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Review

Bamboo: A new source of carbohydrate for biorefinery

Ming-xiong He[a,b,*], Jing-li Wang[a,c], Han Qin[a], Zong-xia Shui[a,c], Qi-li Zhu[a], Bo Wu[a], Fu-rong Tan[a], Ke Pan[a], Qi-chun Hu[a,b], Li-chun Dai[a], Wen-guo Wang[a], Xiao-yu Tang[a], Guo Quan Hu[a,b,**]

[a] Biogas Institute of Ministry of Agriculture, Biomass Energy Technology Research Centre, Section 4-13, Renming Nanlu, Chengdu 610041, PR China
[b] Key Laboratory of Development and Application of Rural Renewable Energy, Ministry of Agriculture, Chengdu 610041, PR China
[c] Graduate School of Chinese Academy of Agricultural Sciences, Beijing 10081, PR China

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ABSTRACT

Bamboo is perennial woody grass, which distributed widely in the world and belonged to the Gramineae family and Bambuseae subfamily. It may be consider as a candidate lignocellulosic substrate for bio-ethanol production for its environmental benefits and higher annual biomass yield. The conversion of bamboo into bio-ethanol, bio-methane, natural food, flavonoids, and functional xylo-oligosaccharides production were reviewed in this paper. Future prospects for research include pretreatment, enzymatic hydrolysis and fermentation will also be performed to improve the whole process of ethanol production more economical. And revealing the molecular regulation mechanism of the fast growth of bamboo will provide chance for improving bamboo or other energy plants biomass yield through genetic engineering.

Contents

Abbreviations: AFEX, ammonia fiber explosion; H-AFEX, hydrogen peroxide ammonia fiber explosion; COSLIF, concentrated phosphoric acid and organic solvent-based lignocellulose fractionation; FPU, filter paper unit; IL, ionic liquid; 2D-PAGE, two dimensional-gels; nonoLC/MS–MS, nano-high performance liquid chromatography–tandem mass spectrometry; NGS, next-generation sequencing.

* Corresponding author at: Biogas Institute of Ministry of Agriculture, Biomass Energy Technology Research Centre, Section 4-13, Renming Nanlu, Chengdu 610041, PR China. Tel.: +86 28 85242281.
** Corresponding author at: Biogas Institute of Ministry of Agriculture, Biomass Energy Technology Research Centre, Section 4-13, Renming Nanlu, Chengdu 610041, PR China. Tel.: +86 28 85212059.
E-mail addresses: hemingxiong@caas.cn, hemxion@hotmail.com (M.-x. He), huguoquan1@hotmail.com (G.Q. Hu).

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1. Introduction

Bio-ethanol has attracted more and more attention as a strategy for greenhouse gas (GHG) reduction or global energy security. Currently, commercial bio-ethanol production mainly depend on fermentation of sucrose and glucose (Davis, Rogersb, Pearcec, & Peirisa, 2006). Brazil and the United State together accounted for about 60.0% of the world ethanol production by using sugarcane and corn as feedstock, respectively (Chandel et al., 2007). Actually, global ethanol yield grew rapidly since 2007, led by the world's two largest fuel producer (Chum, Warner, Seabra, & Macedo, 2013), as shown in Fig. 1. USA is the largest ethanol producer in the world, the yield of bio-ethanol has increased dramatically from 175 million gallons in 1980 to more than 13 billion gallons in the past five years (data come from 2013 Ethanol Industry OUTLOOK – Renewable Fuels Association). However, during 2012, its ethanol production experienced decline from 2011 for the first time in 16 years. The same trend has also been seen in Brazil ethanol industry. After 2010, ethanol yield in Brazil has also decreased nearly 20%. Even China has kept a constant ethanol yield in past five years, ranged from 502 to 555 millions of gallon, these data also indicated that increased ethanol production may be limited by corn or sugarcane feedstock.

Actually, in recent years, many scientists or organization have provide some debate on corn-based or sugarcane-based bio-ethanol industry, which may raise concerns of food security (Schmer, Mitchell, & Perrin, 2008), environmental degradation debate (Pimentel & Patzek, 2005) and other issues. To overcome these limitations, many scientist are focusing on developing novel

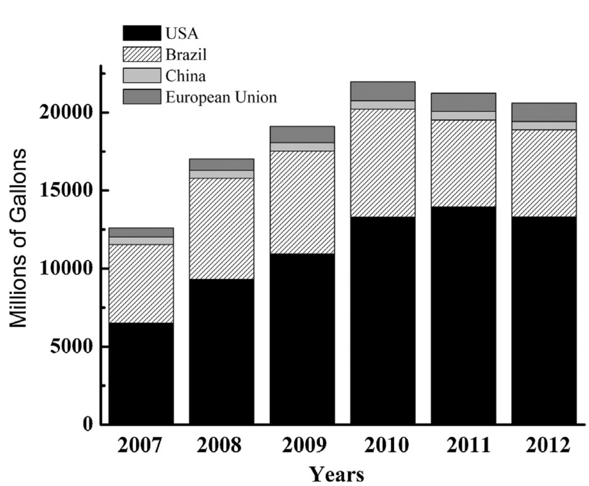

Fig. 1. Global ethanol production by country/region and year (2007–2012). *Data source*: Renewable Fuels Association (RFA). *Web site*: http://www.ethanolrfa.org/pages/statistics.

or cheaper feedstocks to substitute corn or sugarcane for bioenergy production in the future (Balat & Balat, 2009). The most attractive substrate is lignocellulosic biomass, from which ethanol or other value-added products can be produced via bioconversion (Lynd, Cushman, Nichols, & Wyman, 1991; Zaldivar, Nielsen, & Olsson, 2001). In the past decades, some energy crops, such as switchgrass (Schmer et al., 2008), aquatic *Eichhornia crassipes* (Ogawa Masami & Naoto Urano, 2008), and agricultural or forestry residues, have attracted more and more attention for bioenergy utilization (Perlack et al., 2005). Actually, most process concepts for bio-ethanol including three steps, including biomass pretreatment, enzymatic hydrolysis and engineered strain-based fermentation of the fermentable sugars (Olofsson, Bertilsson, & Lidén, 2008). Although lignocellulosic biomass provides an abundant and renewable source for bio-ethanol production, the process on a commercial scale is also limited in pretreatment, enzymatic hydrolysis and robust microorganisms, etc.

