing lignin contents ensued. The results showed no significant differences among the nine genotypes for panicle weight, widely ranging from 47.17 (Pahat) to 87.33 (Kawali). The wide range with nonsignificant means indicated higher variability among and within genotypes. The findings of Abraha *et al.* (2015) revealed that landraces and breeding lines have huge morpho-agronomical variations. It also showed variability in the trait of hundred-seed weights, while the genotype G181 was significantly greater than other sorghum genotypes, i.e., JP and Pahat.The sorghum genotypes with promising yield-contributing qualities and the highest grain yield are essential for food.

The harvest index is a good indicator of how the plant partition assimilates, and past studies mentioned the positive correlation between the economic yield, biological yield, and harvest index (Tariq *et al.*, 2007). Harvest index is a panicle weight value from the total biomass. This research revealed that the harvest index indicated highly significant differences among the genotypes. The sorghum genotype Pahat is more suitable for food purposes than the genotypes JP and 181 because Pahat has a lower lignin content and the highest harvest index (0.248). The sorghum genotypes with low harvest index, indicating high biomass in stem and leaves, are more appropriate for biomaterial combined with high lignin content. The sorghum genotypes KS, 4183, and SMM owned the low harvest index, and these genotypes are better options as a source for biomaterials due to high lignin content.

In the presented study, the high biomass, represented by stem weight, is vital for biomaterial production. The sorghum genotypes differing with lignin content showed the genotypes with high lignin content (KS, G4183, and SMM), medium-high lignin content (Kawali, Super1, and G181), and low lignin content (Jagung Rote, JP, and Pahat), confirmed the greater diversity among the genotypes for plant height (Table 4). The evaluated sorghum genotypes showed different plant architectures, and this variability can aid in selecting genotypes suitable for biomaterial purposes. The results revealed that genotypes KS and G4183 were significantly taller than the national varieties and landraces. According to UPOV (2014), sorghum plants classification ranked as very short (<76 cm), short (76–150 cm), medium (151–225 cm), tall (226–300 cm), and very tall (>300 cm). In this classification, genotype Pahat belonged to the short sorghum and genotype Kawali in the medium group. The sorghum characteristics used for biomaterial production bore classification, and genotypes with a plant height between 3.5 and six meters with high lignocellulosic biomass are the chief properties for producing biomaterials, including fiber, particleboard, and bioparticles (Silva *et al.*, 2022). Based on such criteria, sorghum genotype KS, with the highest plant height, superior lignin content, and highest biomass

Table 4. Agronomic characteristics and biomass of sorghum genotypes differing in lignin content.

Genotypes	Plant height (cm)	Stem diameter (mm)	Leaf weight (g)	Stem weight (g)	Total biomass (g)
KS	384.17[a]	22.65[a]	46.50[bcd]	509.67[a] (81.94)**	622.00
G4183	346.43[b]	21.68[ab]	48.67[abc]	357.33[c] (72.83)	490.67
SMM	301.57[c]	20.54[abcd]	35.17[cde]	365.67[c] (78.08)	468.34
Kawali	178.57[e]	18.32[cd]	61.33[a]	266.00[d] (64.15)	414.66
Super1	304.80[c]	19.32[bcd]	33.20[de]	342.00[cd] (78.17)	437.53
G181	260.23[d]	18.98[bcd]	51.83[ab]	449.83[ab] (77.25)	582.33
Jagung Rote	312.53[c]	18.33[cd]	42.83[bcde]	262.83[d] (69.66)	377.33
JP	241.80[d]	20.78[abc]	37.67[bcde]	393.33[bc] (76.47)	514.33
Pahat	128.97[f]	17.86[d]	29.60[e]	114.17[e] (59.79)	190.94

* Means followed by the same letters are not significantly different in Duncan's Multiple Range Test (α = 5%).
** Percent to total biomass weight.

value, was the most appropriate genotype as a source of raw material in biomaterial production.

