



Giant reed: A competitive energy crop in comparison with miscanthus



Xumeng Ge, Fuqing Xu, Juliana Vasco-Correa, Yebo Li*

Department of Food, Agricultural and Biological Engineering, The Ohio State University, Ohio Agricultural Research and Development Center,
1680 Madison Ave., Wooster, OH 44691, USA

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ABSTRACT

Arundo donax L. (giant reed) is a perennial rhizomatous grass and a promising energy crop due to its high biomass yield, adaptation to different types of soils and weather conditions, lower tillage requirement than traditional crops, and phytoremediation properties. This review is a comprehensive comparison of giant reed with miscanthus, a well-known energy crop, in terms of biomass production and conversion to bioenergy and bioproducts. Compared with miscanthus, giant reed has higher biomass yield and can adapt to a broader range of environments, but it requires more energy input for planting. Giant reed has a higher invasive potential than *Miscanthus × giganteus*, necessitating ecological control, such as preventing cultivation sites from flooding, strict nutrient management in surrounding areas, and removal of giant reed from riparian ecosystems adjacent to fire prone shrub lands. Generally, giant reed showed comparable yields to miscanthus in bioenergy production, but achieved better performance than miscanthus in production of particle boards, paper, and xylo-oligosaccharides. Suggested future research on giant reed includes testing multiple harvests per year, assessing environmental benefits and reducing potential hazards, evaluating advanced pretreatment technologies, integrating processes for producing different bioenergy/bioproducts, and investigating effects of management practices on the production of fuels and products.

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* Corresponding author. Tel.: +1 330 263 3855.

E-mail address: li.851@osu.edu (Y. Li).

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1. Introduction

Concerns about fossil fuel depletion and environmental degradation have spurred great interest in renewable energy sources, which can reduce dependence on fossil fuels and mitigate climate change caused by carbon dioxide emissions [1]. As the largest potential source of renewable energy, biomass currently provides about 10% of world's primary energy supply, and is expected to contribute up to a third to meet the global energy demand in the future [1]. Different types of bioenergy, such as gaseous, liquid, and solid fuels can be produced from biomass [2–4]. Besides, many value-added bioproducts can also be derived from biomass, which can improve the sustainability of bioenergy production processes [2,3]. However, existing biomass feedstocks are very diverse and include energy crops, forestry and agricultural residues, and other organic wastes (such as organic municipal solid waste), creating processing challenges. In order to meet the increasing bioenergy demand, dedicated energy crops that can provide reliable and sustainable biomass feedstocks with high yields and low production costs are highly desirable, although other biomass sources can be alternatives.

Arundo donax L. (giant reed), is a perennial rhizomatous grass that belongs to the *Arundo* genus of the *Poaceae* family, *Arundinoideae* subfamily, and *Arundineae* tribe. It has recently been highlighted due to its high biomass yield and other advantages, such as adaptation to different types of soils and weather conditions, lower tillage requirement than traditional crops, and phytodepuration properties [2]. However, compared to many other candidate energy crops, giant reed has been less studied. Plants can be classified into three groups, i.e. C3, C4, and crassulacean acid metabolism (CAM), based on their photosynthetic pathways. So far, most of the studies on energy crops for bioenergy production have focused on C4 plants, which are generally more productive than C3 and CAM plants, and have higher water and nitrogen use efficiency than C3 plants. *Miscanthus* (a genus of the *Poaceae* family, *Panicoideae* subfamily, and *Andropogoneae* tribe) is a typical C4 perennial rhizomatous grass, and has been well studied and considered as one of the most promising energy crops [5]. Interestingly, although giant reed is a C3 plant, it has unusually high saturation levels in its photosystem compared to normal C3 plants. As a result, giant reed can achieve high biomass yields that could be competitive to those of C4 plants, such as *miscanthus* [2].