Bamboo is perennial woody grass, which distributed widely in the world and belonged to the Gramineae family and Bambuseae subfamily. China is the largest bamboo-producing country and has about 300 species in 44 genera, occupying 3% of global forest area (Scurlock, Dayton, & Hames, 2000). Currently, the widely utilization of bamboo are not only paper, textile and food industry, but also used for construction and reinforcing fibers. Recently, some studies also showed that bamboo resource could be considered as a candidate feedstock of biomass energy for its high growth efficiency (Kobayashi, Take, Asada, & Nakamura, 2004; Littlewood, Wang, Turnbull, & Murphy, 2013; Scurlock et al., 2000; Tsuda, Aoyama, & Cho, 1998). So, in this paper, we reviewed that the progress on bamboo resource from its potential of ethanol production, including environmental benefits, annual biomass yield, chemical composition, pretreatment, saccharification and fermentation, etc.). Other value-added applications, such as bio-methane, natural food, flavonoids, functional xylo-oligosaccharides production were also reviewed in this article. Future prospects for research including pretreatment, enzymatic hydrolysis and fermentation will also be performed to improve the whole process of ethanol production more economical. And revealing the molecular regulation mechanism of the fast growth of bamboo will provide chance for improving bamboo or other energy plants biomass yield through genetic engineering techniques.

2. Bamboo: A candidate cellulosic biomass resource

Currently, different cellulosic biomass, such as crop residues (i.e. corn straw, wheat straw, sugarcane bagasse, etc.), energy crops (i.e. switchgrass, miscanthus, etc.), which were considered as candidate feedstocks for bio-ethanol production (Phitsuwan, Sakka, & Ratanakhanokchai, 2013; Sarkar, Ghosh, Bannerjee, & Aikat, 2012; Vohra, Manwar, Manmode, Padgilwar, & Patil, 2013). Many research articles have also focusing on bio-ethanol production from these resource (Hess, Wright, & Kenney, 2007). For example, Kim et al. estimated the global annual potential bio-ethanol production from different crop residues, which showed rice straw, wheat straw, and corn stover are the most favorable bio-ethanol feedstocks in Asia or other regions (Kim & Dale, 2004). Another type of celluolosic biomass is energy crop. For example, switchgrass (*Panicum virgatum* L.) is a typical cellulosic substrate for bioethanol production for its higher biomass yield (excess 20 Mg h^{-1}) and other environmental benefits (Keshwani & Cheng, 2009). Miscanthus represents another key candidate energy crop, which also attracted considerable attention for its special characteristics (such as high biomass yield and high chemical composition) (Brosse, Dufour, Meng, Sun, & Ragauskas, 2012). As a new cellulosic biomass resource, bamboo has aroused interest as an energy crop for production of bamboo in past five years (He et al., 2013b; Kuttiraja et al., 2013; Leenakul & Tippayawong, 2013; Li, Jiang, Fei, Cai, & Pan, 2014; Li, Jiang, Fei, Yu, & Cai, 2012; Littlewood et al., 2013; Sathitsuksanoh, Zhu, Ho, Bai, & Zhang, 2010; Scurlock et al., 2000; Sun, Tang, Iwanaga, Sho, & Kida, 2011; Yamashita, Shono, Sasaki, & Nakamura, 2010; Yasuda et al., 2013). We will review its environmental benefits, biomass yield, chemical composition and some issues related to ethanol or other products production from bamboo resource based on comparison analysis of published data.

3. Bio-ethanol production from bamboo

As lignocellulosic biomass, bio-ethanol production from bamboo shared the general process for ethanol production from lignocellulosic, which including pretreatment, enzymatic hydrolysis, and fermentation (Keshwani & Cheng, 2009). Firstly, pretreatment play an important role in improving accessibility of enzymes to lignocellulosic biomass fractions (Govumoni, Koti, Kothagouni, & Linga, 2013). Pretreatment is the most crucial step as it has a large impact on all the followed steps, including enzymatic hydrolysis and fermentation. Major research efforts have been spent to find efficient and environmental friendly pretreatment methods, which render a structure that is easy to hydrolyze by enzymes. Secondly, holocellulose (including cellulose and hemicellulose fractions) could be hydrolyzed into fermentable sugars by enzyme mixture, while lignin can be recovered or used as type of fuel or other utilizations. Thirdly, after hydrolysis, the resulting sugars will be fermented into ethanol for distilling by engineered ethanologenic strain (Littlewood et al., 2013). Currently, there are some technological or economical barriers of ethanol production from these lignocellulosic biomass in the whole conversion process (Koppram, Tomás-Pejó, Xiros, & Olsson, 2013; Margeot, Hahn-Hagerdal, Edlund, Slade, & Monot, 2009).

