

Early-Generation Evaluation of Marker-assisted transfer of *bmr6* and *bmr12* alleles into sweet and high-biomass sorghum

Abstract

The effects of transferring brown midrib (*bmr*) alleles in sweet and high biomass sorghums (SS/HBM) are not fully understood, and available works produced mixed results depending upon the genetic background of the recurrent parent used. Early-generation testing of the effects of the two mutations in the background of the recurrent parents can help predict the final products and make appropriate early go/no-go breeding decisions, yet, this information is missing. The present study was therefore carried out to reduce these gaps. Marker-assisted transfer of the *bmr6* and *bmr12* was performed using four (SSV84, ICSB474, ICSV18003, ICSV100324) SS and one (ICSV15024) HBM wild type (WT) lines as recurrent parents, and one *bmr6* (N609) and two *bmr12* (ICSV101039 and N600) lines as donor parents. Crossing and backcrossing techniques were used to transfer the *bmr* alleles to develop BC₂F₂ and F₃ populations. Kompetitive allele-specific PCR (KASP) marker genotyping assays were performed and implemented for the indirect selection of the *bmr* transfer in F₁ and BC_F₁ populations. While the *bmr6* markers were polymorphic, the *bmr12* markers were monomorphic. The successful *bmr6* transfer was therefore confirmed by markers in F₁ and BC_F₁, while for *bmr12* the transfer was confirmed after segregation assessment in F₂ and BC_F₂ populations. The transfer of *bmr12* improved the cellulose content relative to WT genotypes, and *bmr12* populations were shorter-statured relative to *bmr6* individuals, meaning that *bmr12* gene can be considered in sorghum breeding to boost 2G bioethanol bioconversion and to control lodging, and hence favouring mechanical harvesting and limiting yield losses. The observed earliness in the *bmr* lines is an attractive trait conferring adaptation in the drylands, particularly in the world's semi-arid tropics characterized by terminal drought stress. Both *bmr* alleles did not show any negative trade-offs relative to the must-have sorghum plant characteristics, implying that they can safely be deployed in sorghum breeding for bioenergy production purposes. The observed superior *bmr* lines with farmer-preferred phenotypic acceptance are candidates not only for advancement in breeding pipelines but also for subsequent pyramiding *bmr6* and *bmr12* in the same genetic background, further improving the *bmr*-conferred benefits. The successfully used molecular

markers will be uploaded in the public domain and can help breed sorghum products other than SS/HBM such as high-quality forage sorghums.

Key words: KASPar markers, *bmr transfer*, Sweet sorghum, High biomass sorghum, Fiber components, Cellulose, Marker-assisted backcrossing.

1. Introduction

Sorghum bicolor (L.) Moench is one of the important cereal crops; it can be used for food, fodder, and biofuel production. It belongs to the Poaceae family with five races (caudatum, bicolor, durra, guinea, and kafir) and several hybrids therefrom. It is an annual crop with a minimal life cycle of 3-4 months (Reddy *et al.*, 2005), and can be grown in almost all seasons i.e., rainy, post-rainy and summer, because of its wide adaptability (Oliveira *et al.* 2020; da Silva *et al.* 2020). The increase in biomass productivity depends upon many characteristics like the plant height, maturity, and fresh and dry stalk yields (Nagaiah *et al.*, 2012). Unlike other crop species used for renewable energy bioconversion, sweet sorghum produces biofuels in a sustainable way and without compromising food production (Mathur *et al.*, 2017) because it is possible to produce both grain and 1G and 2G bioethanol (Mask and Morris 1991; Bennett and Anex 2009). Sweet and high biomass sorghum yields 23% more fermentable carbohydrates, uses 37% less nitrogen fertilizer and 17% less irrigation water, and yields more ethanol than maize (*Zea mays*) (Putnam *et al.*, 1991; Hills *et al.*, 1990).

Sweet and high biomass sorghum is the prominent feedstock for second-generation (2G) lignocellulosic production of biofuel which can produce about 288 L of ethanol per each ton of dry biomass by fermenting both C5 and C6 sugars (Umakanth *et al.*, 2022); this is substantial as SS/HBM dry biomass yields of 30-35 t/ha were reported in previous works (Habyarimana *et al.*, 2004). According to Kim and Day (2011), the primary components of lignocellulosic material are lignin (20–30%), hemicellulose (30–40%), cellulose (15–40%), and pectin. The composition of these structural polymers differs across primary and secondary cell walls, various plant tissues, and various plant species (Kim and Day, 2011; Welker *et al.*, 2015). All plant cell types contain primary cell walls (PCW); however only a few cell types, including tracheary elements (TE) and sclerenchymal cells, have the secondary cell walls (SCW) which are present in few plants like Sorghum (Scavuzzo-Duggan *et al.*, 2021). The SCWs are the major components of plant biomass, and they are therefore

central to second-generation biofuels production (Kumar *et al.*, 2016). Cellulose is the common polymer on Earth, which is a homopolymer of -(1,4)-linked glucose monomers, whereas, hemicelluloses are branched heteropolymers made of monomers of pentose and hexose sugar (Cosgrove, 2005; Somerville, 2006). Pectin is a complex polymer with a -(1-4)-linked D-galacturonic acid backbone which is another polysaccharide that is predominant in primordial cell walls. Based on the type of sugars present on the branches, three different types of pectins called rhamnogalacturonans-I (RG-I), rhamnogalacturonans-II (RG-II) and homogalacturonans (HG), have been identified in plants (Burton *et al.*, 2010). The microfibrils of cellulose are cross-linked with different matrices of polysaccharides such as pectins and hemicelluloses (Cosgrove, 2005; Muthamilarasan *et al.*, 2015). Lignin has a significant function in plants, and is concentrated in plant secondary cell walls together with cellulose, hemicellulose, and pectin. Lignin is a complex phenolic polymer that increases the stiffness and hydrophobicity of the cell walls as well as the transport of minerals through the plant's vascular bundles (Schuetz *et al.*, 2014). In addition, lignin also has a protective effect against pathogens and pests (Ithal *et al.*, 2007). However, increased lignin concentration limits enzymatic digestibility and biofuel recovery, suggesting that reducing the lignin quantity in biomass can be a game changer in biofuel production industry (Oliveira *et al.*, 2020).

Brown midrib (*bmr*) mutants are characterized phenotypically by the presence of brown vascular tissues observed on the leaf midribs and stems. These *bmr* mutations appeared in sorghum and maize through chemical or spontaneous mutagenesis. From the intense brown coloration (compared with wild-type green or white leaf midrib colour) of leaf midrib in sorghum derives the name brown midrib (*bmr*) trait, which is correlated with the reduction in lignin content in the stover when compared with wildtype sorghums (Porter *et al.*, 1978; Oliver *et al.*, 2005). However, the intensity of the brown colour is not related to further lignin reduction, but it is an indicator of the presence of *bmr* alleles (Sattler *et al.*, 2014). This phenotype (reddish brown coloration) was found to be positively correlated with two homologous loci *Bm1* and *Bm3*, that are commonly found in maize (*Zea mays*) and *bmr6* and *bmr12* in sorghum (Sattler *et al.*, 2014). The introgression of *bmr6* and *bmr12* showed the ability to reduce lignin concentration and improve cellulose and hemicellulose contents in the aboveground biomass (Diakitét *et al.*, 2021). Various *bmr* loci were identified and were extensively investigated in sorghum (*Sorghum bicolor*) and maize (*Zea mays*) by many researchers (Sattler *et al.*, 2010; Rao *et al.*, 2012; Adeyanju *et al.*, 2021). The *bmr* plants exhibit less polymerized lignin with fewer phenolic monomers, which positively affects

digestion e.g., increased digestibility in the livestock, and can enhance 2G biofuel bioconversion process yields (Fahey, 1983; Habyarimana *et al.*, 2016; Anderson and Akin 2008; Corredor *et al.*, 2009).

