Journal of Integrative Agriculture 2017, 16(6): 1236–1243

Available online at www.sciencedirect.com

ScienceDirect

REVIEW

Sweet sorghum and *Miscanthus*: Two potential dedicated bioenergy crops in China

HU Shi-wei[1, 2], WU Lei-ming[1, 2], Staffan Persson[2, 3], PENG Liang-cai[1, 2], FENG Sheng-qiu[1, 2]

[1] *National Key Laboratory of Crop Genetic Improvement/National Centre of Plant Gene Research, Huazhong Agricultural University, Wuhan 430070, P.R.China*

[2] *Biomass and Bioenergy Research Centre, College of Plant Science and Technology, Huazhong Agricultural University, Wuhan 430070, P.R.China*

[3] *ARC Centre of Excellence in Plant Cell Walls, School of Botany, University of Melbourne, Parkcille 3010, Australia*

Abstract

Among the potential non-food energy crops, the sugar-rich C_4 grass sweet sorghum and the biomass-rich *Miscanthus* are increasingly considered as two leading candidates. Here, we outline the biological traits of these energy crops for large-scale production in China. We also review recent progress on understanding of plant cell wall composition and wall polymer features of both plant species from large populations that affect both biomass enzymatic digestibility and ethanol conver-

Keywords: sweet sorghum, *Miscanthus*, conversion

1. Introduction

Bioenergy is regarded as a sustainable alternative to fossil energy supply (Chen and Peng 2013; Cotton *et al*. 2013). As the second largest energy consumer globally, China has launched several non-fossil energy developing plans, including the 11th Five-Year Plan for Energy Development Planning of China (NDRC 2007a), and the Medium- and Long-Term Developmental Plan for Renewable Energy in China (NDRC 2007b).

To reach the goals outlined in these plans, the selection of bioenergy crops is an important priority to meet the need of biomass production. In general, bioenergy crops can be

and lignocellulose-rich crops for bioethanol production, as well as oilseed crops for biodiesel (Li *et al*. 2010). Starch or sugar-based bioethanol and edible-oil-derived biodiesel may, however, impose challenges for food security if produced on a large scale in China. Nevertheless, conversion of lignocellulosic residues from food crops is a potential alternative (Xie and Peng 2011). Despite those approximately 0.7–0.9 billion tons of crop residues are produced each year, almost half of the residues are burnt to ash or

et al. 2009). In addition, approximately 0.1 billion ha of marginal lands not suitable for food crops can be applied to grow energy

---

Received 16 April, 2015 Accepted 26 August, 2015
Correspondence FENG Sheng-qiu, Tel: +86-27-87281765, Fax: +86-27-87280066, E-mail: fengsq@mail.hzau.edu.cn

doi: 10.1016/S2095-3119(15)61181-9

crops to meet the large demand of biomass feedstock in China (Yan *et al*. 2008). We argue that sweet sorghum and *Miscanthus* should be considered as major candidates of non-food energy crops for marginal lands.

2. Biological characteristics of sweet sorghum and *Miscanthus*

biomass into biofuels, efforts have been made to grow dedicated biomass crops in China. Sweet sorghum and *Miscanthus*, which are respectively originated in Africa and East Asia, are the candidate crops with extremely high biomass yields. Moreover, as these two species are evolutionary related, research advances in each of the crops will expedite improvement in the other crops (Van der Weijde *et al*. 2013).

Sweet sorghum grows rapidly (a life-cycle is around 120–150 days), and has high biomass yield (6.0–7.5 t dry matter (DM) ha^{-1} yr^{-1}). Sweet sorghum is, furthermore,

third of water compared to sugarcane and half of that of corn (Li J *et al.* 2013). It is also drought, salt and cold tolerant as compared to conventional bioenergy crops (e.g., sugarcane and corn). As sweet sorghum can adapt to various environments with low fertilizer requirements, it is extensively grown globally, and is particularly well suited for agriculture in the north of China (Li and Chan-Halbrendt 2009; Xie and Su 2012). Li *et al*. (2014a) and Wu *et al*. (2015) examined over 200 sweet sorghum germplasm accessions stored in the National Plant Germplasm System of China. These accessions were collected from across the world and displayed clear differences in agronomic trait, such as plant height, stem diameter, pitch numbers, lodging resistance, soluble sugar levels and seed yield. From such germplasm collec-

sorghum accessions that are rich in soluble sugars and that have high digestible lignocellulosic bagasse suitable for bioenergy purposes (Byrt *et al*. 2011; Zegada-Lizarazu and Monti 2012; Li *et al*. 2014a).