3.1. Environmental benefits of bamboo resource

As a typical forest type in subtropical and tropical areas, bamboo forest paly an important role for its biological characteristic and growth habits. It is not only an ideal economic plant for utilization in many ways, but also has a positive effect on many environmental issues. As reviewed by Zhou et al., bamboo have showed some ecological functions on soil erosion control, water conservation, land rehabilitation, and carbon sequestration, etc. (Zhou, Fu, Xie, Yang, & Li, 2005). Song et al. also reviewed the ecological function in Chinese bamboo forests, including carbon sequestration, water and soil conservation, its benefits for soci-economic development, and its potential to mitigate climate change (Song et al., 2011). Importantly, bamboo forests are recognized as a large carbon sink in the global cycles of carbon in China. As shown in Chen et al., the carbon stocks in bamboo forest have been dramatically increasing from 318.55 to 631.58 Tg C since the 1950s (Chen, Zhang, Zhang, Booth, & He, 2009). Chen et al. also predicted that the carbon stocks in bamboo stands based on previous data for 2050 will reach to 1017.64 Tg C (Chen et al., 2009), which showed great potential in carbon fixation. In another example by Zhou et al., carbon storage in bamboo forest system in China may be reached 1138.8 Tg C (Zhou, Meng, Jiang, & Xu, 2011), which showed 11.9% higher than Chen et al. (Chen et al., 2009). From this issue, we conclude that bamboo may be not only an ideal economic, but also a dominant plant for environmental consideration.

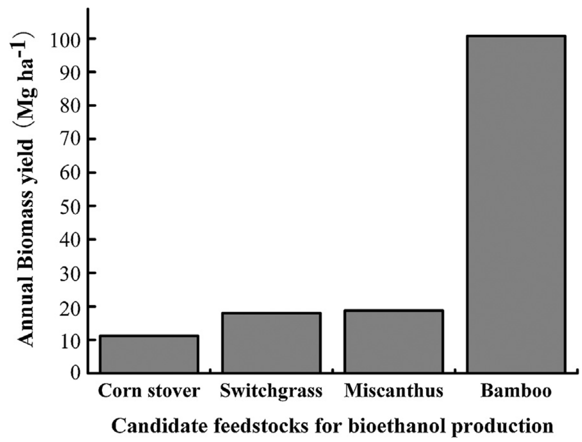

Fig. 2. Comparsion of biomass yield between representative lignocellulosic biomass resources than bamboo. Data come from the average in Table 1.

3.2. Higher annual biomass yield of bamboo resource

Previous study showed that bamboo have higher growth rate (ranged from 30–60 cm/day) and height (about 36 m) in growing season (Zhou et al., 2005), which indicated that bamboo could produce higher biomass yield than other crops. Suzuki and Jacalne et al. firstly reported above-ground biomass and the growth of bamboo stands in the Philippines (Suzuki & Jacalne, 1986). The above ground biomass of bamboo was 146.8 Mg ha^{-1} yr^{-1}. Above ground biomass of bamboo in northeast India was also investigated by Nath et al., total above ground standing biomass of the grove was 42.98 Mg ha^{-1} yr^{-1} (Nath, Das, & Das, 2008). Hong et al. firstly compared the annual biomass yield between bamboo and *Miscanthus* species, which ranged from 5.9 to 49.5 Mg ha^{-1} yr^{-1} for bamboo and 3.2–49.0 Mg ha^{-1} yr^{-1} for *Miscanthus*. However, up to date, comparisons of biomass yield of bamboo and other representative lignocellulosic biomass resources have not been previously reported in the literature. In this paper, average of annual biomass yield of different cellulosic biomass resources were firstly compared based on these published data (as shown in Table 1). Biomass yield of corn stover have been studied by many scientists, which ranged from 6 to 15.6 Mg ha^{-1} yr^{-1} (We re-calculated its yield as average of 11.2 Mg ha^{-1} yr^{-1} in Fig. 2) (Pordesimo, Edens, & Sokhansanj, 2004; Sokhansanj, Turhollow, Cushman, & Cundiff, 2002; Varvel, Vogel, Mitchell, Follett, & Kimble, 2008). As dedicated energy crops, switchgrass (*Panicum virgatum* L.) and miscanthus (*Miscanthus* × *giganteus*) have also studied by many scientists. The biomass yield was ranged from 9 to 36.7 Mg ha^{-1} yr^{-1} and 4.7–49 Mg ha^{-1} yr^{-1} based on different published paper, respectively (We also re-calculated its yield as average of 17.96 Mg ha^{-1} yr^{-1} and 18.74 Mg ha^{-1} yr^{-1} in Fig. 2, respectively). Hybrid poplar and *Eucalyptus* were also studied by many scientists. The biomass yield was ranged from 3.04 to 22.7.7 Mg ha^{-1} yr^{-1} (McLaughlin, Hansen, & Pope, 1987; Verlinden,

Table 1
Comparsion of biomass yield between representative lignocellulosic biomass resource and bamboo.

Feedstock	Average of annual biomass yield (Mg ha^{-1})	References
	6	Varvel et al. (2008)
Corn stover	15.6	Pordesimo, Edens, and Sokhansanj (2004)
	12	Sokhansanj et al. (2002)
	26	Sanderson et al. (1996)
	36.7	Thomason et al. (2005)
	11.1	Schmer et al. (2008)
	14.2	Fike et al. (2006)
Switchgrass (*Panicum virgatum* L.)	13	Burks (2013)
	9	Lemus et al. (2002)
	15.87	Aravindhakshan, Epplin, and Taliaferro (2010)
	17.8	Kering, Butler, Biermacher, and Guretzky (2012)
	38	Burks (2013)
	12.39	Aravindhakshan et al. (2010)
	4.7	Kering, Butler, Biermacher, and Guretzky (2012)
Miscanthus (*Miscanthus × giganteus*)	13.1	Hastings et al. (2013)
	35	Johnson, Wyse, and Sheaffer (2013)
	27.4	Maughan et al. (2012)
	14.4	Larsen, Jørgensen, Kjeldsen, and Lærke (2013)
	49	Hong et al. (2011)
	22.7	McLaughlin et al. (1987)
Hybrid Poplar (*Populus*)	11.46	Zamora et al. (2013)
	3.04–14.43	Verlinden et al. (2013)
	16.8–28	Gonzalez et al. (2011)
Eucalyptus	8.2–45.2	Ahimana and Maghembe (1987)
	20.19	Binkley and Ryan (1998)
	241.7	Kumar, Rajesh, and Sudheesh (2005)
	105.33	Yen, Ji, and Lee (2010)
	42.98	Nath, Das, and Das (2008)
Bamboo	61.05	Jyoti Nath, Das, and Das (2009)
	49.5	Hong et al. (2011)
	146.8	Suzuki and Jacalne (1986)
	58.2	Suzuki and Jacalne (1986)