The *bmr* mutations are generally associated with reduced lignin in crops like sorghum, maize and pearl millet (Kuc and Nelson, 1964), but most available literature was reported in crops used as ruminant forage (Oliver *et al.*, 2004; Wahyono *et al.*, 2021), while fewer information is available in sweet sorghum. In addition, the *bmr* mutations can reduce the concentration of lignin in the sorghum biomass, but this is not in a systematic way meaning that there are instances where lignin was not reduced and other instances where traits other than lignin were affected (Oliver *et al.*, 2005). In most available literature, backcrossing of *bmr* mutations were evaluated later (>F₃) in the breeding pipelines (Kawahigashi *et al.* 2022; Rivera-Burgos *et al.* 2019; Deshavath *et al.* 2018; Cotton *et al.* 2013; Theerarattananoon *et al.* 2010; Pedersen *et al.* 2008; Pedersen *et al.* 2006; Oliver *et al.* 2005; Oliver *et al.* 2004; Bout and Vermerris 2003; Grant *et al.* 1995; Pillonel *et al.* 1991), which can lead to wasting resources on inferior families that will not be selected. The present study was therefore carried out to reduce this gap. Inferences in this work were based on the results from early-generation (EGT) testing F₃ families derived from several unique crosses between *bmr* sorghum donor parents and sweet and high biomass recurrent sorghum parental lines. EGT is a robust breeding technique (Jones and Smith, 2006) used to identify superior segregating populations containing the greatest frequency of favorable genotypes and to discard inferior populations with limited promise. In sweet and high-biomass sorghum the sweet stem trait and the *bmr* mutation were found to act in an additive manner to reduce lignin content in the stover; the outcome of the introgression of *bmr* alleles into this type of crop cannot therefore be readily predicted (Velmurugan *et al.*, 2020; Espinal, 2009). More research is needed to shed light on the issues related with *bmr* deployment in sorghum breeding and on the best approaches to optimize sweet/high-biomass sorghum must-have and long-term traits that are relevant to bioethanol production. Thus, the aim of this study was to understand the impact of *bmr6* and *bmr12* alleles on agronomic and quality traits in SS/HBM, and produce plant materials and molecular data information that are meaningful for downstream research works in *bmr* sorghum cultivar development.

2. Materials and Methods

The present research was carried out in five seasons (from postrainy 2020 to postrainy 2022) with as an outcome the development of BC₂F₂ and F₃ populations of sweet sorghum and high-biomass sorghum lines. The experimental sites were located at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Patancheru, Hyderabad, India (17°27'N and 78°28'E).

2.1 Plant materials

The experiments were set up to transfer *bmr6* and *bmr12* in diverse recurrent parent genetic backgrounds with the aim of developing high-biomass sweet sorghum lines with improved bioethanol production traits. The parental lines included four and one Bmr WT sweet sorghum varieties (SSV84, ICSV18003, ICSB474, and ICSV100324) and high-biomass sorghum variety (ICSV15024), respectively, one and two *bmr6* (N609) and *bmr12* (ICSV101039 and N600) mutants, respectively, as *bmr* trait donor parents (Table 1).

Table 1: Parental lines used in the *bmr* transfer experiments.

S. N.	Parent	<i>bmr</i> /Bmr	Sorghum type
1	SSV84	Bmr	SS/HBM
2	ICSV15024	Bmr	HBM
3	ICSV18003	Bmr	SS
4	ICSB474	Bmr	SS
5	ICSV100324	Bmr	SS
6	N609	<i>bmr</i>	<i>bmr6</i>
7	ICSV101039	<i>bmr</i>	<i>bmr12</i>
8	N600	<i>bmr</i>	<i>bmr12</i>

SS: Sweet Sorghum, HBM: High-Biomass Sorghum, *bmr* - brown midrib mutation, Bmr: wild type

2.2 Population development

The selection of parents and successive crossing was started in the post-rainy 2020, by hand-emasculating the recurrent parents and pollinating it with pollen collected from the *bmr6* and *bmr12* donor parents separately. The resulting physiologically mature crossed seeds were collected from the recurrent parents and F₁s were backcrossed to the recurrent parents during second season of rainy 2021 to generate the BC₁F₁ populations followed by selfing to obtain BC₁F₂ populations. In the third season post-rainy 2021, the BC₁F₁s were further backcrossed for generating BC₂F₁ populations that were selfed to produce BC₂F₂s during fourth season i.e., rainy 2022. In parallel with the backcrossing pipeline,

F₃ populations were developed to evaluate fiber production potential and other agronomic traits (Table 6). The BC₁F₂s were used to assess the expected *bmr* and Bmr segregation in 3:1 ratio during the fifth season, post-rainy 2022.

These F₁ and BC₁F₁ populations were confirmed for heterozygosity at the *bmr6* locus using validated KASPar SNP markers; *bmr12* markers were monomorphic in our populations. To identify successful *bmr12* transfer, aliquots F₁ seeds from all crosses were planted and selfed to observe the segregation of the recessive *bmr12* allele in the F₂s and BC.F₂s. True F₁ or BC.F₁ heterozygotes at the *bmr12* locus were subsequently used for advancement or for further backcrossing with the recurrent parents. For *bmr6*, only F₁ and BC₁F₁ plants that showed SNP polymorphism (heterozygosity) at the Bmr6 locus were used in backcrossing.

2.3 DNA extraction

After obtaining BC₁F₁ generations, the phenol-chloroform method was used for genomic DNA extraction (Xia *et al.*, 2019) where, one ml of DNA extraction buffer (150 mM NaCl, 20 g SDS/l, 25 mM EDTA, 100 mM Tris/HCl, pH 8.0) was added to 100 mg of grounded sorghum seedling leaf samples, followed by the addition of 10 µl of Proteinase K-10 mg/ml and incubated at 65 °C for 1 hour, while being stirred every 10 minutes. Then, the reaction mixture was centrifuged at 12000 xg for 10 min and the supernatant was extracted twice using Phenol: Chloroform: Isoamyl alcohol (25: 24: 1, v/v/v) and Chloroform: Isoamyl alcohol (24: 1, v/v) respectively. Then, 0.1 volume of potassium acetate solution (3 M, pH 5.5) and ethanol (double volume with 95%, v/v, 20°C) were added to the upper aqueous phase (first precipitation), which was then gently inverted and vortexed at 15000 g for 10 min to pellet DNA. The pellet was washed twice with 70%, v/v, ethanol solution at 20°C and allowed to air dry for five minutes. The pellet was then dissolved in 400 µl of Tris/EDTA buffer (10 mM Tris, 1 mM EDTA). The mixture was treated with 10 mg of RNase, and any residual RNA was removed by incubating it at 37 °C for 30 min. Further, another extraction was carried out using C:I (third extraction) for removing protein from the DNA solution.

2.4 Marker-assisted selection

The above genomic DNA was analyzed for CAPS for *bmr6* and *bmr12*, by PCR amplification using specific primers in a 20-µl reaction (Sattler *et al.*, 2009). Further, the foreground marker-assisted selection across the donor-recurrent parent combinations was

performed by identifying the presence of KASPar SNP (snpSB00519_CALL) *BMR6*-132 and KASPar SNP (snpSB00520_CALL) *BMR12*-129 markers in the target *bmr6* and *bmr12* loci on chromosomes 4 and 7, respectively (Gorthy *et al.*, 2013), adapted from Burow *et al.* (2019). The primers used in this study are listed in Table 2. The final volume of the reaction mixture used for genotyping was 10 µl which consists of 10–20 ng of DNA along with 1x KASP Reaction Mix, 1 µl of the assay mix containing the two allele-specific SNP primers as well as the common reverse primer. Fifteen minutes at 94 °C, 10 touchdown cycles of 20 s at 94 °C, 60 s at 63–55 °C (dropping 0.8 °C every cycle), and 30 cycles of 20 s at 94 °C, 60 s at 55 °C were the PCR cycling conditions.

2.4.1 KASPar assays for SNP validation and foreground marker-assisted backcrossing

KASPar assays were performed for all the identified SNPs in the *bmr* transferred plants. KASPar genotyping assays were performed in parents and off-springs (F₁ and BC₁F₁) at the four-leaf stage, using specific KASP markers i.e., *BMR6*-132 (snpSB00519_CALL) for *bmr6* and *BMR12*-129 (snpSB00520_CALL) for *bmr12*. PCR products were size fractionated using capillary electrophoresis on an ABI3700 automatic DNA sequencer (Applied Biosystems USA). The KASPar SNP genotyping of sorghum samples was done at Intertek Hyderabad. KASPar-SNP markers for *bmr12* allele resulted monomorphic. The designed *bmr6* allele specific KASPar-SNP markers, on the other hand, were polymorphic and used as proxy to screen and classify the F₁, BC₁F₁, and BC₂F₂ individuals into *bmr6* heterozygotes, homozygotes, and Bmr; the BC₂F₂s derived from self-fertilizing true BC₂F₁s.