The sorghum stems are better for particleboard use; hence, stem weight features are the characteristics considered in this study. The stem diameter classification of the sorghum plant rankings is small (<2cm), medium (2–4 cm), and large (>4 cm) (UPOV, 2014). This study had all the evaluated sorghum genotypes belonging to the small to medium stem diameter. The stem weight of these genotypes determines the total biomass. Two sorghum genotypes (KS and G181) were notable, with the highest stem weight and total biomass, but have different levels of lignin content. However, the two genotypes were different in plant architecture, and in that category, the genotype G181 shorter than KS (Table 4). In the high-lignin group, genotype KS was evident with the maximum lignin and recommended as a biomass source for board and paper production. However, the genotype SMM was also suitable for the number of percent to total biomass. The genotype G181 was preferable over KS because KS has the maximum plant height with a medium stem diameter prone to lodging. According to its origin, genotype G181 was an option over KS for cultivation because it is a commonly used breeding line. Genotype G181 has medium lignin content with high biomass; thus, this genotype was appropriate for providing the source material for biopellets.

The genotypic coefficient of variation (GCV) compares the genetic variation of various quantitative traits (Mustakim *et al.*, 2019). Bekele *et al.* (2013) categorized the GCV into three groups, i.e., high (if the GCV is greater than 20%), moderate (if the GCV is between 10% and 20%), and low (if the GCV is less than 10%). High GCV values can be effective for quick selection and obtaining promising genotypes because GCV indicates the availability of genetic variability for selection. In the relevant study, GCV values ranged from 3.1% to 24.8% (Table 5). The results revealed a high genotypic coefficient of variation for stem weight (24.8%). The trait stem weight can be best for sorghum genotype selection and useful for particleboards. Based on this analysis, the stem weight obtained similar results from the heritability analysis, as discussed below.

Heritability measures how much a plant genotype's genetic makeup affects the phenotypic variance and the ability of the parental genotype to transmit agronomic characteristics to its progeny (Mustakim *et al.*, 2019). Examining the broad sense heritability values helps determine the most suited characteristic in the selection in addition to the GCV values (Kishore *et al*., 2015). Past studies also reported the effectiveness of selection for any trait depends on the degree of genetic variability and the ease with which it is transferred from one generation to the next (Mangshin *et al*., 2023). Therefore, heritability

Table 5. Estimates of genetypic variance and broad sense heritability values for various traits in the sorghum genotypes.

Characteristics	Ve	Vg	Vp	h^2_{bs}	GCV (%)
Plant height	111.804	2485.750	2597.560	0.957	17.143
Stem diameter	0.654	1.711	2.365	0.723	6.572
Leaf weight	14.513	7.878	22.391	0.352	6.855
Stem weight	413.094	7270.350	7683.440	0.946	24.792
Panicle weight	0.006	0.003	0.009	0.356	3.089
Panicle length	0.999	9.072	10.070	0.901	10.659
Hundred seed weight	0.001	0.198	0.199	0.995	13.815

Ve: Environment Variation, Vg: Genetic Variation, Vp: Phenotypic Variation, h^2_{bs}: Broad Sense Heritability, GCV: Genotypic coefficient of variation.

values determine how quickly the trait transmits to the next generation. Heritability values also comprised three categories, according to Mustakim *et al.* (2019), viz., heritability values are high (>50%), moderate (20%–50%), and low (<20%).

The heritability estimation showed that the highest heritability in the broad sense (0.99) resulted in hundred-seed weight and the lowest (0.35) for leaf weight. According to the results, plant height (0.96), stem diameter (0.72), stem weight (0.95), panicle length (0.90), and hundred-seed weight (0.99) belonged with the high heritability category, while leaf weight (0.35) and panicle weight (0.36) were with moderate heritability. Castro *et al.* (2015) also recorded higher heritability for plant height in sorghum genotypes. The heritability estimation indicates the presence of a positive response to sorghum improvement through selecting these traits because of their higher heritability (Gebregergs and Mekbib, 2020). The information on agronomic characteristics affecting the biomass in sorghum genotypes was successful through high heritability values, such as plant height (Fernandes *et al.*, 2018). Broad-sense heritability also improves the probability of transmitting an agronomic trait to the next generation under all environmental conditions. In addition, the higher heritability value also indicates that the genetic role increases, rendering a high heritability value beneficial for effective selection in developing superior cultivars (Mustakim *et al.*, 2019).