Miscanthus is also a typical C$_4$ plant that grows rapidly with low fertilizer requirement and high tolerance/resistance to drought, salt and cold conditions. It has wide geographic distributions and high biomass yields ranged from 37.5 to 60.8 t DM ha^{-1} yr^{-1}. For instance, the natural distribution of *Miscanthus sinensis* in China is 100.45–127.55°E, 18.34–43.70°N, alititude –12–1 900 m across 23 provinces (Table 1). So far, eleven species of *Miscanthus* have

et al. 2009), and over 1 400 natural *Miscanthus* accessions, including four different species (*M. sacchariflorus*, *Miscanthus lutarioriparius*, *Miscanthus sinensis*, and *Miscanthus floridulua*) have been collected in China (Xie and Peng 2011).

Regardless of the relatively low soluble sugars in the stalks compared with sweet sorghum, *Miscanthus* is considered as a leading lignocellulosic bioenergy crop in China, and across the world (Lewandowski *et al*. 2003; Angelini *et al*. 2009; Xie and Peng 2011). While *Miscanthus* is mainly exploited for lignocellulosic biomass, sweet sorghum, maize, and sugarcane are dual-purpose crops for foods and biofuels (Table 1).

3. Bioethanol production from lignocellulosic residues of sweet sorghum and *Miscanthus*

Various technologies have been applied to enhance biomass

-

cy. Sweet sorghum contains approximately 160–180 g L^{-1} fermentable sugars, including sucrose, glucose and fructose, in the stalk juice (Laopaiboon *et al*. 2009), which can be readily converted into ethanol by yeast fermentation (Sipos *et al*. 2009; Ratnavathi *et al*. 2010). It is also an ideal substrate for fuel gas production, such as hydrogen,

et al. 2008). A two-step membrane separation process has been developed to increase sugar concentrations and thus ethanol productivity from the stalk juice (Sasaki *et al*. 2014). The remaining bagasse of sweet sorghum is lignocellulose-rich which can also be processed to ethanol. To enhance the enzymatic digestibility of sweet sorghum bagasse, various pretreatment methods have been examined. Dilute NaOH solution autoclaving and H$_2$O$_2$ immersing pretreatment

sugar yield and ethanol concentration by approximately 6-, 10- and 20-folds, respectively, compared with the control (Cao *et al*. 2012). Integrating hydrothermal pretreatment

et al

enzymatic hydrolysis of bagasse and conversion of 85 to 90% of the bagasse into ethanol (Sipos *et al*. 2009). Integration of solid-state fermentation technology and alkaline pretreatment has been shown to be a cost-effective process for the production of the ethanol from the sweet sorghum bagasse (Li J *et al*. 2013). In addition, sweet sorghum stalk has been examined as the feedstock for methane (Matsakas *et al*. 2014) and hydrogen production (Antonopoulou *et al*. 2008). It has also been used for heat production (Sipos *et al*. 2009). Sweet sorghum produces grains at a yield of about 2.2–4.5 t DM ha^{-1} yr^{-1}, which can be used as food as well as the feedstock for bioethanol and pigment production (Gao *et al*. 2010).

Unlike sweet sorghum, *Miscanthus* is a dedicated lignocellulosic crop. Field trials in Europe during the last 15 years with the sterile, triploid hybrid *Miscanthus×giganteus* (Clifton-brown *et al*. 2004; Heaton *et al*. 2004) have produced annual harvestable yields that range from 10 to 40 t DM ha^{-1} yr^{-1}; more than double that of switchgrass. One ton of *Miscanthus* could produce up to 80 gallons of cellulosic ethanol (Lewandowskiet *et al*. 2000). Compared with maize (*Zea mays*), *Miscanthus* (*Miscanthus× giganteus*) is almost 60% more productive (Dohleman and Long 2009). An almost complete digestion (95%) was achieved by employing a two-stage method (alkaline peroxide and electrolyzed water). This was a better yield than the use of 1% H_2SO_4 pretreatment (200°C, 8 min) (Wang *et al*. 2010). Various chemical and physical pretreatments have also been applied to enhance biomass enzymatic digestibility and ethanol production from *Miscanthus* (Zhang *et al*. 2013; Li *et al*. 2014b). However, harsher pretreatment conditions are required in *Miscanthus* than that of sweet sorghum bagasse, probably due to its distinct biomass recalcitrance.