S.N.	SNP marker	Primer	Primer sequence	Reference
1	<i>BMR6</i> -132	Wild-type allele Mutant allele	5'- GGCGAAGCCGCCCTG-3' 5'-GGCGAAGCCGCCCTA-3'	Burrow <i>et al.</i> , 2019

		Common primer	3'-GCAACAAGAAGATCTGGTCCT-5'	
2	<i>BMR12-129</i>	Wild-type allele	5'-TCTCCATGAGGACCTTGTCATG-3'	Burrow <i>et al.</i> , 2019
		Mutant allele	5'-TCTCCATGAGGACCTTGTCATA-3'	
		Common primer	3'-GCTCACCCCTAACGAGGAC-5'	

Table2:List of primers used in the study

2.5 Fiber components analysis

The proximate fiber components analysis was carried out in the F₃ generation. The different fiber quality traits (Table 6) i.e., cellulose, hemicellulose, acid detergent fiber (ADF), lignin (ADL), neutral detergent fiber (NDF), metabolizable energy, nitrogen, *in vitro* organic matter digestibility (IVOMD), and ash were measured using Near-Infrared Reflectance Spectroscopy (NIRS) as adapted from Rivera-Burgos *et al.*, (2019). The Near infrared spectroscopy (NIRS) is by now a well-developed and mature technology used cost-effectively by the scientific community. NIRS was widely applied as a rapid and non-destructive analysis tool for several products e.g., meat, fruit, or biomass feedstocks. Our samples were analyzed by the International Livestock Research Institute (ILRI), in their lab at the International Crops Research Institute for the Semi-Arid Tropics, headquarters, India, using FOSS DS 2500 Forage analyzer and WinISI calibration software. The ILRI reported Determination Coefficients (R²) were satisfactory (i.e., 0.83, 0.91, 0.82, 0.91, and 0.9, respectively for NDF, ADF, ADL, ME, and IVOMD) and greater than previously reported works (e.g., Otero *et al.*, 2023)

2.6 Data analysis

The genotypic segregation of individuals in BC₁F_{2s} was assessed using Chi-square test (χ^2) and the obtained proportions were compared with expected codominant (marker) segregation (1:2:1) for *bmr6*. In addition, the goodness of fit for phenotypic segregation (*bmr6* and *bmr12*) was assessed against the 3:1 monohybrid phenotypic ratio. The statistical analyses were carried out using the GENES program (Cruz, 2016), ASREML-R (Butler *et al.*, 2009) as implemented under the 'R' software environment *version 4.3.1* (R Core Team., 2023)

3. Results

3.1 Development of *bmr6* hybrids through marker-assisted backcrossing

Marker-assisted transfer of the *bmr6* and *bmr12* was performed using four (SSV84, ICSB474, ICSV18003, ICSV100324) sweet sorghum and one (ICSV15024) high-biomass sorghum wild type (WT) lines as recurrent parents, and one and two *bmr6* (N609) and *bmr12* (ICSV101039 and N600) lines, respectively, as donor parents.

3.2 Phenotypic characteristics

The *bmr6* and *bmr12* transferred plants showed brown midrib colour in the matured plant (Fig. 1). However, the brown midrib phenotype was observed only in F₂ and BC₁F₂ generations but not in F₁s, confirming the recessive inheritance of the trait. Among the WT x *bmr6* derived F₂ populations, 20% of individuals were transferred with *bmr* allele, whereas in BC₁F₂ population 14.6% were transferred. For the *bmr12* trait, 22.8% of F₂ individuals were *bmr* transferred, whereas in BC₁F₂ population 20.35% of the individuals were found to be *bmr* transferred. The phenotypic data collected from F₂ and BC₁F₂ populations were presented in Table 3.

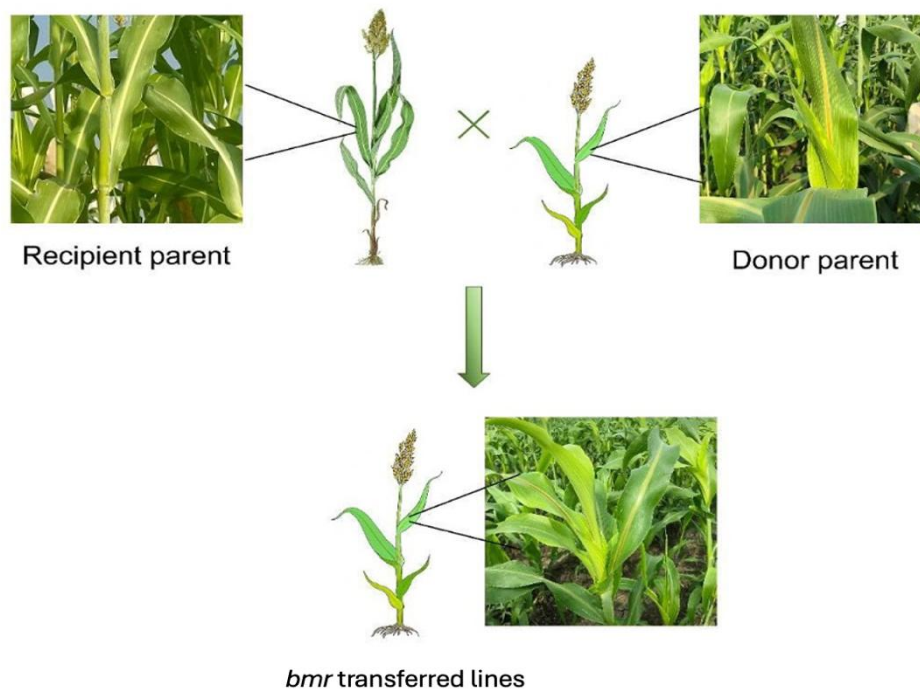


Figure 1-Display of the recurrent and the donor parents along with *bmr* transferred lines

Table 3: Phenotypic data of *bmr6* and *bmr12* in F₂ and BC₁F₂ Populations

S. N.	Cross Combination	Stage	<i>bmr</i>	<i>bmr</i> plants	Bmr Plants	Total Plants
1	SSV84 × N609	F ₂	<i>bmr6</i>	7	15	22
2	ICSV18003 × N609	F ₂	<i>bmr6</i>	3	19	22
3	ICSV15024 × N609	F ₂	<i>bmr6</i>	3	18	21
4	{{SSV84 × N609} × SSV84}	BC ₁ F ₂	<i>bmr6</i>	28	180	208
7	{{ICSV18003 × N609} × ICSV18003}	BC ₁ F ₂	<i>bmr6</i>	10	46	56
8	{{ICSV15024 × N609} × ICSV15024}	BC ₁ F ₂	<i>bmr6</i>	35	200	235
1	SSV84 × ICSV101039	F ₂	<i>bmr12</i>	6	15	21
2	ICSB474 × ICSV101039	F ₂	<i>bmr12</i>	5	16	21
3	ICSB474 × N600	F ₂	<i>bmr12</i>	3	17	20
4	ICSV100324 × ICSV101039	F ₂	<i>bmr12</i>	5	16	21
5	{{SSV84 × ICSV101039} × SSV84}	BC ₁ F ₂	<i>bmr12</i>	13	103	116
6	{{ICSB474 × ICSV101039} × ICSB474}	BC ₁ F ₂	<i>bmr12</i>	8	49	57
7	{{ICSB474 × N600} × ICSB474}	BC ₁ F ₂	<i>bmr12</i>	12	69	81
8	{{ICSV100324 × ICSV101039} × ICSV100324}	BC ₁ F ₂	<i>bmr12</i>	103	311	414

3.3 KASPar assays for *bmr6* specific SNP

The parent N609 harbors homozygous SNP mutation for *bmr6* as expected and the SSV84 parent is WT. The resulting F₁- SSV84 × N609 was heterozygous for *bmr6*, and similar results were obtained with the other recipient recurrent parents ICSV18003 and ICSV15024 (Table 4). The F₁ individuals with *bmr* locus in heterozygous state were further backcrossed to increase the dose of the recurrent parents.

Table 4. Marker assisted *bmr6* diagnostics and development of *bmr6* transferred populations.