Heritability and GCV values can be used individually; however, numerous studies combined these values to improve an effective selection further. Elangovan *et al.* (2014) explained that heritability and variability coefficient will increase the estimate value if the heritability value is combined with the GCV value, it will provide more accurate information on selection efficiency. Gebregergs and Mekbib (2020) also mentioned that the high broad sense heritability does not always give a high prediction of genetic gain to ensure effective selection for improvement, but rather a higher heritability with a higher GCV estimate. This suggestion implies that these qualities require support by a greater GCV estimate to benefit selection for sorghum biomass improvement. In light of the present results, high heritability values emerged for the traits, viz., plant height, stem diameter, stem weight, panicle length, and hundred-seed weight. In these five characteristics, the plant height, panicle length, and hundred-seed weight manifested with moderate GCV values, while the stem weight has a high GCV and a high broad-sense heritability (h^2_{bs} = 0.95; GCV = 24.79%).

Characteristics with high heritability and moderate GCV values signify the presence of non-additive gene action, and such qualities (plant height, panicle length, and hundred-seed weight) can be advantageous for heterosis breeding. The traits of leaf and panicle weight with medium heritability and low GCV suggest that these traits have epistatic interactions controlling them (Elangovan et al. 2014). Regarding the lignin content, the sorghum genotypes with the stem weight as selected criteria with high values genotype KS and G181 were superior as sources for biomaterials (Table 4). Genotype KS with high lignin content and biomass was also notable as a source for particleboard production. Sorghum genotype G181 was prominent as a source for biopellets because even though it has high biomass, it only has medium lignin content. Based on the lignin content data in Table 4, genotypes KS and G181 were choices as sources for biomaterials. With their high stem weight, these sorghum genotypes have become choices in the latest study. Based on the high biomass and low lignin content, sorghum genotype KS stands out as a feedstock for particleboard manufacturing. The sorghum genotype G181 was better as a source for biopellets due to its medium lignin content and high biomass. The parameters with high heritability and GCV values indicate that genetic influences control such traits (Mustakim *et al*., 2019; Hassan *et al*., 2022; Munarti *et al*., 2022; Bogapov *et al*., 2024). Mangshin *et al*. (2023) also reported similar findings; and the traits with high heritability and GCV values suggest the presence of additive gene action in these traits, improving the potential for selection.

CONCLUSIONS

The latest study showed that sorghum genotypes with diverse levels of lignin content have variable biomass and yield components. In these sorghum genotypes, the highest stem weight was the main contributor to total biomass. Stem weight correlated to high lignin content and has the highest broad-sense heritability. It is a better selection criterion in sorghum genotypes for biomaterial purposes. The two sorghum genotypes, K2 and G181, showed ideotypes suitable for biomaterials.

ACKNOWLEDGMENTS

The authors thank the Research Organization for Life Sciences and Environment, the National Research and Innovation Agency (BRIN) for funding support of this research by Bottom-Up New Initiative to Dwi Astuti. Thanks also to Wahyuni for the raw data on lignin content analysis.

REFERENCES

Abraha T, Githiri SM, Kasili R, Araia W, Nyende AB (2015). Genetic variation among Sorghum (*Sorghum bicolor* L. Moench) landraces from Eritrea under post-flowering drought stress conditions. *Am. J. Plant Sci*. 6: 1410–1424.

Bekele BD, Rakhi S, Naveen GK, Kundura PJ, Shashidhar H (2013). Estimation of genetic variability and correlation studies for grain Zinc concentrations and yield related traits in selected rice (*Oryza sativa* L.) genotypes. *Asian J. Exp. Biol. Sci*. 4(3): 391–397. https://www.cabdirect.org/cabdirect/abstract/20133302620.

Bogapov I, Memeshov S, Kibalnik O, Sagalbekov U (2024). Sweet sorghum (*Sorghum bicolor* L.) genotypes assessment for food, fodder, and energy values in Northern Kazakhstan. *SABRAO J. Breed. Genet.* 56(1): 156-167. http://doi.org/10.54910/sabrao2024.56.1.14.