A number of aspects need to be considered when selecting plants as energy crops. Cultivation and harvesting practices may significantly affect biomass yields. Environmental impacts must be evaluated prior to farm scale application. Furthermore, suitable technologies and their performance for biomass conversion to bioenergy and bioproducts may vary for different crops. Based on studies of biomass production and conversion performance of giant reed and *miscanthus* that have been reported in the literature, giant reed has the potential to be competitive with *miscanthus* in these aspects. However, to date, there have been no reviews that

systematically and comprehensively compare giant reed and *miscanthus* as feedstocks for production of bioenergy and bioproducts.

This paper reviews the current status in biomass production and conversion technologies for production of bioenergy and bioproducts from giant reed and *miscanthus*. The discussion on biomass production covers cultivation and harvesting, biomass yield, and environmental impacts. Following that, composition and theoretical energy potential, and production of liquid, gaseous, and solid fuels and various bioproducts are reviewed. Challenges and future approaches in giant reed-based bioenergy and bioproducts are also discussed.

2. Biomass production

2.1. Plant Propagation

A massive number of energy crops must be planted in order to meet the huge biomass demand for energy. For example, about 500 million of *Miscanthus × giganteus* plants (or 50,000 ha with a density of 10,000 plants per ha) would be needed to achieve 25% of the total requirement for renewable energy in the UK [6]. Giant reed and *M. × giganteus*, the *miscanthus* species most commonly studied for biomass production, are sterile plants that normally do not produce seeds. Alternatively, they can be propagated asexually from their vegetative parts, such as the rhizome and stem, or from axillary buds using *in vitro* propagation technologies.

2.1.1. Rhizome propagation

Rhizome propagation is the most commonly used method for establishing giant reed in field-plot experiments [7–9], and has also been well studied for establishing *M. × giganteus* [6]. Manual inspection and sizing of rhizomes is helpful to ensure their compatibility with planting equipment, but is unpractical and labor intensive for cultivation at farm scale. The estimated cost for traditional rhizome propagation was estimated to be about \$1.25 per plant in 2006 [8]. Assuming a density of 10,000 plants ha⁻¹ and an average biomass yield of 40 t ha⁻¹ per year for 10 years, the establishment cost would be \$31 t⁻¹, which is economically unfeasible considering the expected farm gate price of \$40 t⁻¹ [10,11]. Another drawback of rhizome propagation is the limitation in the multiplication ratio, which is the increase in planting material over what is planted. For example, the multiplication ratio for *M. × giganteus* is typically about 1:3, allowing the planted area to increase by only three-fold annually [6]. In other words, about 33% of area is required for preparing rhizomes.

There have been few reports on mechanization of giant reed rhizome propagation. However, Assirelli et al. [12] demonstrated the viability of a mechanical method for on-site giant reed rhizome collection using a modified stump grinder. Mechanization of rhizome propagation (or macro-propagation) has been developed for cultivation of *M. × giganteus*. The mechanical method includes

cutting up rhizomes mechanically in the field with a rotary tiller, and then collecting rhizome pieces with a harvester from the field. The harvested rhizome pieces can be planted with conventional planting machinery. By using the macro-propagation technology, the rhizome propagation cost has been reduced to be about \$0.12–\$0.18 per plant (or \$3–\$4.5 t⁻¹ at a density of 10,000 plants ha⁻¹ and an average biomass yield of 40 t ha⁻¹ per year for 10 years) [6].

2.1.2. Stem propagation

Regeneration of giant reed by stem cuttings depends on temperature and other factors. Wijte et al. [13] reported successful regeneration of 30–80% for stem fragments (1–10 cm) at controlled temperature (16/8 h at 28/16 °C). Regenerations of 0–20% and 90–100% were observed in an unheated greenhouse in winter and summer, respectively. In spring, fragments plagiotropic branches, or hangings showed higher regeneration (30–40%) than those from upright stems (0–10%). Regeneration by upright stem fragments in spring can be improved to 30–40% by using exogenous indole-3-acetic acid (IAA) [13]. Ceotto and Candilo reported that auxiliary stems of giant reed can be rooted in water or moist soil first, and then transplanted to the field later, achieving high survival rates of close to 100%, depending on the type of water or soil [8]. Furthermore, with sufficient water supply during the first growing season, giant reed stems can be rooted directly in the field by laying down the cuttings in a shallow furrow and covering them by hand or with machinery, which could be more practical than other methods [8,14]. However, Assirelli et al. suggested that stem propagation for giant reed is inefficient due to uneven germination which, consequently, causes low yields [12].