S.No	Parent/Cross	Generation	snpSB00519 _CALL	Status
1	SSV84	RP	G:G	Polymorphic
2	N609	DP	A:A	Polymorphic
3	SSV84 × N609	F ₁	A:G	Polymorphic
4	{{SSV84 × N609} × SSV84}	BC ₁ F ₁	A:G	Polymorphic
5	{{SSV84 × N609} × (SSV84) × (SSV84)}	BC ₂ F ₁	Advanced for BC ₂ F ₂	
6	ICSV18003	RP	G:G	Polymorphic
7	N609	DP	A:A	Polymorphic
8	ICSV18003 × N609	F ₁	A:G	Polymorphic
9	{{ICSV18003 × N609} × ICSV18003}	BC ₁ F ₁	A:G	Polymorphic
10	{{ICSV18003 × N609} × (ICSV18003) × (ICSV18003)}	BC ₂ F ₁	Advanced for BC ₂ F ₂	
11	ICSV15024	RP	G:G	Polymorphic
12	N609	DP	A:A	Polymorphic

13	ICSV15024 × N609	F ₁	A:G	Polymorphic
14	{(ICSV15024 × N609) × ICSV15024}	BC ₁ F ₁	A:G	Polymorphic
15	{(ICSV15024 × N609) × (ICSV15024) × (ICSV15024)}	BC ₂ F ₁	Advanced for BC ₂ F ₂	

RP-Recipient or recurrent parent, DP-Donor parent, F₁-F₁ generation without back cross, BC₁F₁-F₁ generation with one back cross, BC₂F₁- F₁ generation with two backcrosses, snpSB00519_CALLKASP SNP (BMR6-132) marker for bmr6

3.4 Development of *bmr12* hybrids through marker-assisted and phenotypic backcrossing

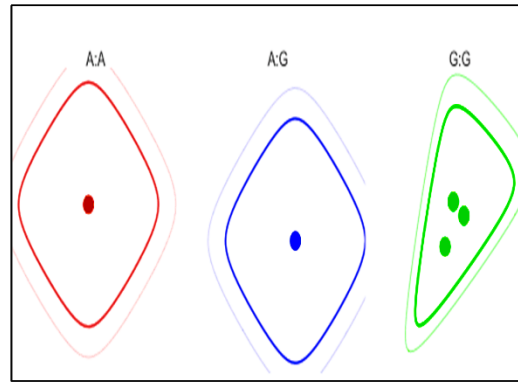
The brown midrib trait, as conferred by *bmr12* expressed in ICSV101039 and N600 (sources), was successfully introgressed into three sweet/high-biomass sorghum lines for developing superior elite bmr transferred lines expressing the *bmr* trait. Foreground marker-assisted selection using KASPar SNP markers was not successful due to lack of polymorphism in our populations. The successful *bmr12* transfer was therefore confirmed by the monohybrid 3:1 Mendelian segregation approach in F₂s and BC-F₂s, accounting for the recessiveness of the *bmr12* allele (Table 5).

Table -5- Development of *bmr12* transferred lines

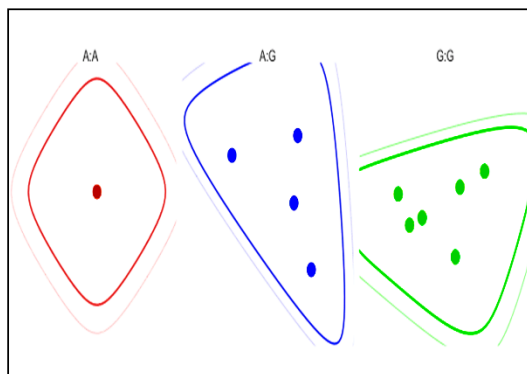
S. No	Cross Combinations	Population	Trait	BC ₂ F ₁ Advanced
1	{(SSV84 × ICSV101039) × (SSV84) × (SSV84)}	BC ₂ F ₁	<i>bmr12</i>	BC ₂ F ₂
2	{(ICSB474 × ICSV101039) × (ICSB474) × (ICSB474)}	BC ₂ F ₁	<i>bmr12</i>	BC ₂ F ₂
3	{(ICSB474 × N600) × (ICSB474) × (ICSB474)}	BC ₂ F ₁	<i>bmr12</i>	BC ₂ F ₂
4	{(ICSV100324 × ICSV101039) × (ICSV100324) × (ICSV100324)}	BC ₂ F ₁	<i>bmr12</i>	BC ₂ F ₂

3.5 Foreground marker-assisted selection for *bmr6*

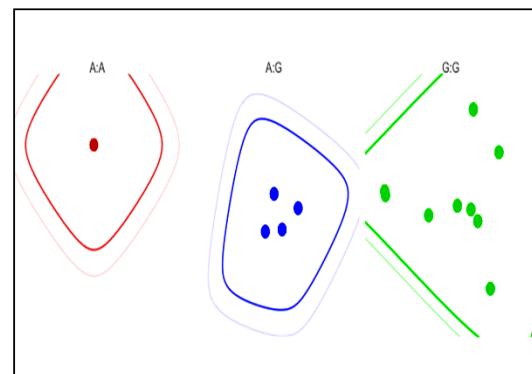
Six recurrent parent (SSV84) plants were crossed with six (6) donor parent (N609) plants in the first cross combination (SSV84 × N609), and three true hybrids were obtained in F₁ generation. Similarly for the other recurrent parents, four plants ICSV18003 and seven plants ICSV15024 were crossed with the respective number of donor parents N609 to produce two and four true hybrids in F₁ generation, respectively. Further, the obtained true hybrids were backcrossed with the respective recurrent parent resulting in three true hybrids for {(SSV84 × N609) × SSV84}, one in {(ICSV18003 × N609) × ICSV18003} and four in {(ICSV15024 × N609) × ICSV15024} in the BC₁F₁ generation (Fig. 2).



(a) $BC_1F_1 - \{(ICSV18003 \times N609) \times ICSV18003\}$



(b) $BC_1F_1 - \{(ICSV15024 \times N609) \times ICSV15024\}$



(c) $BC_1F_1 - \{(SSV84 \times N609) \times SSV84\}$

Figure 2-Genotyping of BC_1F_1 individuals with the KASP marker (snpSB00519).

From the above diagrammatic representation, *bmr* transferred plants were screened at BC_1F_1 stages using KASPar SNPs. The dots show polymorphism at a locus on the chromosome SBI 4. The red spots represent the homozygous gene (A: A) from the donor parents N609 (*bmr6*) and the blue spots represent the heterozygous allele (A: G) from both the parents, whereas green spots indicate the homozygous gene (G: G) from high-biomass parent and sweet sorghum recurrent parents *i.e.*, ICSV15024, and ICSV18003 and SSV84. Highest number of true hybrids were obtained in the BC_1F_1 cross $\{(ICSV15024 \times N609) \times ICSV15024\}$ and $\{(SSV84 \times N609) \times SSV84\}$ compared with $BC_1F_1\{(ICSV18003 \times N609) \times ICSV18003\}$.

3.6 Proximate composition of the biomass

The genotypes expressing *bmr6* and *bmr12* matured earlier, showed less metabolizable energy and more ash relative to Bmr populations (Table 6). In addition, *bmr12* genotypes showed higher cellulose concentration than Bmr populations and were shorter-statured than *bmr6* genotypes. The two *bmr* alleles had no effect on other must-have and long-term sweet/high-biomass sorghum plant characteristics such as lignin concentration, cellulosic

content (NDF neutral detergent fiber), Brix, and stem girth. The results obtained from the chi-square analysis between the *bmr* and *Bmr* populations are presented in Table 6.