4. Lignocellulosic features affecting bio-

-

cation negatively in sweet sorghum, *Miscanthus* and other plants (Yang *et al*. 2011; Wu *et al*. 2013; Zhang *et al*. 2013; Li *et al*. 2014b). This is likely due to the fact that reduced cellulose DP increases cellulose chain-reducing ends and therefore reduces cellulose crystallinity (Zhang and Lynd 2004; Pan *et al*. 2008). In addition, the mole number (MN) of

enzymatic digestibility. The cellulose MN can be determined by dividing cellulose content per unit length by mole weight of cellulose (Kokubo *et al*. 1991). In *Miscanthus*, the MN correlates negatively with biomass enzymatic digestion after pretreatments with NaOH and H_2SO_4 (Zhang *et al*. 2013).

Hemicelluloses are a class of heterogeneous polysaccharides with various hexose and pentose units. In grasses, xylans are the major hemicelluloses and are commonly

and/or C3-position (Girio *et al*. 2010; Scheller and Ulvskov 2010). Hemicelluloses are generally believed to provide cross-linking interactions with cellulose and lignin, which strengthens the cell wall and possibly function as molecular

Miscanthus accessions with diverse cell wall compositions, hemicelluloses were found to be a predominant factor that positively determines biomass enzymatic digestibility after pretreatments with NaOH and H_2SO_4 by reducing cellulose crystallinity (Xu *et al*. 2012). Furthermore, a higher degree of arabinose substitution of xylan (reverse Xyl/Ara)

Miscanthus (Li F *et al*. 2013). Here, hemicelluloses with high arabinose levels correlated negatively with cellulose crystallinity and enhanced both plant lodging resistance and biomass enzymatic digestibility in rice (Li *et al*. 2015). In sweet sorghum and wheat, a high arabinose substitution degree of non-KOH-extractable hemicelluloses can also enhance biomass enzymatic digestibility by reducing cellulose crystallinity (Wu *et al*. 2013; Li *et al*. 2014a).

Lignin is a stable and complex polymer consisting of three major phenylpropane units: *p*-hydroxyphenyl (H), guaiacyl (G), and syringyl (S) (Sun *et al*. 2013). As lignin is associated with other wall polymers *via* ester- and ether-linked bonds, it acts as barriers that hinder enzyme penetration to access cellulose surfaces (Achyuthan *et al*. 2010). Due to its structural diversity and heterogeneity, lignin has multiple roles in biomass enzymatic digestions. For example, increased S/G ratios negatively affect digestibility of *Miscanthus* biomass, whereas increased H/G ratios pos-

(Xu *et al*. 2012; Wu *et al*. 2013; Jia *et al*. 2014; Li *et al*.

crystallinity in sweet sorghum, high levels of lignin G-monomers had a negative impact on biomass digestion, and

inhibited yeast fermentation (Li *et al*. 2014b). In *Miscanthus*, the minor wall-networks between monolignols and interlinked-phenolics predominantly affects biomass digestibility, and mild alkali-pretreatment effectively extracts guaiacyl-rich lignin for high lignocellulose digestibility coupled with largely diminishing yeast fermentation inhibitors (Li *et al*. 2014b). In addition, lignin extraction enhances biomass enzymatic

Miscanthus species under various alkali and acid pretreatments (Si *et al*. 2015).

In conclusion, reduced CrI/DP and increased arabinose

both sweet sorghum and *Miscanthus*, whereas high levels of G-monomers and low S/G ratios of lignin negatively affect biomass digestibility, respectively (Table 2). This suggests that optimizing certain wall characteristics will make sweet sorghum and *Miscanthus* more suitable as the feedstock for liquid biofuel production.

5. Biotechnology for sweet sorghum and *Miscanthus* bioenergy breeding

As large populations of natural germplasm accessions of

Table 2 *Miscanthus*

Plant species	Cell wall polymers	Cell wall composition (% dry matter)	Polymer features[1)]	Impacts on biomass	References
Sweet sorghum	Cellulose	27–37	CrI, DP	Negative	Yang *et al*. (2011); Li *et al*. (2014a); Wang *et al*. (2014)
	Hemicellulose	29–33	Reverse Xyl/Ara	Positive	Li *et al*. (2014a); Wang *et al*. (2014)
	Ligin	17–20	G, S/G	Negative	Li *et al*. (2014a); Wang *et al*. (2014)
Miscanthus	Cellulose	28–49	CrI, DP, MN	Negative	Zhang *et al*. (2013); Van der Weijde *et al*. (2013); Wang *et al*. (2014)
	Hemicellulose	24–32	Reverse Xyl/Ara	Positive	Xu *et al*. (2012); Li F *et al*. (2013); Wang *et al*. (2014)
	Ligin	15–28	S/G	Negative	Li *et al*. (2014b); Li Z *et al*. (2014); Wang *et al*. (2014)