Bonawitz ND, Kim JI, Tobimatsu Y, Ciesielski PN, Anderson NA, Ximenes E, Maeda J, Ralph J, Donohoe BS, Ladisch M (2014). Disruption of mediator rescues the stunted growth of a lignin-deficient Arabidopsis mutants. *Nature.* 509: 376–380. https://doi.org/10.1038/nature13084.

Castro FMR, Bruzi AT, Nunes JAR, Parrella RAC, Lombardi GMR, Albuquerque CJB, Lopes M (2015). Agronomic and energetic potential of biomass sorghum genotypes. *Am. J. Plant Sci.* 6: 1862–1873. https://doi.org/10.4236/ajps.2015.611187.

Chen F, Tobimatsu Y, Jackson L, Nakashima J, Ralph J, Dixon RA (2013). Novel seed coat lignins in the Cactaceae: Structure distribution and implications for the evolution of lignin diversity. *The Plant J.* 73: 201–211. https://doi.org/10.1111/tpj.12012.

Elangovan M, Babu PK, Seetharama N, Patil JV (2014). Genetic diversity and heritability characters associated in sweet sorghum [*Sorghum bicolor* (L.) Moench]. *Sugar Tech*. 16(2): 200–210. https://doi.org/10.1007/s12355-013-0262-5.

Fernandes SB, Dias KOG, Ferreira DF, Brown PJ (2018). Efficiency of multi-trait, indirect, and trait-assisted genomic selection for improvement of biomass sorghum. *Theor. Appl. Genet.* 131: 747–755. https://doi.org/10.1007/s00122-017-3033-y.

Gebregergs G, Mekbib F (2020). Estimation of genetic variability, heritability, and genetic advance in advanced lines for grain yield and yield components of sorghum (*Sorghum* *bicolor* [L.] Moench) at Humera, Western Tigray, Ethiopia. *Soil Crop Sci.* 6(1764181): 1–9. https://doi.org/10.1080/23311932.2020.1764181.

Gladman N, Jiao Y, Lee Y, Zhang L, Chopra R, Regulski M, Burow G, Hayes C, Christensen SA, Dampanaboina L, Chen J, Burke J, Ware D, Xin Z (2019). Fertility of pedicellate spikelets in sorghum is controlled by a jasmonic acid regulatory module. *Int. J. Mol. Sci*. 20(19): 1–15. https://doi.org/10.3390/ijms20194951.

Goswami SJ, Patel PT, Gami RA, Patel RN, Khatri AB (2020). Correlation and path analysis study of different characters for grain yield and fodder purpose in sorghum (*Sorghum bicolor* [L.] Moench). *Electr. J. Plant Breed.* 11(4): 1053–1061. https://doi.org/10.37992/2020.1104.171 Vol 11(4):1053-1061.

Grossman A, Vermerris W (2019). Lignin-based polymers and nanomaterials. *Curr. Opin. Biotechnol*. 56: 112–120. https://doi.org/10.1016/j.copbio.2018.10.009.

Hassan AM, Ahmed MF, Rashed MA (2022). Performance and transcriptomic analysis of *Sorghum bicolor* responding to drought stress. *SABRAO J. Breed. Genet*. 54(4): 814-825. http://doi.org/10.54910/sabrao2022.54.4.12.

Hoch K, Koopman B, Tiedemann A (2021). Lignin composition and timing of cell wall lignification are involved in *Brassica napus* resistance to stem rot caused by *Sclerotinia sclerotiorum*. *Phytopathology* 111: 1438–1448. https://doi.org/10.1094/PHYTO-09-20-0425-R.

Hussain S, Iqbal N, Ting P, Khan MN, Wei-Guo L, Wen-yu Y (2019). Weak stem under shade reveals the lignin reduction behavior. *J. Integr. Agric.* 18(3): 496–505. https://doi.org/10.1016/S2095-3119(18)62111-2.

Jajang S, Hadi YS, Nawawi DS, Abdillah IB, Zulfiana D, Lubis MAR, Nugrogo S, Astuti D, Zhao Z, Handayani M, Lisak G, Kusumah SS, Hermawan D (2022). The properties of particleboard composites made from three sorghum accessions using maleic acid adhesive. *Chemosphere* 290: 133–163. doi: 10.3390/polym15010166.