Table 6. Agronomic and quality traits in F₃ and wild type populations

Trait: Days to flowering								
Group	Means	Group1	Group2	Estimate	StdErr	DF	t Value	Pr > t
<i>bmr12</i>	64.50	<i>bmr12</i>	<i>bmr6</i>	-0.64	1.69	47	-0.38	0.7077
<i>bmr6</i>	65.14	<i>bmr12</i>	<i>Bmr</i>	-11.35	3.10	47	-3.66	0.0006
<i>Bmr</i>	75.85	<i>bmr6</i>	<i>Bmr</i>	-10.71	3.12	47	-3.43	0.0012
Trait: Days to maturity								
Group	Means	Group1	Group2	Estimate	StdErr	DF	t Value	Pr > t
<i>bmr12</i>	86.59	<i>bmr12</i>	<i>bmr6</i>	-1.28	1.55	47	-0.83	0.4131
<i>bmr6</i>	87.87	<i>bmr12</i>	<i>Bmr</i>	-10.68	2.83	47	-3.77	0.0005
<i>Bmr</i>	97.27	<i>bmr6</i>	<i>Bmr</i>	-9.40	2.85	47	-3.29	0.0019
Trait: Plant height								
Group	Means	Group1	Group2	Estimate	StdErr	DF	t Value	Pr > t
<i>bmr12</i>	270.72	<i>bmr12</i>	<i>bmr6</i>	-19.30	8.56	47	-2.26	0.0288
<i>bmr6</i>	290.03	<i>bmr12</i>	<i>Bmr</i>	-26.14	15.66	47	-1.67	0.1017
<i>Bmr</i>	296.86	<i>bmr6</i>	<i>Bmr</i>	-6.84	15.76	47	-0.43	0.6663
Trait: Stem Girth								
Group	Means	Group1	Group2	Estimate	StdErr	DF	t Value	Pr > t
<i>bmr12</i>	19.93	<i>bmr12</i>	<i>bmr6</i>	0.74	0.70	47	1.06	0.2961
<i>bmr6</i>	19.18	<i>bmr12</i>	<i>Bmr</i>	2.28	1.29	47	1.78	0.0824
<i>Bmr</i>	17.65	<i>bmr6</i>	<i>Bmr</i>	1.54	1.29	47	1.19	0.2401
Trait: Metabolizable energy								
Group	Means	Group1	Group2	Estimate	StdErr	DF	t Value	Pr > t
<i>bmr12</i>	6.82	<i>bmr12</i>	<i>bmr6</i>	-0.16	0.18	47	-0.87	0.3905
<i>bmr6</i>	6.98	<i>bmr12</i>	<i>Bmr</i>	-0.82	0.33	47	-2.5	0.0158
<i>Bmr</i>	7.64	<i>bmr6</i>	<i>Bmr</i>	-0.67	0.33	47	-2.02	0.0494
Trait: ADF								
Group	Means	Group1	Group2	Estimate	StdErr	DF	t Value	Pr > t
<i>bmr12</i>	47.59	<i>bmr12</i>	<i>bmr6</i>	1.73	1.27	47	1.37	0.1783
<i>bmr6</i>	45.86	<i>bmr12</i>	<i>Bmr</i>	6.11	2.32	47	2.63	0.0115
<i>Bmr</i>	41.48	<i>bmr6</i>	<i>Bmr</i>	4.38	2.34	47	1.87	0.0673
Trait: ADL								
Group	Means	Group1	Group2	Estimate	StdErr	DF	t Value	Pr > t
<i>bmr12</i>	5.45	<i>bmr12</i>	<i>bmr6</i>	0.44	0.25	47	1.74	0.0883
<i>bmr6</i>	5.01	<i>bmr12</i>	<i>Bmr</i>	0.41	0.46	47	0.87	0.3874
<i>Bmr</i>	5.04	<i>bmr6</i>	<i>Bmr</i>	-0.04	0.47	47	-0.08	0.9379
Trait: Ash								
Group	Means	Group1	Group2	Estimate	StdErr	DF	t Value	Pr > t
<i>bmr12</i>	9.30	<i>bmr12</i>	<i>bmr6</i>	0.42	0.65	47	0.65	0.5198
<i>bmr6</i>	8.88	<i>bmr12</i>	<i>Bmr</i>	3.13	1.19	47	2.63	0.0115
<i>Bmr</i>	6.17	<i>bmr6</i>	<i>Bmr</i>	2.71	1.20	47	2.26	0.0284
Trait: Brix								
Group	Means	Group1	Group2	Estimate	StdErr	DF	t Value	Pr > t
<i>bmr12</i>	13.98	<i>bmr12</i>	<i>bmr6</i>	0.11	0.37	47	0.29	0.7746

<i>bmr6</i>	13.88	<i>bmr12</i>	Bmr	0.01	0.67	47	0.02	0.9828
Bmr	13.97	<i>bmr6</i>	Bmr	-0.09	0.68	47	-0.13	0.8933
Trait: NDF								
Group	Means	Group1	Group2	Estimate	StdErr	DF	t Value	Pr > t
<i>bmr12</i>	72.53	<i>bmr12</i>	<i>bmr6</i>	1.70	1.53	47	1.11	0.2724
<i>bmr6</i>	70.83	<i>bmr12</i>	Bmr	5.48	2.80	47	1.96	0.0559
Bmr	67.05	<i>bmr6</i>	Bmr	3.79	2.82	47	1.34	0.1852
Trait: Nitrogen								
Group	Means	Group1	Group2	Estimate	StdErr	DF	t Value	Pr > t
<i>bmr12</i>	0.49	<i>bmr12</i>	<i>bmr6</i>	0.00	0.05	47	0.03	0.9749
<i>bmr6</i>	0.49	<i>bmr12</i>	Bmr	0.13	0.10	47	1.34	0.1871
Bmr	0.36	<i>bmr6</i>	Bmr	0.13	0.10	47	1.31	0.1956
Trait: IVOMD								
Group	Means	Group1	Group2	Estimate	StdErr	DF	t Value	Pr > t
<i>bmr12</i>	47.06	<i>bmr12</i>	<i>bmr6</i>	1.07	1.67	47	0.64	0.5259
<i>bmr6</i>	45.99	<i>bmr12</i>	Bmr	0.28	3.05	47	0.09	0.9285
Bmr	46.78	<i>bmr6</i>	Bmr	-0.79	3.07	47	-0.26	0.798
Trait: Cellulose								
Group	Means	Group1	Group2	Estimate	StdErr	DF	t Value	Pr > t
<i>bmr12</i>	41.78	<i>bmr12</i>	<i>bmr6</i>	0.89	1.23	47	0.73	0.4712
<i>bmr6</i>	40.88	<i>bmr12</i>	Bmr	4.84	2.24	47	2.16	0.0363
Bmr	36.94	<i>bmr6</i>	Bmr	3.95	2.26	47	1.75	0.0872
Trait: Hemicellulose								
Group	Means	Group1	Group2	Estimate	StdErr	DF	t Value	Pr > t
<i>bmr12</i>	25.26	<i>bmr12</i>	<i>bmr6</i>	0.22	0.65	47	0.34	0.7358
<i>bmr6</i>	25.04	<i>bmr12</i>	Bmr	0.11	1.18	47	0.09	0.9261
Bmr	25.15	<i>bmr6</i>	Bmr	-0.11	1.19	47	-0.09	0.9273

ADF-Acid detergent fibre, ADL- Acid detergent lignin, NDF- Neutral detergent fibre,
IVOMD-Invitro organic matter digestibility

3.7 Discussion

Historically, sorghum was mostly grown for grain and forage (Hoffmann and Rooney., 2013). Grain sorghums are generally shorter (usually having recessive alleles at three of the four Dw genes) relative to biomass sorghums (having recessive alleles at two Dw genes at most), and have been selected to have the grain as the primary sink for photosynthates. Biomass sorghum includes high-biomass sorghum and sweet sorghum (Damasceno *et al.*, 2014; Hoffmann and Rooney., 2013; Prakasham *et al.*,2014). Sweet sorghum translocates photosynthates to seeds and stem, their stems are juicy (d recessive to D) instead of dry, and sweet (x recessive to X) instead of nonsweet (Rooney, 2000). Sweet sorghums are high biomass and sugar yielding crops and were traditionally bred for syrup or molasses production. High-biomass and sweet sorghum are mainly bred for sustainable renewable feedstock production targeting different market segments with particular focus on

first and second generation biofuels (Kanbar *et al.*, 2020). The sustainability of sorghum cultivation is imparted by the resilience of this crop to climate adversities, adaptability to harsh environments, resource use efficiency particularly nitrogen use efficiency, and adaptability across latitudes (Mullet *et al.*, 2014, Habyarimana *et al.*, 2020). Sweet/High-biomass sorghum give an increased energy yield and net gain than sugar beet (*Beta vulgaris* L.) and have a more net energy balance compared with other plants like grain sorghum and maize (Palumbo *et al.*, 2014). Furthermore, recent studies (Bhattarai *et al.*, 2020) confirmed sorghum's higher silage yield and water use efficiency compared to pearl millet and corn under limited irrigation conditions.

Brown midrib (*bmr*) 6 and 12 in sorghum are loss-of-function mutations that impair the last two enzymatic steps of monolignol synthesis, resulting in reduction of the amount of lignin of diverse structure in the cell wall, particularly in forage sorghums (Sattler *et al.*, 2010). In the present study, we aimed at transferring the *bmr6* and *bmr12* alleles into SS/HBM lines for developing new elite ideotypes with improved agronomic and quality traits for the biofuel market segment. Marker-assisted introgression of the *bmr6* and *bmr12* was performed using four (SSV84, ICSB474, ICSV18003, ICSV100324) sweet sorghum and one (ICSV15024) high-biomass sorghum wild type (WT) lines as recurrent parents, and one and two *bmr6* (N609) and *bmr12* (ICSV101039 and N600) lines, respectively, as donor parents. According to da Silva (2020), sorghum plants can be visually recognised and categorised as either *bmr* or WT phenotypes as early as the 8-leaf growth stage. In this study, we were able to visually identify *bmr* trait in the field at a relatively later growth stage compared to da Silva *i.e.*, at 30-35 days after planting. At this growth and development stage, sorghum plants are 12 to 15 inches tall, have more than eight leaves and, are starting the growing point differentiation that occurs typically at 30 to 40 days after emergence. Clearly, the importance of early generation testing was confirmed in this study and can be recommended in other *bmr* transfer experiments including: (1) crossing and selection in the segregating populations, and (2) conventional and (3) marker-assisted backcrossing.