[1)] CrI, cellulose crystallinity index; DP, degree of polymerization of crystalline cellulose; Reverse Xyl/Ara, degree of arabinose substitution of xylan; G, guaiacyl; S/G, syringyl/guaiacyl ratio; MN, the mole number of cellulose.

sweet sorghum and *Miscanthus* have exhibited a diverse

appropriate to screen for high biomass digestibility for biofuel production. However, traditional screening approaches are labor-intensive, time-consuming and expensive as it includes chemical analyses of plant cell wall compositions and estimates of total sugar yields released *via* enzymatic hydrolysis (Roberts *et al*. 2011; Li *et al*. 2014b). Recently, near infrared spectroscopy has been used for high-throughput screening of sweet sorghum and *Miscanthus* accessions (Huang *et al*. 2012; Wu *et al*. 2015). Using 199 *Miscanthus*

upon various physical (heat) and chemical (1% NaOH, 1% H_2SO_4) pretreatments (Huang *et al*. 2012). In addition, a total of 123 sweet sorghum accessions and 50 mutants were examined for stalk soluble sugars, bagasse enzymatic

measurements, calibration equations were generated that can effectively determine the relationships between stalk

cell wall polymers (Wu *et al*. 2015).

Miscanthus is a natural hybrid, and has more than 20 excellent biological characteristics. Over the past years, various new technologies of biomass pretreatments have been applied in sweet sorghum and *Miscanthus* to enhance biomass enzymatic digestibility and to reduce ethanol -

tions that affect the plant cell wall have been proposed as holding great promise to overcome biomass recalcitrance by reducing cellulose crystallinity, increasing arabinose substitution degree of xylans, or altering the relative proportions of the three monolignols in lignin in sweet sorghum and *Miscanthus*. Furthermore, screening of large populations of natural germplasm accessions and cell wall mutants is an alternative approach to identify new lines with improved

approach to develop new varieties for bioenergy production in sweet sorghum and *Miscanthus*.

Acknowledgements

This work was supported by grants from the Fundamental Research Funds for the Central Universities Project , China (2013QC042), the Fundamental Research Funds for the 111 Project of Ministry of Education of China (B08032), and the Starting Foundation for Changjiang Scholars Program of Ministry of Education of China (52204-14004).

References

Achyuthan K E, Achyuthan A M, Adams P D, Dirk S M, Harper J C, Simmons B A, Singh A K. 2010. Supramolecular self-assembled chaos: Polyphenolic lignin's barrier to cost-effective lignocellulosic biofuels. *Molecules*, **15**, 8641–8688.

Angelini L G, Ceccarini L, Nasso N, Bonari E. 2009. Comparison of *Arundo donax* L. and *Miscanthus×giganteus* in a

productive characteristics and energy balance. *Biomass and Bioenergy*, **33**, 635–643.

Antonopoulou G, Gavala H N, Skiadas I V, Angelopoulos K, Lyberatos G. 2008. Biofuels generation from sweet sorghum: Fermentative hydrogen production and anaerobic digestion of the remaining biomass. *Bioresource Technology*, **99**,110–119.

Arioli T, Peng L, Betzner A S, Burn J, Wittke W, Herth W, Camilleri C, Höfte H, Plazinski J, Birch R, Cork A, Glover J, Redmond J, Williamson R E. 1998. Molecular analysis of cellulose biosynthesis in *Arabidopsis*. *Science*, **279**, 717–720.

generation. *Current Opinion in Biotechnology*, **23**, 1–8.

Byrt C, Grof C, Furbank R. 2011. C_4 plants as biofuel feedstocks: Optimizing biomass production and feedstock quality from a lignocellulosic perspective. *Journal of Integrative Plant Biology*, **53**, 120–135.

Cao W, Sun C, Liu R, Yin R, Wu X. 2012. Comparison of the enzymatic digestibility and ethanol production from sweet sorghum bagasse. *Bioresource Technology*, **111**, 215–221.