Harvesting and culturing of stem cuttings under proper environmental conditions are crucial for propagation by stem cuttings of *M. × giganteus* [6]. The optimal conditions for root and shoot growth from *M. × giganteus* stem cuttings were reported to be temperatures > 25 °C, humidity of 60%, and levels of around 1250 μmol m⁻² s⁻¹ of photosynthetically active radiation (PAR) [6]. While only about 40% of stems rooted without using artificial growth stimulants, auxins, such as [2-(1H-indol-3-yl) acetic acid] (IAA), and indolebutyric acid (IBA), can increase shoot and root reproduction of miscanthus nodes by about 2-fold, with older nodes (closer to the rhizome) developing better than younger nodes [6]. Recently, Boersma and Heaton achieved 75% emergence from *M. × giganteus* stems by planting the lowest five nodes in 30 °C soil in sunlight with a light/dark period of 16 h/8 h and an average photosynthetic photon flux density of 507 μmol m⁻² s⁻¹ [15]. Compared to rhizome-based propagation, a major advantage of stem propagation is that high multiplication rates of up to 1:200 can be achieved [15].

2.1.3. Micro-propagation

Successful lab-scale micro-propagation of giant reed from callus culture and axillary buds has been reported, although studies are limited compared to those on miscanthus [16,17]. In vitro *M. × giganteus* propagation from axillary buds has been conducted using a shoot-inducing media (modified Murashige and Skoog) with benzyladenine (BA) [N-(phenylmethyl)-1H-purin-6-amine] followed by indol-3-butyric acid (IBA) supplementation to induce root formation [6]. Performance of *in vitro* propagation of *M. × giganteus* could be linked to many factors, such as nitrogen, phosphorus, growth hormone thidiazuron (a phenylurea-type cytokinin), proline, and carbon sources [6]. Using micro-propagation technologies, the propagation cost can be lowered to about \$0.27 per plant, but is still higher than those of macro-propagation [5].

In summary, macro-propagation currently offers the lowest cost per plant, but is limited by the low multiplication rates. In contrast, micro-propagation, which provides high multiplication

rates, could be more feasible in the near future if the cost per plant is reduced to be comparable to that for macro-propagation. Stem propagation by directly planting cuttings, which has been demonstrated for giant reed, is also attractive, but an in depth cost analysis is needed. It should be noted that both giant reed and miscanthus are perennial plants that need propagation only for the first year. Therefore, the influence of propagation cost will be decreased by distributing the cost over a longer period (e.g. more than 10 years).

2.2. Growth and planting requirements

Both giant reed and miscanthus are adapted to a wide range of soils, while well-drained soil is preferred for best growth [18,19]. Although both have the ability to grow in low quality soils, such as marginal land and post-mining land, giant reed was reported to be more resilient to drought and moisture stresses than miscanthus, especially in rhizome persistence [20]. Besides, giant reed was found to tolerate wider ranges of pH and salinity than *M. × giganteus* (Table 1). A plowing depth of 40–45 cm is suggested for rhizomes of giant reed [2], while a plowing depth of 20–30 cm is recommended for rhizomes of *M. × giganteus* [5]. The recommended planting depth for rhizomes of giant reed is 15–20 cm from March to April in temperate climates, or 20–25 cm from December to February in warmer climates [2], while the recommended planting depth for rhizomes of *M. × giganteus* is 5–10 cm [21]. The planting density for giant reed and *M. × giganteus* is in the range of 10,000–30,000 plants ha⁻¹ (or 1–3 plants per square meter). High density can be selected for high biomass yield, but it can also result in high planting costs. In summary, compared to miscanthus, giant reed can adapt to a broader range of environments, but may require a higher energy input for planting.