Marker-assisted foreground selection showed the potential to speed up the development of near isogenic lines in sorghum and other crops in 3 years as opposed to 5–6 years using the conventional backcrossing strategy. This was demonstrated in our study and has the promise to increase genetic gain per unit time and cost. The *bmr6* mutation induces change from CAG to T/UAG at amino acid position 132 (Glutamine) of the CAD gene, resulting in a stop codon (Sattler *et al.* 2009; Li *et al.*, 2015). Similarly, the *bmr12* mutation induces change from CAG to T/UAG at amino acid position 129 (Glutamine) of the COMT

gene, resulting in a stop codon (Bout and Vermerris, 2003). Relative to the WT, *bmr6* sorghum mutants display a significant reduction in all three main lignin subunits, p-hydroxyphenyl (H), G, S in the magnitude of 4.8-, 7.3-, and 17.7-fold, respectively; the most significant reduction being in S-lignin, which leads to a reduced S:G ratio (Sattler *et al.*, 2009). Thus far, *bmr6*, *Bmr12*, and *bmr18* are among the known *bmr* mutants that can be grown well in sorghum (Kamireddy *et al.*, 2013). According to Oliver *et al.* (2005), Oliveira *et al.* (2020) and Espinal (2009), the allelic genes *bmr12* and *bmr6* inhibit the activity of the enzymes cinnamyl alcohol dehydrogenase (CAD) and caffeic acid o-methyltransferase (COMT) with significant effects on sorghum fiber components. The above was the set of working hypotheses of this work. For each gene, heterozygotes were easily distinguished, and the observed F₂ phenotypes matched the identified genotypic conditions. In the present study, the *bmr6* gene was transferred successfully in sweet sorghum/high-biomass lines and identified in BC₁F₁ generation at chromosome 4 position by utilizing the KASP marker SNP-SB00519. The *bmr12* was transferred using classic approach of backcrossing coupled with selfed progeny to trace back the true heterozygous F₁. The development of *bmr12* marker is underway in our laboratory to assist both the transfer of single alleles as well as the pyramiding of *bmr6* and *bmr12* in the same genetic background.

The genotypes expressing *bmr6* and *bmr12* matured earlier, showed less metabolizable energy and more ash relative to Bmr populations (Table 6). In addition, *bmr12* genotypes showed higher cellulose concentration than Bmr populations and were shorter-statured than *bmr6* genotypes. The two *bmr* alleles had no effect on other must-have sweet/high-biomass sorghum plant characteristics such as lignin concentration, cellulosic content (NDF neutral detergent fiber), Brix, and stem girth, implying their good safety for deployment in sorghum breeding pipelines. In this study, the comparative lignin concentration between *bmr* and Bmr populations was not expected (Barrière *et al.*, 2007 and Saballos *et al.* 2009) since the *bmr* mutations are usually associated with reduced lignin in several cereal crops like sorghum, maize and pearl millet (Kuc and Nelson, 1964).

Our hypothesis was that SS/HBM would behave like forage sorghums (Barrière *et al.*, 2007 and Saballos *et al.* 2009) and it was expected that *bmr* genotypes would express reduced lignin concentration as in forage sorghums (Sattler *et al.*, 2010; Oliveira *et al.*, 2020; Wahyono *et al.*, 2021). However, our findings are supported by previous research works showing that the *bmr* mutations can reduce the concentration of lignin in the sorghum biomass, but the pattern was not consistent because there are instances where lignin was not reduced and other instances where traits other than lignin were modified in the recurrent parents (Oliver *et al.*,

2005). More research is needed including using other *bmr* alleles and different sorghum types, in order to get insight into the interaction *bmr* × sweet SS/HBM sweet stem and optimize lignin concentration in this sorghum market segment. In addition, the investigation of the effects of *bmr* mutations on the lignin structure is in order to decipher the extent to which the biomass digestibility can be significantly improved by structural changes in lignin units instead of ponderal reduction of the lignin concentration in the cell wall.

Remarkably, we were able to observe that the transferred *bmr12* improved the cellulose content relative to WT genotypes, and *bmr12* populations were shorter-statured relative to *bmr6* individuals, meaning that *bmr12* gene can be considered in sorghum breeding to boost 2G bioethanol bioconversion and to control lodging, and hence favoring mechanical harvesting and limiting yield losses (Habyarimana *et al.*, 2016, Tse *et al.*, 2021). The observed earliness in the *bmr* lines is another attractive trait as it confers adaptation in the drylands, particularly in the semi-arid tropics characterized by terminal drought stress (Shavrukov *et al.*, 2017). Both *bmr* alleles did not show any deleterious effects on must have traits (e.g., Brix, stem girth, NDF, etc.) and hence they can be safely deployed in sorghum breeding. The observed increased ash in *bmr* vs. *Bmr* populations can have mixed evaluation. Biomass ash is naturally alkaline which tends to lower the fusion point of ashes leading to fouling, slagging and poor combustion system performance (Carrillo *et al.*, 2014), meaning that *bmr6* and *bmr12* sorghums should not be considered as good candidate for combustion-derived biofuels. However, ash being alkaline and containing phosphorus, potassium, calcium, boron, and other mineral elements, *bmr6* and *bmr12* sorghums ash by-product can be used as to improve soil health and for growing plants healthily. In this work however, the ash percentage was not more than 10%. The requirement for ash content in raw material for bioethanol production is 10% or less, which is accomplished by the *bmr* lines produced in this study. Higher ash concentration beyond 10% is usually undesirable as it might impede the fermentation process and result in crust on the tool during the distillation process (Carrillo *et al.*, 2014). It can therefore be inferred that the *bmr6* and *bmr12* alleles can safely be deployed in sorghum breeding for bioenergy production purposes.

4. Conclusions

The importance of early generation testing was confirmed in this study and can be suggested in other *bmr* transfer experiments. The *bmr6* and *bmr12* alleles were successfully transferred and true F_{1s} were identified in backcrosses using SNP markers and phenotypic segregation in F_{2s} . The transfer of *bmr12* improved the cellulose content relative to WT genotypes, and *bmr12* populations were shorter-statured relative to *bmr6* individuals, meaning

that *bmr12* alleles can be considered in sorghum breeding to boost 2G bioethanol bioconversion and to control lodging, and hence favoring mechanical harvesting and limiting yield losses. The observed earliness in the *bmr* lines is an attractive trait conferring adaptation in the drylands, particularly in the semi-arid tropics characterized by terminal drought stress. Both *bmr* alleles did not show any negative trade-offs relative to must have traits in sorghum, implying that they can safely be deployed in sorghum breeding for bioenergy production purposes. The produced transferred lines can be used to directly pyramid *bmr6* and *bmr12* in the same genetic background, further improving the listed *bmr*-conferred benefits. The *bmr* molecular markers successfully used in this work will be published in the public domain and are expected to help breed sorghum products other than SS/HBM types such as high-quality forage sorghums.

References

- Adeyanju, A.O., Sattler, S.E., Rich, P.J., Rivera-Burgos, L.A., Xu, X., & Ejeta, G., 2021. Sorghum brown *midrib19* (*Bmr19*) gene links lignin biosynthesis to folate metabolism. *Genes*, 12(5), 660.
- Anderson, W.F., & Akin, D.E., 2008. Structural and chemical properties of grass lignocelluloses related to conversion for biofuels. *Journal of Industrial Microbiology and Biotechnology*, 35(5), 355-366.
- Barrière, Y., Riboulet, C., Méchin, V., Maltese, S., Pichon, M., Cardinal, A., and Martinant, J. P., 2007. Genetics and genomics of lignification in grass cell walls based on maize as model species. *Genes Genomes Genomics*, 1, 133-156.
- Bout S, Vermerris W (2003) A candidate-gene approach to clone the sorghum Brown midrib gene encoding caffeic acid O-methyltransferase. *Mol Genet Genomics* 269 (2):205-214
- Bhattarai, B., Singh, S., West, P.C., Ritchie, G.L., & Trostle, C.L., 2020. Water depletion pattern and water use efficiency of forage sorghum, pearl millet, and corn under water limiting condition. *Agricultural Water Management*, 238, 106206. Doi: <https://doi.org/10.1016/j.agwat.2020.106206>.

Bennett, A.S., and Anex, R.P., 2009. Production, transportation and milling costs of sweet sorghum as a feedstock for centralized bioethanol production in the upper Midwest. *Bioresource technology*, 100(4), 1595-1607.

Burow, G., Chopra, R., Sattler, S., Burke, J., Acosta-Martinez, V., & Xin, Z., 2019. Deployment of SNP (CAPS and KASP) markers for allelic discrimination and easy access to functional variants for brown midrib genes *bmr6* and *bmr12* in *Sorghum bicolor*. *Molecular Breeding*, 39, 1-10.