Broeckx, Van den Bulcke, Van Acker, & Ceulemans, 2013; Zamora, Wyatt, Apostol, & Tschirner, 2013) and 8.2–28 Mg ha^{-1} yr^{-1} (Ahimana & Maghembe, 1987; Binkley & Ryan, 1998; Gonzalez et al., 2011) based on different published paper, respectively. Based on these data, biomass yield of bamboo was 100.79 Mg ha^{-1} yr^{-1}, which showed 8.9-fold, 5.61-fold, and 5.38-fold than corn stover, switchgrass, and miscanthus, respectively (as shown in Fig. 2). Although these data are differential based on different source or culture condition, from this issue, we also deduced that bamboo may be consider as a potential feedstock for bioenergy production as same the other representative lignocellulosic biomass resources. It also showed some advantages for its higher biomass yield.

3.3. Chemical composition of bamboo resource

The major chemical composition of bamboo are also cellulose, hemicellulose and lignin, which closely associated in a complex structure (Li et al., 2014; Sun et al., 2011). Table 2 and Fig. 3 show the amount of cellulose, hemicelluloses and lignin of bamboo in comparison to different typical biomass resource. Bamboo showed higher cellulose and lignin content, lower hemicellulose content than corn straw, swichgrass and aquatic plants. In some study case, the cellulose content of bamboo reached 47% (Li et al., 2014; Sun et al., 2011), which showed 9%, 10% higher than corn stover and switchgrass, respectively. Another study also showed that bamboo consisted predominantly of glucan, xylan and acid insoluble lignin that added up to 78.5% on a dry weight basis (García-Aparicio et al., 2011). In general, an equal content of total lignocellulose (about 83%) will receive when used an average data from different references (Fig. 3a), which indicated that bamboo has a large amount of sugars and may consider as a candidate feedstock for ethanol production as may crop residues or energy crop. On the other hand, based on the data of annual biomass yield (Table 1 and Fig. 2) and chemical composition of bamboo resource (Table 2), the distribution of celluolse and hemicellulose were re-calculated. As shown in Fig. 3b, the total holocellulose of corn stover, switchgrass, miscanthus will reach to 7.39 Mg ha^{-1} yr^{-1}, 11.49 Mg ha^{-1} yr^{-1}, and 5.81 Mg ha^{-1} yr^{-1}, respectively. However, the total holocellulose of bamboo may be reached to 60.48 Mg ha^{-1} yr^{-1} for its higher annual biomass yield, which showed 8.18-fold, 5.26-fold, and 10.41-fold than corn stover, switchgrass and miscanthus, respectively (Fig. 3b). It means that bamboo have more great potential for biomass production on limited land use.

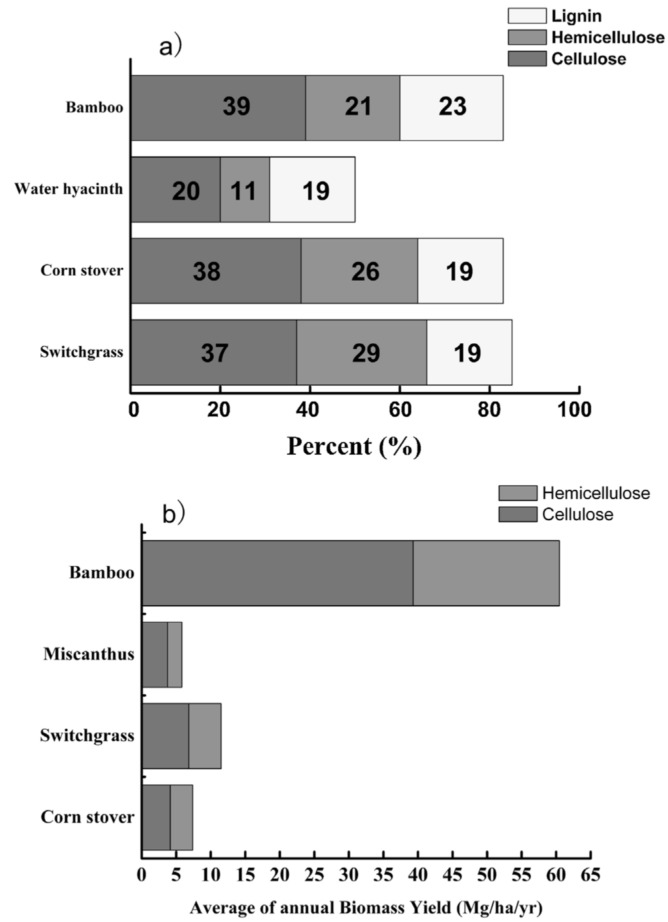

Fig. 3. Comparison of feedstock composition and annual holcellulose yield. (a) Comparison of feedstock composition of switchgrass, corn stover, water hyacinth and bamboo. Data were summarized from Table 1, and bamboo data come from the average in Table 2. (b) Comparison of annual holocellulose yield between representative lignocellulosic biomass resources than bamboo. Data come from the average in Table 1 and Table 2.

3.4. Pretreatment of bamboo

Pretreatment is a necessary step during the whole process of cellulosic ethanol production (Galbe & Zacchi, 2012; Sanderson,

Table 2
Comparsion of chemical composition between representative lignocellulosic biomass resource and bamboo.