Jamaluddin, Indrayani Y, Munawar SS (2018). Kualitas papan partikel dari campuran batang sorgum (*Sorghum bicolor* L.) dan kayu akasia (*Acasia mangium* W.) berdasarkan konsentrasi perekat urea formaldehida. *J. Hutan Lestari* 6(3): 486–498. http://dx.doi.org/10.26418/jhl.v6i3.26777. (In Indonesian).

Khazaeian A, Ashori A, Dizay MY (2015). Suitability of sorghum stalk fibers for production of particleboard. *J. Carbohydrate Polymers* 120: 15–21.

Kishore NS, Srinivas TU, Nagabhushanam M, Pallavi, Sameera SK (2015). Genetic variability, correlation and path analysis for yield and yield components in promising rice (*Oryza sativa* L.) genotypes. *SAARC J. Agric.* 13(1): 99–108. https://doi.org/10.3329/sja.v13i1.24184.

Koshiba T, Yamamoto N, Tobimatsu Y, Yamamura M, Suzuki S, Hattori T, Mulai M, Noda S, Shibata D, Sakamoto M, Umezawa T (2017). MYB-mediated upregulation of lignin biosynthesis in *Oryza sativa* towards biomass refinery. *Plant Biotechnol*. 34(1): 7–15. https://doi.org/10.5511/plantbiotechnology.16.1201a.

Mangshin GB, Gangashetty P, Mohammed R, Buba UM, Andrea D (2023). Genetic variability, heritability and genetic advance in sorghum (*Sorghum bicolor* [L.] Moench) accessions from West and Central Africa. *Dutse J. Pure Appl. Sci.* 7(2): 1–14. https://doi.org/10.13140/RG.2.2.25823.53927.

Munarti, Wirnas D, Trikoesoemaningtyas, Sobir, Syukur M, Sopandie D (2022). Stay green genes fragment homology analysis of Indonesian sorghum. *SABRAO J. Breed. Genet.* 54(4): 742-754. http://doi.org/10.54910/sabrao2022.54.4.6.

Mustakim, Samuddin S, Maemunah (2019). Genetic diversity, heritability and correlation between local cultivars of upland rice. *The Agric. Sci. J.* 6(1): 20–26.

Silva TN, Thomas JB, Dahlberg J, Rhee SY, Mortimer JC (2022). Progress and challenges in sorghum biotechnology, a multipurpose feedstock for the bieconomy. J. Exp. Bot. 73(3): 646–664.

Tariq M, Awan SI, Irsyad-Ul-Haq M (2007). Genetic variability and character association for harvest index in sorghum under rainfed conditions. *Int. J. Agric. Biol*. 9(3): 470–472.

Umezawa T (2018). Lignin modification in plants for valorization. *Phytochem. Rev.* 17: 1305–1327. https://doi.org/10.1007/s11101-017-9545-x.

UPOV (2014). Guidelines for the conduct of tests for distinctness, uniformity and stability: Sorghum. International Union for the Protection of New Varieties of Plants, Geneva. http://www.upov.int/edocs/tgdocs/en/tg122/4.pdf.

Wahyuni Y, Rachmat A, Miyamoto T, Hartati H, Widjayantie W, Windiastri VE, Sulistyowati Y, Hartati NS, Ragamustari SK, Tobimatsu Y, Nugroho S, Umezawa T (2019). Variation in lignocellulose characteristics of 30 Indonesian sorghum (*Sorghum bicolor*) accessions. *Ind. Crops Prod.* 142(111840): 1–10. https://doi.org/10.1016/j.indcrop.2019.111840.

Wiloso EI, Setiawan AAR, Prasetia HM, Wiloso ARS, Sudiana IM, Lestari R, Nugroho S, Hermawan D, Fang K, Heijungs R (2020). Production of sorghum pellets for electricity generation in Indonesia: A life cycle assessment. *Biofuel Res. J.* 7(3): 1178–1194. https://doi.org/10.18331/BRJ2020.7.3.2.

Yang M, Dahlberg J, Baral NR, Putnam D, Scown CD (2021). Identifying forage sorghum ideotypes for advanced biorefineries. *ACS Sustain. Chem. Eng.* 9: 7873–7881.