Burton, R. A., Gidley, M.J., & Fincher, G.B., 2010. Heterogeneity in the chemistry, structure and function of plant cell walls. *Nature chemical biology*, 6(10), 724-732.

Butler, D.G., Cullis, B.R., Gilmour, A.R., & Gogel, B.J. 2009., ASReml-R reference manual. The State of Queensland, Department of Primary Industries and Fisheries, Brisbane.

Carrillo, M.A., Staggenborg, S.A., & Pineda, J.A. 2014., Washing sorghum biomass with water to improve its quality for combustion. *Fuel*, 116, 427-431.

Cruz, C.D., 2016. Genes Software-extended and integrated with the R, Matlab and Selegen. *Acta Scientiarum. Agronomy*, 38, 547-552.

Corredor, D.Y., Salazar, J.M., Hohn, K.L., Bean, S., Bean, B.R.E.N.T., & Wang, D.O.N.G.H.A.I., 2009. Evaluation and characterization of forage sorghum as feedstock for fermentable sugar production. *Applied biochemistry and biotechnology*, 158, 164-179.

Cosgrove, D.J., 2005. Growth of the plant cell wall. *Nature reviews molecular cell biology*, 6(11), 850-861.

Cotton J, Burow G, Acosta-Martinez V, Moore-Kucera J (2013) Biomass and Cellulosic Ethanol Production of Forage Sorghum Under Limited Water Conditions. *Bioenergy Research* 6 (2):711-718. doi:10.1007/s12155-012-9285-0

da Silva, M.J., Damasceno, C.M.B., Guimarães, C.T., de Oliveira Pinto, M., de Almeida Barros, B., de Souza Carneiro, J. E., & da Costa Parrella, R.A., 2020. Introgression of the *bmr6* allele in biomass sorghum lines for bioenergy production. *Euphytica*, 216(6), 95.

Damasceno, C.M.B., Schaffert, R.E., Duweikat, I., 2014. Mining genetic diversity of sorghum as bioenergy feedstock. In: McCann, M.C., Buckeridge, M.S., Carpita, N.C. (Eds.), *Plants and Bioenergy*. Springer, NY, pp. 81–107.

Diakit , M.S., Lenormand, H., Lequart, V., Arufe, S., Martin, P., & Leblanc, N., 2021. Cell Wall Composition of Hemp Shiv Determined by Physical and Chemical Approaches. *Molecules*, 26(21), 6334.

Deshavath NN, Mahanta S, Goud VV, Dasu VV, Rao PS (2018) Chemical composition analysis of various genetically modified sorghum traits: Pretreatment process optimization and bioethanol production from hemicellulosic hydrolyzates without detoxification. *J Environ Chem Eng* 6 (4):5625-5634. doi:10.1016/j.jece.2018.08.002

Espinal, A. I. M. S., 2009. Genetic dissection of sorghum traits important for biofuel production (Doctoral dissertation, Purdue University).

Gorthy, S., Mayandi, K., Faldu, D., and Dalal, M., 2013. Molecular characterization of allelic variation in spontaneous brown midrib mutants of sorghum (*Sorghum bicolor* (L.) Moench). *Molecular breeding*, 31, 795-803.

Grant RJ, Haddad SG, Moore KJ, Pedersen JF (1995) Brown midrib sorghum silage for midlactation dairy cows. *Journal of dairy science* 78 (9):1970-1980

Habyarimana, E., Laureti, D., De Ninno, M., Lorenzoni, C., 2004. Performances of Biomass Sorghum [*Sorghum Bicolor* (L.) Moench] under Different Water Regimes in Mediterranean Region. *Industrial Crops and Products*, 20, 23–28, doi:10.1016/j.indcrop.2003.12.019.

Habyarimana, E., Lopez-Cruz, M., & Baloch, F.S., 2020. Genomic selection for optimum index with dry biomass yield, dry mass fraction of fresh material, and plant height in biomass sorghum. *Genes*, 11(1), 61.

Habyarimana, E., Lorenzoni, C., Marudelli, M.; Redaelli, R., Amaducci, S., 2016. A Meta-Analysis of Bioenergy Conversion Relevant Traits in Sorghum Landraces, Lines and Hybrids in the Mediterranean Region. *Industrial Crops and Products*, 81, 100–109, doi: 10.1016/j.indcrop.2015.11.051.

Hills, F., Lewellen, R., and Skoyen, I., 1990. Sweet sorghum cultivars for alcohol production. California agriculture, 44 (1), 14-16.

Hoffmann Jr., L., Rooney, W.L., 2013. Cytoplasm has no effect on the yield and quality of biomass sorghum hybrids. JSBS 3, 129–134.

Ithal N., Recknor J., Nettleton D., Maier T., Baum T.J., Mitchum M.G., 2007. Developmental transcript profiling of cyst nematode feeding cells in soybean roots. Mol. Plant Microbe Interact. 20:510–525. doi 10.1094/MPMI-20-5-0510.

Jones, G.D. and Smith, C.W. (2006). Early Generation Testing in Upland Cotton. Crop Science - CROP SCI. 46. 10.2135/cropsci2004.0517.

Jung, H.G. and G.C. Fahey., 1983. Nutritional implications of phenolic monomers and lignin: a review. J. Anim. Sci. 57:206.

Kamireddy, S.R., Li, J., Abbina, S., Berti, M., Tucker, M., & Ji, Y., 2013. Converting forage sorghum and sunn hemp into biofuels through dilute acid pretreatment. Industrial Crops and Products, 49, 598-609.

Kanbar, A., Shakeri, E., Alhajturki, D., Horn, T., Emam, Y., Tabatabaei, S. A., and Nick, P., 2020. Morphological and molecular characterization of sweet, grain and forage sorghum (*Sorghum bicolor* L.) genotypes grown under temperate climatic conditions. Plant Biosystems-An International Journal Dealing with all Aspects of Plant Biology, 154(1): 49-58.

Kim, M., & Day, D.F., 2011. Composition of sugar cane, energy cane, and sweet sorghum suitable for ethanol production at Louisiana sugar mills. Journal of industrial microbiology and biotechnology, 38(7), 803-807.

Kawahigashi H, Yonemaru JI, Kiyosawa A, Mizuno H, Kasuga S (2022) DNA marker analysis of flowering time, semi-dwarf, fertility restorer, and brown midrib genes in sorghum (*Sorghum bicolor* [L.] Moench). Grassland Science 68 (2):101-113. doi:10.1111/grs.12343

Kuc, J. and O.E. Nelson., 1964. The abnormal lignins produced by the brown midrib mutants of maize. I. The brown midrib-1 mutants. Arch. Biochem. Biophys. 105:103.

Kumar, M., Campbell, L., & Turner, S., 2016. Secondary cell walls: biosynthesis and manipulation. *Journal of experimental botany*, 67(2), 515-531.

Li, Y., Liu, G., Li, J., You, Y., Zhao, H., Liang, H., & Mao, P., 2015. Acid detergent lignin, lodging resistance index, and expression of the caffeic acid O-methyltransferase gene in brown midrib-12 sudangrass. *Breed Sci.*, 65(4), 291–297. doi: 10.1270/jsbbs.65.291

Mask, P.L., and Morris, W.C., 1991. Sweet sorghum culture and syrup production. Circular ANR-Alabama Cooperative Extension Service, Auburn University (USA).

Mathur, S., Umakanth, A.V., Tonapi, V.A., Sharma, R., and Sharma, M.K., 2017. Sweet sorghum as biofuel feedstock: recent advances and available resources. *Biotechnology for Biofuels*, 10, 1-19.

Mullet, J., Morishige, D., McCormick, R., Truong, S., Hilley, J., McKinley, B., & Rooney, W., 2014. Energy Sorghum—a genetic model for the design of C4 grass bioenergy crops. *Journal of experimental botany*, 65(13), 3479-3489.

Muthamilarasan, M., Khan, Y., Jaishankar, J., Shweta, S., Lata, C., & Prasad, M., 2015. Integrative analysis and expression profiling of secondary cell wall genes in C4 biofuel model *Setaria italica* reveals targets for lignocellulose bioengineering. *Frontiers in plant science*, 6, 965.

Nagaiah D., Srinivasa Rao P., Prakasham R.S., Uma A., Radhika K., Barve Y., Umakanth A.V., 2012. High-biomass sorghum as a potential raw material for biohydrogen production: a preliminary evaluation. *Current Trends in Biotechnology and Pharmacy*, 6: 1-6.

Oliver A.L., Pedersen J.F., Grant R.J., Klopfenstein T.J., 2005. Comparative effects of the sorghum *bmr6* and *bmr-12* genes. Forage sorghum yield and quality. *Crop Sci* 45:2234–2239.