Feedstock	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Reference
Crop residues				
Corn stover	38	26	19	
Wheat straw	38	29	15	
Barley straw	42	28		
Rye straw	31	25		
Sugarcane Bagasse	39	25	23	
Coffee husks	43	7	9	Biomass Feedstock Composition and Property Database of NREL[a]
Energy plant				
Switchgrass	37	29	19	
Miscanthus	43	24	19	
Hybrid Poplar	39	17	25	
Black Locust	40	18	29	
Tall Fescue	25	19	13	
Yellow Poplar	42	19	23	
Eucalyptus	48	13	27	
Aquatic plants				
Water hyacinth (Eichhornia crassipes)[b]	20	11	19	
Bamboo[b]				
Bamboo	42	24	28	Scurlock et al. (2000)
Bamboo (Kumamoto, Japan)	47	23	28	Sun et al. (2011)
Bamboo	43	15	26	Sathitsuksanoh et al. (2010)
Bamboo (*Dendrocalamus* sp.)	47	16	18	Kuttiraja et al. (2013)
Bamboo	44	30	26	Yasuda et al. (2013)
Moso bamboo (*Phyllostachys pubescens* Mazel)	46	23	26	Yamashita et al. (2010)
Bamboo (*Dendrocalamus asper*)	41	27	27	Leenakul and Tippayawong (2013)
Moso bamboo (*Phyllostachys heterocycla*)	42–47	22–23	23–31	Li, Jiang, Fei, Cai, and Pan (2014)
Bamboo	38.4	20.5	20.8	Littlewood et al. (2013)
Moso bamboo (*Phyllostachys heterocycla*)	37	22	24	Li, Jiang, Fei, Yu, and Cai (2012)
Bamboo shoots shell fiber (BSSF)	23	14	11	He et al. (2013a,b)
Bamboo stem and leaf (BSL)	21	12	12	He et al. (2013a,b)

[a] All data come from Biomass Feedstock Composition and Property Database of NREL (http://www.afdc.energy.gov/biomass/progs/search1.cgi).
[b] Data come from other references.

2011). Importantly, an effective pretreatment method is required for the efficient production of fermentable sugars from bamboo via enzyme saccharification. Currently, different pretreatment methods have developed in many labs. Many articles have reviewed those pretreatment methods in this process, including physical (i.e. mechanical reduction), chemical (i.e. steam explosion, hydrothermolysis, dilute acid, lime, and ammonia pretreatments) or biological, etc. (Galbe & Zacchi, 2012; Mosier et al., 2005). Compared to these methods, biological pretreatment, such as fungal pretreatment, which could reduce the recalcitrance of lignocellulosic biomass by special enzyme mixture secreted from lignin-degrading microorganisms and thus potentially provide an environmental friendly or energy-efficient technology for further purpose, which have also paid attention in recent years (Wan & Li, 2012). Up to date, kinds of pretreatment methods have used for pretreating bamboo resource, including physical, chemical or biological pretreatment, as shown in the following.

3.4.1. Steam explosion

Steam-treated giant bamboo for production of fermentable sugars have investigated firstly in 1996 by Aoyama (1996). An improved method based on acid catalyzed steaming for releasing of bamboo xylan was also reported (Aoyama & Seki, 1999). Yamashita et al. reported the maximum value of 456 mg glucose/g initial dry sample from bamboo under condition of 20 atm steam explosion (Yamashita et al., 2010). In order to improve enzymatic susceptibility, the effect of different acid catalysts on steam explosion (197 °C for 10 min) were also investigated, which showed a positive effect on sugar yield (Tsuda et al., 1998). In another study, sulphur dioxide (SO_2) was also used as a novel type of catalysts for improve the effect of steam explosion. The maximum overall sugar yield of 81.2% (52.4 g/100 g dry giant bamboo) was obtained for the pretreatment performed at 214 °C for 6 min (García-Aparicio et al., 2011).

3.4.2. Chemical pretreatment

Different chemical pretreatment methods, including ozone, acids, alkali, organic solvents and peroxides, etc., which have used for pretreating lignocellulosic biomass (Alvira, Tomás-Pejó, Ballesteros, & Negro, 2010; Mosier et al., 2005). For example, dilute acid pretreatment of bamboo shoots shell fiber (BSSF) and bamboo stem and leaf (BSL) were investigated in our lab, the yield of xylose reached to 83.90–95.69%, and the yield of glucose only reached to 12.13–25.65% (He et al., 2011). Bamboo (*Dendrocalamus asper*) was pretreated with dilute sulfuric acid prior to enzymatic hydrolysis process to produce fermentable sugars, which was also investigated in other lab (Leenakul & Tippayawong, 2013). In this study, maximum glucose and xylose yields were achieved under 140 °C, 1.2% sulfuric acid concentration and 90 min residence times (Leenakul & Tippayawong, 2013). Dilute phosphoric acid pretreatment of bamboo was also studied for producing dissolving pulp for textile utilization. Optimum conditions were 170 °C and 45 minutes residence times, which could lead to a weight loss of 26.5% of the solid and liquid fraction after pretreatment (Hong, Xue, Weng, & Guo, 2012). Sun et al. also developed a process of concentrated sulfuric acid hydrolysis, the highest sugar recovery efficiency was 81.6% when concentrated sulfuric acid hydrolysis was carried out (Sun et al., 2011). The process was improved by recyling the water and sulfuric acid, which could reduce the environmental impact of the whole process (Sun, Tang, Morimura, & Kida, 2013).

Dilute alkali was also used for pretreating bamboo (*Dendrocalamus* sp.) process waste by Kuttiraja et al., the total sugar polymers were recovered, and the hydrolysis efficiency is 82.36% (Kuttiraja et al., 2013). Recently, Zhang et al. developed a solvent-(Concentrated phosphoric acid) and organic solvent-(95% ethanol) based Lignocellulose Fractionation (COSLIF) methods to pretreat bamboo. In this study, glucan digestibility was 88.2% at cellulase loading of 1 FPU/g glucan. Maximum glucose and xylose yields were 86.0% and 82.6%, respectively (Sathitsuksanoh et al., 2010).