Chen L G, Xing L, Han L J. 2009. Renewable energy from agro-residues in China: Solid biofuels and biomass briquetting technology. *Renewable and Sustainable Energy Reviews*, **13**, 2689–2695.

Chen P, Peng L. 2013. The diversity of lignocellulosic biomass resources and their evaluation for use as biofuels and chemicals. In: Sun J Z, Ding S Y, Peterson J D, eds., *Biological Conversion of Biomass for Fuels and Chemicals: Exploration from Natural Biomass Utilization Systems*. Royal Society of Chemistry, Oxfordshire. pp. 83–113.

Miscanthus biomass production for energy in Europe and its potential contribution to decreasing fossil fuel carbon emissions. *Global Change Biology*, **10**, 509–518.

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**, 711–718.

Dohleman F G, Long S P. 2009. More productive than maize in the midwest: How does *Miscanthus* do it? *Plant Physiology*, **150**, 2104–2115.

Feng Y, Zou W, Li F, Zhang J, Zhang H, Xie G, Tu Y, Lu T, Peng L. 2013. Studies on biological characterization of rice brittle

Journal of Agricultural Science and Technology, **15**, 77–83.

Fry S C. 1988. *The Growing Plant Cell Wall*: *Chemical and Metabolic Analysis*. Longman, London. pp. 95–97.

Gao C, Zhai Y, Ding Y, Wu Q. 2010. Application of sweet sorghum for biodiesel production by heterotrophic microalga *Chlorella protothecoides*. *Applied Energy*, **87**, 756–761.

screening marker. *Genome Research*, **48**, 321–333.

Gao Z, Xie X, Ling Y, Muthukrishnan S, Liang G H. 2005b. *Agrobacterium* tumefaciens-mediated sorghum transformation using a mannose selection system. *Plant Biotechnology*, **3**, 591–599.

Girio F M, Fonseca C, Carvalheiro F, Duarte L C, Marques S, Bogel-Lukasik R. 2010. Hemicelluloses for fuel ethanol: A review. *Bioresource Technology*, **101**, 4775–4800.

Guo K, Zou W, Feng Y, Zhang M, Zhang J, Tu F, Xie G, Wang L, Wang Y, Senbastian K, Persson S, Peng L. 2014. An integrated genomic and metabolomic framework for cell wall biology in rice. *BioMed Central Genomics*, **15**, 596–609.

Heaton E, Clifton-Brown J, Voigt T, Jones M, Long S. 2004. *Miscanthus* for renewable energy generation: European union experience and projections for illinois. *Mitigation and Adaptation Strategies for Global Change*, **9**, 433–451.

Himmel M E, Ding S, Johoson D K, Adney W S, Nimlos M R, Brady J W, Foust T D. 2007. Biomass recalcitrance: Engineering plants and enzymes for biofuels production. *Science*, **315**, 804–807.

Huang J, Xia T, Li A, Yu B, Li Q, Tu Y, Zhang W, Yi Z, Peng L. 2012. A rapid and consistent near infrared spectroscopic assay for biomass enzymatic digestibility upon various physical and chemical pretreatments in *Miscanthus*. *Bioresource Technology*, **121**, 274–281.

Huang Y, Wei X, Zhou S, Liu M, Tu Y, Li A, Chen P, Wang

Y, Zhang X, Tai H, Peng L, Xia T. 2015. Steam explosion of cotton stalks by largely reducing cellulose polymerization degree in *G. barbadense* and *G. hirsutum*. *Bioresource Technology*, **181**, 224–230.

Hwang O J, Cho M A, Han Y J, Kim Y M, Lim S H, Kim D S, Kim J I. 2014. *Agrobacterium*-mediated genetic transformation of *Miscanthus sinensis*. *Plant Cell Tissue and Organ Culture*, **117**, 51–63.

Hyoung S K, Guirong Z, John A J, Jack M W. 2010. *Miscanthus ×giganteus* plant regeneration: Effect of callus types, ages and culture methods on regeneration. *Global Change Biology Bioenergy*, **2**, 192–200.

Jakob K, Zhou F S, Paterson A H. 2009. Genetic improvement of C_4 grasses as cellulosic biofuel feedstocks. *In Vitro Cellular and Developmental Biology* (Plant), **45**, 291–305.

Jia J, Yu B, Wu L, Wang H, Wu Z, Li M, Huang P, Feng S, Chen P, Zheng Y, Peng L. 2014. Biomass enzymatic wall polymer features that predominately affect cellulose crystallinity in corn. *PLOS ONE*, **9**, e108449.