Oliveira, D. M., Mota, T. R., Grandis, A., de Morais, G. R., de Lucas, R. C., Polizeli, M. L., ... and dos Santos, W. D., 2020. Lignin plays a key role in determining biomass recalcitrance in forage grasses. *Renewable Energy*, 147. 2206-2217.

Oliver, A.L., Grant, R.J., Pedersen, J.F., & O'Rear, J.E.R.R.Y., 2004. Comparison of brown midrib-6 and-18 forage sorghum with conventional sorghum and corn silage in diets of lactating dairy cows. *Journal of dairy science*, 87(3), 637-644.

A. Otero, C. Segura, L. Tey, G. Masferrer, J. Comaposada, B. Fernández, (2023). Near infrared spectroscopy for fast characterization of animal by products feedstocks for biogas

production: Calibration of a handheld device. *Biomass and Bioenergy*, 169. <https://doi.org/10.1016/j.biombioe.2022.106691>.

Palumbo, A.D., Vonella, A.V., Garofalo, P., D'Andrea, L., & Rinaldi, M., 2014. Response of a two-year sugar beet-sweet sorghum rotation to an agronomic management approach diversified by soil tillage and nitrogen fertilisation. *Italian Journal of Agronomy*, 9(3), 109-114.

Prakasham, R.S., Nagaiah, D., Vinutha, K.S., Uma, A., Chiranjeevi, T., Umakanth, A.V., 2014. Sorghum biomass: a novel renewable carbon source for industrial bioproducts. *Biofuels* 5, 159–174.

Porter, K.S., Axtell, J.D., Lechtenberg, V.L., and Colenbrander, V.F., 1978. Phenotype, Fiber Composition, and in vitro Dry Matter Disappearance of Chemically Induced Brown Midrib (bmr) Mutants of Sorghum 1. *Crop Science*, 18(2), 205-208.

Putnam, D.H., Lueschen, W.E., Kanne, B.K., and Hoverstad, T.R., 1991. A comparison of sweet sorghum cultivars and maize for ethanol production. *Journal of Production Agriculture*, 4(3), 377-381.

Pedersen JF, Funnell DL, Toy JJ, Oliver AL, Grant RJ (2006) Registration of seven forage sorghum genetic stocks near-isogenic for the brown midrib genes bmr-6 and bmr-12. *Crop Sci* 46 (1):490-491

Pedersen JF, Toy JJ, Funnell DL, Sattler SE, Oliver AL, Grant RA (2008) Registration of BN611, AN612, BN612, and RN613 Sorghum Genetic Stocks with Stacked bmr-6 and bmr-12 Genes. *Journal Of Plant Registrations* 2 (3):258-262. doi:10.3198/jpr2008.01.0065crs.

Pillonel C, Mulder MM, Boon JJ, Forster B, Binder A (1991) Involvement of Cinnamyl-Alcohol Dehydrogenase in the Control of Lignin Formation in Sorghum-Bicolor L Moench. *Planta* 185 (4):538-544

R Core Team., 2023. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. <https://www.r-project.org/>

Rivera-Burgos, L.A., Volenec, J.J., and Ejeta, G., 2019. Biomass and bioenergy potential of brown midrib sweet sorghum germplasm. *Frontiers in plant science*, 10, 1142.

Rao, P.S., Deshpande, S., Blümmel, M., Reddy, B.V., and Hash, T., 2012. Characterization of brown midrib mutants of sorghum (*Sorghum bicolor* (L.) Moench). *European Journal of Plant Science and Biotechnology*.

Rooney, W.L., 2000. Genetics and cytogenetics. In: Smith, C.W., Frederiksen, R.A.(Eds.), *Sorghum: Origin, history, technology, and production*. John Wiley & Sons, NY, pp. 261–307.

Reddy, B.V., Ramesh, S., Reddy, P.S., Ramaiah, B., Salimath, M., and Kachapur, R., 2005. Sweet sorghum a potential alternate raw material for bio-ethanol and bio-energy. *International Sorghum and Millets Newsletter*, 46, 79-86.

Sattler, S.E., Funnell-Harris, D.L., and Pedersen, J.F., 2010. Brown midrib mutations and their importance to the utilization of maize, sorghum, and pearl millet lignocellulosic tissues. *Plant Science*, 178(3), 229-238.

Saballos, A., Ejeta, G., Sanchez, E., Kang, C., and Vermerris, W., 2009. A genome-wide analysis of the cinnamyl alcohol dehydrogenase family in sorghum [*Sorghum bicolor* (L.) Moench] identifies SbCAD2 as the brown midrib6 gene. *Genetics*, 181(2), 783-795.

Sattler, S.E., Funnell-Harris, D.L., and Pedersen, J.F., 2010. Efficacy of singular and stacked brown midrib 6 and 12 in the modification of lignocellulose and grain chemistry. *Journal of Agricultural and Food Chemistry*, 58(6), 3611-3616.

Sattler, S.E., Palmer, N.A., Saballos, A., Greene, A.M., Xin, Z., Sarath, G., Vermerris, W., and Pedersen, J.F., 2012. Identification and characterization of four missense mutations in Brown midrib 12 (Bmr12), the caffeic O-methyltransferase (COMT) of sorghum. *Bioenergy Research* 5: 855–865.

Sattler, S.E., Saathoff, A.J., Haas, E.J., Palmer, N.A., Funnell-Harris, D.L., Sarath, G., & Pedersen, J.F., 2009. A nonsense mutation in a cinnamyl alcohol dehydrogenase gene is responsible for the sorghum brown midrib6 phenotype. *Plant physiology*, 150(2), 584-595.

Sattler, S.E., Saballos, A., Xin, Z., Funnell-Harris, D.L., Vermerris, W., and Pedersen, J.F., 2014. Characterization of novel sorghum brown midrib mutants from an EMS-mutagenized population. *G3: Genes, Genomes, Genetics*, 4(11): 2115-2124.

Scavuzzo-Duggan, T., Varoquaux, N., Madera, M., Vogel, J.P., Dahlberg, J., Hutmacher, R., & Scheller, H.V., 2021. Cell wall compositions of *Sorghum bicolor* leaves and roots remain relatively constant under drought conditions. *Frontiers in Plant Science*, 12, 747225.

Schuetz M., Benske A., Smith R.A., Watanabe Y., Tobimatsu Y., Ralph J., Demura T., Ellis B., Samuels A.L., 2014. Laccases direct lignification in the discrete secondary cell wall domains of protoxylem. *Plant Physiology*, 166: 798–807. doi: 10.1104/pp.114.245597.

Shavrukov, Y., Kurishbayev, A., Jatayev, S., Shvidchenko, V., Zotova, L., Koekemoer, F., & Langridge, P., 2017. Early flowering as a drought escape mechanism in plants: how can it aid wheat production? *Frontiers in plant science*, 8, 1950.

Somerville, C., 2006. Cellulose synthesis in higher plants. *Annu. Rev. Cell Dev. Biol.*, 22, 53-78.

Tse, T.J., Wiens, D.J., & Reaney, M.J., 2021. Production of bioethanol-A review of factors affecting ethanol yield. *Fermentation*, 7(4), 268.

Theerarattananoon K, Wu X, Staggenborg S, Propheter J, Madl R, Wang D (2010) Evaluation and characterization of sorghum biomass as feedstock for sugar production. *Trans ASABE* 53 (2):509-525

Umakanth, A.V., Datta, A., Reddy, B.S., and Bardhan, S., 2022. Biomass feedstocks for advanced biofuels: Sustainability and supply chain management. *Advanced Biofuel Technologies*, 39-72.

Velmurugan, B., Narra, M., Rudakiya, D.M., & Madamwar, D., 2020. Sweet sorghum: a potential resource for bioenergy production. In *Refining biomass residues for sustainable energy and bioproducts* (pp. 215-242). Academic Press.

Wahyono, T., Indiratama, W.M., & Human, S., 2021. White Midrib (WMR) vs Brown Midrib (BMR) sorghum: perspective of nutrient value for ruminant forage. In *IOP Conference Series: Earth and Environmental Science* (Vol. 788, No. 1, p. 012164). IOP Publishing.

Welker, C.M., Balasubramanian, V.K., Petti, C., Rai, K.M., DeBolt, S., & Mendu, V., 2015. Engineering plant biomass lignin content and composition for biofuels and bioproducts. *Energies*, 8(8), 7654-7676.

Xia, Y., Chen, F., Du, Y., Liu, C., Bu, G., Xin, Y., & Liu, B., 2019. A modified SDS-based DNA extraction method from raw soybean. *Bioscience reports*, 39(2), BSR20182271.

UNDER PEER REVIEW