Table 3
Comparsion of different pretreatment methods for bamboo.

Pretreatment	Glucose yield (%)	Xylose yield (%)	Conditions[c]	References
Dilute acid	12.13–25.65	83.90–95.69	1.5% H_2SO_4, 121 °C, 60 min	He et al. (2011)
	3.19[a]	46.23[ap]	1.2% H_2SO_4, 140 °C, 90 min	Leenakul and Tippayawong (2013)
Concentrated acid	42.89–77.46	46.06–53.49	83% H_3PO_4, 50 °C, 90 min	He et al. (2013a,b, 2011)
Alkaline peroxide	83.16[a,b]		1% (v/v) NaOH, 90 °C, 60 min	Yamashita et al. (2010)
	58.42[a,b]		1% (v/v) hydrogen peroxide, 90 °C, 60 min	
	36.56–58.2	68.5–97.96	1% NaOH, room temperature, 12 h	He et al. (2011)
Steam explosion	66.76[a,b]		20 atm steam explosion	Yamashita et al. (2010)
	81.2%[b]		2.5% SO_2, 214 °C for 6 min	García-Aparicio et al. (2011)
AFEX	64.8–72.7%		150 °C, 0.8 or 2.0 (w/w) water, 10–30 min, 2.0–5.0 (w/w) ammonia	Shao et al. (2013)
H-AFEX	83.4–92.1%		150 °C, 0.8 or 2.0 (w/w) water, 10–30 min, 2.0–5.0 (w/w) ammonia, with 0.7–1.9 (w/w) 30% (wt) hydrogen peroxide	
Catalyzed steaming	60–70%[b]		197 °C for 10 min with different acid catalysts	Tsuda et al. (1998)
Microwave-KOH	20.87	63.06	12% KOH, 400 W for 30 min,	Li, Jiang, Fei, Yu, and Cai (2012)
COSLIF	86	82.6	85% Phosphoric acid and 95% ethanol, 50 °C, 1 atm for 60 min	Sathitsuksanoh et al. (2010)

[a] Re-caluated based on the content of cellulose and hemicellulose.
[b] Total reducing sugar.
[c] In addition of enzymatic hydrolysis.

Alkali combined with microwave pretreatment on enzymatic hydrolysis of bamboo was also investigated. In this study, KOH (12% and 8% w/w bamboo) solutions and exposing the slurry to 400 W microwave power for 30 min residence times was performed. The results showed that the pretreated substrate with microwave assisted KOH had significantly higher sugar yield than the untreated samples. The fermentation inhibitors formic acid, furfural, HMF and levulinic acid were much lower than acid pretreatment reported (Li et al., 2012). Shao et al. developed H-AFEX (Hydrogen peroxide-AFEX) pretreatment method for moso bamboo (*Phyllostachys heterocycla* var. pubescens), which could achieve a theoretical sugars yield of 83.4–92.1% after enzymatic hydrolysis (Shao, Cheng, Ong, Zhu, & Zhao, 2013).

Although these methods are effective for bamboo pretreatment, the comparison of study between different methods need to be performed in the future. Li et al. comprised the behavior of bamboo green, timber, and yellow of moso bamboo to sulfite, dilute acid and NaOH pretreatment. The results indicated that sulfite pretreatment could be able to generate more readily digestible bamboo substrate with higher sugar yield and fewer inhibitors (Li et al., 2014).

For improvement of the environmental problems on chemical preatment, Ninomiya et al. reported an ionic liquid (IL)-based pretreatment method for bamboo. In this study, different ratios of IL/biomass ranged from 0 to 10 g/g were investigated in bamboo pretreatment. The better result was obtained when IL/biomass ratio of 3 g/g was used, which will give us a suitable reference about quantity of IL to decrease the cost of lignocellulosic biomass pretreatment (Ninomiya, Soda, Ogino, Takahashi, & Shimizu, 2013). Actually, Li et al. compared the effect of biomass recalcitrance, delignification and enzymatic saccharification between IL and dilute acid pretreatment for switchgrass, which showed higher glucan yield for IL pretreatment (Li et al., 2010). Although IL was demonstrated as an efficient system for hydrolysis of lignocellulosic biomass under mild conditions (ChangZhi, Qian, & Zhao, 2008), the cost of the IL preatment need to be taken into consideration in the future. Binder and Raines et al. provide a solution for decreasing the cost of IL pretreatment by ionic liquid recover and recycle before fermentation (Binder & Raines, 2010).

3.4.3. Biological pretreatment

Although a variety of chemical pretreatment methods have been developed and showed an effective result for attacking the structure of lignocellulosic biomass, the conditions are severe and higher energy input. Biological pretreatment is superior to these chemical pretreatment methods for its advantage of mild conditions and lower energy consumption, which paid more and more consideration (Akin et al., 1995). For example, white-rot fungi could degrade lignin efficiently, which may be used in biological pretreatment of lignocellulose (Hakala et al., 2005; Hatakka, 2005). Zhang et al. also used white rot fungi to pretreat bamboo culms, which have shown potential for improving enzymatic hydrolysis. Sugar yield from pretreated bamboo culms with white-rot fungi increased 5.15–8.76-fold, and lignin loss was more than 20% (Zhang, Yu, Huang, & Liu, 2007). In another study, Zhang et al. used a white-rot fungus *Coriolus versicolor* B1 to pretreat bamboo, the results showed that this biological pretreatment could enhanced the saccharification rate significantly. Reducing sugars yield was 223.2 mg/g of bamboo residues, which was 2.34 times than that of the raw material (Zhang, Xu, & Wang, 2007). Zeng et al. also investigated thermal characteristics of moso bamboo by white-rot fungal pretreatment, the results showed that the white-rot fungal pretreatment is advantageous to thermal decomposition of lignin in bamboo (Zeng, Yang, Yu, Zhang, & Ma, 2012). However, variety of proteins participated in the biological pretreatment are still unknown. Recently, the secretome of *Irpex lacteus* and other white-rot fungi during pretreatment were investigated by differential proteomic analysis with 2D-PAGE and nonoLC/MS–MS, which will give such insight into the degradation process and suggest novel dedicated enzyme or mixtures for improvement of its efficient hydrolysis (Salvachúa et al., 2013).