Kokubo A, Sakurai N, Kuraishi S, Takeda K. 1991. Culm brittleness of barley (*Hordeum vulgare* L.) mutants is caused by smaller number of cellulose molecules in cell wall. *Plant Physiology*, **97**, 509–514.

Laopaiboon L, Nuanpeng S, Srinophakun P, Klanrit P, Laopaiboon P. 2009. Ethanol production from sweet sorghum juice using very high gravity technology: Effects of carbon and nitrogen supplementations. *Bioresource Technology*, **100**, 4176–4182.

Lewandowski I, Clifton-Brown J C, Scurlock J M O, Huisman W. 2000. Miscanthus: European experience with a novel energy crop. *Biomass and Bioenergy*, **19**, 209–277.

Lewandowski I, Scurlock J, Lindvall E, Christou M. 2003. The development and current status of perennial rhizomatous grasses as energy crops in the USA and Europe. *Biomass and Bioenergy*, **25**, 335–361.

Li F, Ren S, Zhang W, Xu Z, Xie G, Chen Y, Tu Y, Li Q, Zhou S, Li Y, Tu F, Liu L, Wang Y, Jiang J, Qin J, Li S, Li Q, Jing H, Zhou F, Gutterson N, *et al*. 2013. Arabinose substitution degree in xylan positively affects lignocellulose enzymatic digestibility after various NaOH/H_2SO_4 pretreatments in *Miscanthus*. *Bioresource Technology*, **130**, 629–637.

Li F, Zhang M, Guo K, Hu Z, Zhang R, Feng Y, Yi X, Zou W, Wang L, Wu C, Tian J, Lu T, Xie G, Peng L. 2015. High-level hemicellulosic arabinose predominately affects lignocellulose crystallinity for genetically enhancing both plant lodging resistance and biomass enzymatic digestibility in rice mutants. *Plant Biotechnology Journal*, **13**, 514-525.

Li J, Li S, Han B, Yu M, Li G, Jiang Y. 2013. A novel cost-effective technology to convert sucrose and homocelluloses in sweet sorghum stalks into ethanol. *Biotechnology for Biofuels*, **6**, 174–185.

Li M, Feng S, Wu L, Li Y, Fan C, Zhang R, Zou W, Tu Y, Jing H, Li S, Peng L. 2014a. Sugar-rich sweet sorghum is distinctively affected by wall polymer features for biomass digestibility and ethanol fermentation in bagasse. *Bioresource Technology*, **167**, 14–23.

Li M, Si S, Hao B, Zha Y, Wan C, Hong S, Kang Y, Jia J, Zhang J, Li M, Zhao C, Tu Y, Zhou S, Peng L. 2014b. Mild alkali-pretreatment effectively extracts guaiacyl-rich lignin for high lignocellulose digestibility coupled with largely diminishing yeast fermentation inhibitors in *Miscanthus*. *Bioresource Technology*, **169**, 447–454.

Li S, Chan-Halbrendt C. 2009. Ethanol production in (the) People's Republic of China: potential and technologies. *Applied Energy*, **86**, 162–169.

Li X, Hou S, Su M, Yang M, Shen S, Jiang G, Qi D, Chen S, Liu G. 2010. Major energy plants and their potential for bioenergy development in China. *Environmental Management*, **46**, 579–589.

Li Z, Zhao C, Zha Y, Wan C, Si S, Liu F, Zhang R, Li F, Yu B, Yi Z, Xu N, Peng L. 2014. The minor wall-networks between monolignols and interlinked-phenolics predominantly affect biomass enzymatic digestibility in *Miscanthus*. *PLOS ONE*, **9**, e105115.

Liu L, Yu B, Huang P, Jia J, Zhao H, Peng J, Chen P, Peng L. 2013. Frequency of callus induction and plant regeneration among eight genotypes in *Miscanthus sinensis* species. *Chinese Bulletin of Botany*, **48**, 192–198. (in Chinese)

Matsakas L, Rova U, Christakopoulos P. 2014. Evaluation of dried sweet sorghum stalks as raw material for methane production. *BioMed Research International*, **2014**, 1–7.

NDRC (National Development and Reform Commission). 2007a. The Medium- and Long-term Development Plan for Renewable Energy in China. Beijing, China. (in Chinese)

NDRC (National Development and Reform Commission). 2007b. The 11th Five-Year Plan for the Energy Development Planning of China. Beijing, China. (in Chinese)

Pan X, Xie D, Yu R W, Saddler J N. 2008. The bioconversion of mountain pine beetle-killed lodgepole pine to fuel ethanol using the organosolv process. *Biotechnology and Bioengineering*, **1**, 39–48.