3.5. Saccharification and fermentation

After the pretreatment of lignocellulosic material, enzymatic hydrolysis (mainly depend on cellulase, endo-β-1–4-xylanase, exoxylanase and β-xylosidase, etc.) will be performed to produce fermentable sugar (Koppram et al., 2013; Sun & Cheng, 2002). The dominant component of enzymatic hydrolysate are glucose and xylose, the other are arabinose, galactose, mannose, fucose and rhamnose (Margeot et al., 2009). Finally, these fermentable sugar will be used for further fermentation (Table 3). Currently, different strains, such as engineered *Saccharomyces cerevisiae*, *Escherichia coli* and *Zymomonas mobilis* were used for converting these sugars into ethanol (Deanda, Zhang, Eddy, & Picataggio, 1996; Ingram & Vreeland, 1980; Koppram et al., 2013; Linger, Adney, & Darzins, 2010; Matsushika, Inoue, Kodaki, & Sawayama, 2009; Osman & Ingram, 1985; Seo et al., 2005; Stanley, Bandara, Fraser, Chambers, & Stanley, 2010; Zhang, Eddy, Deanda, Finkelstein, & Picataggio, 1995). However, little study have focused on this

Table 4
Comparsion of different pretreatment methods for bamboo.

Pretreatment	Strain	Ethanol (g/l)	Fermentation yield (%)	Ethanol productivity (g/l/h)	References
Concentrated sulfuric acid hydrolysis	*Saccharomyces cerevisiae* strain KF-7	27.2	92	8.2	Sun et al. (2011)
Concentrated phosphoric acid	*Zymomonas mobilis* ZM4	4.72	55.82	0.20	He et al. (2013a,b)
Dilute alkali	*Saccharomyces cerevisiae*	24.3	71.34	0.51	Kuttiraja et al. (2013)

process. For example, *S. cerevisiae* and *Z. mobilis* was also used for converting bamboo hydrolysate into bio-ethanol via batch or continuous fermentation mode, as shown in Table 4. Further research should also be performed to evaluate the potential of ethanol yield and its fermentation kinetics by using different engineered strains.

4. Other products from bamboo

4.1. Natural food, xylitol, flavonoids production and xylo-oligosaccharides from bamboo

As we all known, bamboo shoot contained natural products, such as potassium, carbohydrate, dietary fibers, vitamins and other active materials, which is used for a traditional food in many countries (Choudhury, Sahu & Sharma, 2012). On the other hand, these carbohydrate may be converted into other products, such as xylitol. For example, microbial conversion of bamboo hemicellulose hydrolysate to xylitol was performed by using *Candida magnoliae*, the maximum xylitol production (10.5 g L^{-1}) and the maximum xylitol volumetric productivity (0.42 g L^{-1} h^{-1}) were attained (Miura et al., 2013). The results showed that bamboo may be considered as feedstock for xylitol production.

Furthermore, bamboo contained some active materials, which may be used for medicine. For example, antioxidant of bamboo leaves, an ethanol extract derived from bamboo leaves of the *Phyllostachys Sieb.et Zucc.* family (especially *P. nigra* var. *henonis*, *P. edulis* and *P. bambusoides*), was demonstrated to be strong inhibitory effect on transition metal ions and free radicals (Hu, Zhang, & Kitts, 2000), which may be considered as non-mutagenic, non-embryotoxic and non-genotoxic (Lu, Wu, Shi, Dong, & Zhang, 2006; Lu, Wu, Tie, Zhang, & Zhang, 2005). Another representive product in bamboo is flavonoid, which have shown valuable application in many fields. Currently, a varity of methods about flavonoids extraction from bamboo have been performed (Jiao et al., 2007; Xie et al., 2013; Zhang, Jiao, Liu, Wu, & Zhang, 2008), which will led to a added-value for baomoo utilization.

Xylo-oligosaccharides are xylose-based oligomers, which have multiple applications in fields related to the food, pharmaceutical industries, biodegradable plastics or nanoparticles (Courtois, 2009; Moure, Gullón, Domínguez, & Parajó, 2006; Otieno & Ahring, 2012; Otieno, Dargahi, Thomsen, & Ahring, 2012; Patel & Goyal, 2011; Vazquez, Alonso, Domınguez, & Parajo, 2000). Recently, xylo-oligosaccharides production from lignocellulosic biomass having substituted xylan as the major hemicellulose component (Nabarlatz, Ebringerová, & Montané, 2007; Parajó, Garrote, Cruz, & Dominguez, 2004). As a lignocellulosic biomass, bamboo may be used for functional xylo-oligosaccharides production. Aoyama and Seki et al. reported that the main component is low molecular weight xylo-oligosaccharides when bamboo was pretreated with saturated steam in the presence of various acid catalysts (Aoyama & Seki, 1994, 1999), which could provide a process of xylo-oligosaccharides production. In another study, bamboo was pretreated by using sulfonated allophane as catalyst under 130 to 160 °C condition. The results showed that hemicellulose in bamboo was preferentially decomposed into xylose and xylo-oligosaccharides (Ogaki et al., 2009). Xiao et al. reported a process for xylo-oligosaccharides production from bamboo by autohydrolysis. In this study, bamboo was treated with hot water in non-isothermal conditions under different temperature and various reaction times in a batch reactor, the maximum yield of xylo-oligosaccharides of 47.49% was achieved (Xiao et al., 2013).

In general, these results indicated that bamboo is not only a type of food source, but also an important source for other value-added products.

4.2. Bio-methane production from bamboo

Kobayashi et al. firstly investigated the feasibility of converting bamboo into methane. In this study, bamboo was pretreated by steam explosion (3.53 MPa and a steaming time of 5 min), and then by anaerobic fermentation. The maximum yield of methane is 215 ml, was obtained from 1 g of pretreated bamboo. Shen et al. also evaluated the effects of various pretreatment methods (including acid, alkaline, enzyme and alkaline aided enzyme) on the yield of methane, which demonstrated pretreatment will led to an improved methane production rate as compared to the raw samples (Shen, Nges, Yun, & Liu, 2013). In our lab, we also evaluated the potential of methane by using the residues from bamboo hydrolysis as substrate (unpublished data). It will be a valuable strategy for combining the process of bio-ethanol and methane production. However, little research is focusing on bio-methane production from bamboo or bamboo residues. In general, bamboo resource was also considered as a novel source for bio-methane production for its high holocellulose content, biomass yield and other environmental issues.

5. Prospect

In general, bamboo could be a new candidate feedstock for bio-ethanol production or other value-added applications via biorefinery mode, which will make the whole process more economical through the proper integration of biofuels with biobased products (as shown in Fig. 4).

Although bamboo is recognized as a useful resource due to its higher growth rate and annual biomass yield (as shown in Figs. 2 and 3), its utilization is limited and further development is also required, including life cycle assessment, pretreatment, enzymatic hydrolysis, fermentation, which will make the whole process of bio-ethanol production or other value-added applications more economical. Although considerable efforts have been made to produce bio-ethanol as an alternative source of fuel from lignocellulocis materials in the past decades, the cost-competitive process are also not in hand (Margeot et al., 2009). Many technical bottleneck are need to solve, i.e., effectively releasing the fermentable sugars from lignocellulose is the greatest technical or economic barriers during the whole process (Zhang et al., 2007a,b,c). Another barrier or challenge is absent robust organism for ethanol production. Although different recombinant strains have been engineered by metabolic pathway engineering, such as recombinant *S. cerevisiae* (Eliasson, Christensson, Wahlbom, & Hahn-Hagerdal, 2000; Ho, Chen, & Brainard, 1998; Zhang et al., 1995), *E. coli* (Ingram, Conway, Clark, Sewell, & Preston, 1987), *Klebsiella oxytoca* (Ohta,

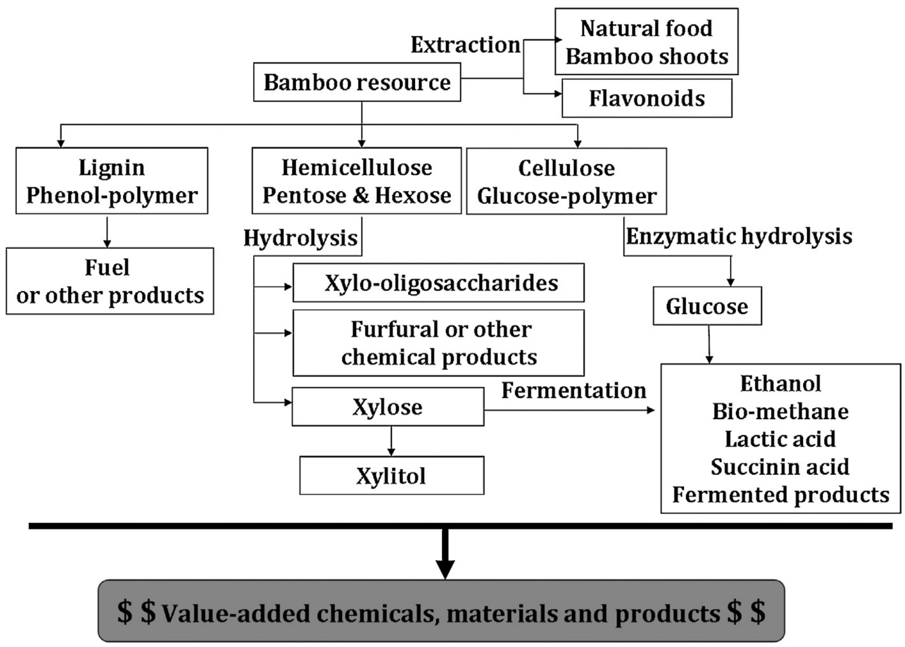

Fig. 4. Simplistic idealized biorefinery flowchart of bamboo utilization.

Mejia, Shanmugam, & Ingram, 1991), and *Z. mobilis* (Deanda et al., 1996; Linger et al., 2010), the robust strains are also absent to convereted these sugar into ethanol efficiently. So, additional research and systematic assessment are required to resolve these limitations.

On the other hand, to better understand the higher growth characteristics of bamboo, numerous studies should focus on its mechanism. Revealing the molecular regulation mechanism of the fast growth of bamboo will play important role for improving its biomass yield even or other plants' fast growth through genetic engineering techniques. Currently, the draft genome of the fast-growing non-timber forest species moso bamboo (*Phyllostachys heterocycla*) was sequenced in 2013 (Peng et al., 2013a). De novo transcriptome sequencing and mapped to the moso bamboo genomic resources (reference genome and genes) to produce a comprehensive dataset for the fast growing shoots of moso bamboo was also performed (Peng et al., 2013b). mRNA and microRNA expression profiling in a developing bamboo culms was also reported by next-generation sequencing (NGS) method, which revealed pathways involved in the rapid growth of developing culms in Moso bamboo (He, Cui, Zhang, Duan, & Zeng, 2013). These useful data will give a better insight into the mechanisms of bamboo rapid growth and provide numerous gene resources for improving other energy plant growth.

Authors' contributions

He Ming-xiong wrote the whole manuscript. The other authors helped in manuscript writing. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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