Paterson A H, Bowers J E, Bruggmann R, Dubchak I, Grimwood J, Gundlach H, Haberer G, Hellsten U, Mitros T, Poliakov A, Schmutz J, Spannagl M, Tang H, Wang X, Wicker T, Bharti A K, Chapman J, Feltus F A, Gowik U, Grigoriev I V, *et al*.

of grasses. *Nature*, **457**, 551–55]TJ0 a. converJ0 a. converJ in sweet sorghum and selection of a new sweet sorghum hybrid for use in syrup production in Appalachia. *Crop Science*, **50**, 1788–1794.

Qazi H A, Paranjpe S, Bhargava S. 2012. Stem sugar accumulation in sweet sorghum

–

of sucrose metabolizing enzymes and sucrose transporters. *Journal of Plant Physiology*, **169**, 605–613.

Ragauskas A J, Williams C K, Davison B H, Britovsek G, Cairney J, Eckert C A, Frederick Jr W J, Hallett J P, Leak D J, Liotta C L, Mielenz J R, Murphy R, Templer R, Tschaplinski T. 2006. The path forward for biofuels and biomaterials. *Science*, **311**, 484–489.

Ratnavathi C, Suresh K, Vijay Kumar B, Pallavi M, Komala V, Seetharama N. 2010. Study on genotypic variation for ethanol production from sweet sorghum juice. *Biomass and Bioenergy*, **34**, 947–952.

&

for industrial applications. *Trends in Biotechnology*, **23**, 22–27.

sweet sorghum bagasse. *Crop Science*, **51**, 2284–2288.

Sasaki K, Tsuge Y, Sasaki D, Teramura H, Wakai S, Kawaguchi H, Sazuka T, Ogino C, Kondo A. 2014. Increased ethanol production from sweet sorghum juice concentrated by a membrane separation process. *Bioresource Technology*, **169**, 821–825.

Scheller H V, Ulvskov P. 2010. Hemicelluloses. *The Annual Review of Plant Biology*, **61**, 263–289.

Shrawat A K, Lorz H. 2006. *Agrobacterium*-mediated transformation of cereals: A promising approach crossing barriers. *Plant Biotechnology Journal*, **4**, 575-603.

Sipos B, Reczey J, Somorai Z, Kadar Z, Dienes D, Reczey K. 2009. Sweet sorghum as feedstock for ethanol production: Enzymatic hydrolysis of steam-pretreated bagasse. *Applied Biochemistry and Biotechnology*, **53**, 151–162.

Si S, Chen Y, Fan C, Hu H, Li Y, Huang J, Liao H, Hao B, Li Q, Peng L, Tu Y. 2015. Lignin extraction distinctively enhances

rich *Miscanthus* species under various alkali and acid pretreatments. *Bioresource Technology*, **183**, 248–254.

Slavov G, Allison G, Bosch M. 2013. Advances in the genetic dissection of plant cell walls: Tools and resources available in *Miscanthus*. *Frontiers in Plant Science*, **4**, 217–237.

rice 4-coumarate:coenzyme A ligase enzyme activity and

biosynthesis in rice. *Biochemical and Biophysical Research Communication*, **430**, 1151–1156.

Sun S L, Sun S N, Wen J, Zhang X, Peng F, Sun R. 2015. Assessment of integrated process based on hydrothermal

of sweet sorghum stems. *Bioresource Technology*, **175**, 473–479.

Wang B, Wang X, Feng H. 2010. Deconstructing recalcitrant *Miscanthus* with alkaline peroxide and electrolyzed water. *Bioresource Technology*, **101**, 752–760.

Wang X, Tetsuya Y, Fan J, Yuki A, Yoichiro H, Hiroko S, Tadashi T, Akira K, Toshihiko Y. 2011. Establishment of an *in vitro* culture and particle bombardment-mediated transformation systems in *Miscanthus sinensis* Anderss., a potential bioenergy crop. *Global Change Biology Bioenergy*, **3**, 322–332.

Wang Y, Xu Z, Peng L. 2014. Research progress in the groove structures of plant cell walls and biomass utilizations. *Scientia Sinica Vitae*, **44**, 766–774. (in Chinese)

Van der Weijde T, Alvim Kamei C L, Torres A F, Vermerris W, Dolstra O, Visser R G F, Trindade L M. 2013. The potential of C_4 grasses for cellulosic biofuel production. *Frontiers in Plant Science*, **4**, 107–124.

Wu L, Li M, Huang J, Zhang H, Zou W, Hu S, Li Y, Fan C, Zhang R, Jing H, Peng L, Feng S. 2015. A near infrared spectroscopic assay for stalk soluble sugars, bagasse

sorghum. *Bioresource Technology*, **177**, 118–124.

Wu Z, Zhang M, Wang L, Tu Y, Zhang J, Xie G, Zou W, Li F, Guo K, Li Q, Gao C, Peng L. 2013. Biomass digestibility is predominantly affected by three factors of wall polymer features distinctive in wheat accessions and rice mutants. *Biotechnol for Biofuels*, **6**, 183–196.

Xie G, Peng L. 2011. Genetic engineering of energy crops: A strategy for biofuel production in China. *Journal of Integrative Plant Biology*, **53**, 143–150.

Xie G, Yang B, Xu Z, Li F, Guo K, Zhang M, Wang L, Zou W,

OsGH9 family members and their involvement in cellulose crystallinity. *PLOS ONE*, **8**, e50171.

Xie T, Su P. 2012. Canopy and leaf photosynthetic characteristics

stress. *Russian Journal of Plant Physiology*, **59**, 224–234.

Xu N, Zhang W, Ren S, Liu F, Zhao C, Liao H, Xu Z, Huang J, Li Q, Tu Y, Yu B, Wang Y, Jiang J, Qin J, Peng L. 2012. Hemicelluloses negatively affect lignocellulose crystallinity for high biomass digestibility under NaOH and H_2SO_4 pretreatments in *Miscanthus*. *Bitechnology for Biofuels*, **5**, 58–69.

Yan L Z, Zhang L, Wang S Q, Hu L. 2008. Potential yields of bioethanol from energy crops and their regional distribution in China. *Transactions of the Chinese Society of Agricultural Engineering*, **24**, 213–216. (in Chinese)

Yang B, Dai Z, Ding S, Wyman C E. 2011. Enzymatic hydrolysis of cellulosic biomass. *Biofuels*, **2**, 421–450.

Yu Y, Yi Z, Zhou G. 2014. Research progress and comprehensive utilization of *Miscanthus*. *Chinese Bulletin of Life Sciences*, **5**, 474–480. (in Chinese)

Zegada-Lizarazu W, Monti A. 2012. Are we ready to cultivate

management practices. *Biomass and Bioenergy*, **40**, 1–12.

Zhang L, Liu Z, Chen B, Hao D, Gao S, Jing H. 2012. Current status and application prospects of sweet sorghum breeding in China. *Journal of China Agricultural University*, **6**, 76–82. (in Chinese)

Zhang W, Yi Z, Huang J, Li F, Hao B, Li M, Hong S, Lv Y, Su W, Ragauskas A, Hu F, Peng J, Peng L. 2013. Three lignocellulose features that distinctively affect biomass enzymatic digestibility under NaOH and H_2SO_4 pretreatments in *Miscanthus*. *Bioresource Technology*, **130**, 30–37.

Zhang Y, Lynd L R. 2014. Toward an aggregated understanding of enzymatic hydrolysis of cellulose: Noncomplexed cellulase systems. *Biotechnology and Bioengineering*, **88**, 797–824.

Zhao Z, Cai T, Tagliani L, Miller M, Wang N, Pang H, Rudert M, Schroeder S, Hondred D, Seltzer J, Pierce D. 2000. *Agrobacterium*-mediated sorghum transformation. *Plant Molecular Biology*, **44**, 789–798.

Zheng L, He B, Sun L, Peng Y, Dong S, Liu T, Jiang S, Ramachandran S, Liu C, Jing H. 2011. Genome-wide patterns of genetic variation in sweet and grain sorghum (*Sorghum bicolor*). *Genome Biology*, **12**, R114.

Zhou J, Li Q, Xiao L, Jiang J, Yi Z. 2012. Potential distribution of *Miscanthus sinensis* and *M. floridulus* in China. *Chinese Journal of Plant Ecology*, **36**, 504–510. (in Chinese)

Zub H W, Brancourt H M. 2010. Agronomic and physiological performances of different species of *Miscanthus*, a major energy crop. A review. *Agronomy for Sustainable Development*, **30**, 201–214.

(Managing editor SUN Lu-juan)