2.3. Irrigation, fertilization and weed control

During establishment in the field, giant reed and miscanthus are more susceptible to water shortage stress, thus irrigation is critical during the first growing season and has been shown to improve establishment rates [2,5]. Once the plants have developed strong root systems, they normally do not need additional water. Giant reed and miscanthus are rhizomatous grasses that translocate nutrients from the above ground parts to the rhizomes at the end of the growing season. Therefore, fertilization is generally not necessary during the second year, although additions of nutrients, mainly nitrogen, may improve biomass yields. Generally, moderate nitrogen fertilization of giant reed (40 kg N ha⁻¹) and *M. × giganteus* (50–70 kg N ha⁻¹) is recommended, which helps reduce costs

Table 1

Comparison of growth and planting requirements between giant reed and *M. × giganteus*.

Parameters	Giant reed	<i>M. × giganteus</i>
pH	5.0–8.7 [22]	5.5 to 8.0 [18]
Preferred average temperature (°C)	Warm period > 10; cold period > 0 [22]	> 8 [23]
Salinity (g L ⁻¹)	Tolerant up to 15 [22]	Growth limited at 5.8, and strongly inhibited at 11.7 [24]
Annual precipitation (mm)	Unknown	700–800 [25]
Plowing depth (cm)	40–45 [2]	20–30 [5]
Planting depth (cm)	15–25 [2]	5–10 [21]
Plant density (plants ha ⁻¹)	5000–10,000 (temperate); 10,000–20,000 (warmer) [2]	10,000–30,000 [23]

and negative environmental effects [2,5]. Giant reed and miscanthus are unlikely to be outcompeted by weeds due to their high growth rates. However, weed control is recommended for the first year in order to ensure successful establishment. Various herbicides used for maize and other cereals can also be used for growing giant reed and miscanthus [5].

2.4. Harvesting

Giant reed and miscanthus are normally harvested once a year [26]. Two harvests per year are feasible for giant reed but not recommended for miscanthus [26]. Frequent clipping may cause a decline in total biomass produced due to reduced growth rates [26]. The moisture and mineral contents will decrease with time, and the leaves will fall off causing additional biomass loss. Harvesting before winter may be helpful to obtain a high biomass yield, but the high moisture content can cause high costs for biomass transportation and storage. Late harvesting, after winter, can obtain low moisture biomass that is easy to handle, but results in higher biomass losses. Therefore, there is a trade-off in the harvesting date. Generally, a late harvesting date when the water content is lower than 30% is recommended in order to decrease the cost for harvesting and drying [26]. Existing equipment, such as silage harvesters, can be used with slight modifications for harvesting giant reed and miscanthus [2,21]. However, specific stock shredders are recommended for harvesting giant reed with a diameter of 2–3 cm and moisture content higher than 40–50% (w/w) [2].

2.5. Biomass yield and energy balance

Giant reed cultivation has been reported in Portugal, Spain, France, Greece, China, Australia, and the United States, with the majority of literature comes from Italy [27]. In contrast, miscanthus has been more widely studied (Table 2). It is generally believed that giant reed has a higher biomass yield than miscanthus [20,28,29]. However, according to literature, a wide range of biomass yield was obtained, mainly attributed to differences of geography and climate, including elevation, temperature, precipitation, etc. [30,31]. It was reported that the shoot dry matter yield of miscanthus was significantly higher in southern European countries, such as France and Portugal, due to the longer growing season and higher temperatures [32]. Besides, compared to fall harvest, winter harvest was reported to obtain a slightly higher dry matter yield per hectare for giant reed, but a significantly lower dry matter yield for miscanthus, (Table 2). The length of the crop establishment also affects biomass yield, because biomass yield can be substantially lower in the first year of establishment but increase several folds after 2 or 3 years [33]. For giant reed, the yields generally increase from the first to the third year, reach a steady phase from the fourth to eighth year, and then start to decrease from the 9th year onward [34]. The biomass yield of *M. × giganteus* was reported to be only 2.4 dry tonne ha⁻¹ during the first year, while it increased to 14.28,

19.77, and 29.43 dry tonne ha⁻¹, respectively, from the second to the fourth year [35]. Finally, different management practices, soil types, and other environmental conditions also contribute to the variation of biomass yields reported in the literature. Mild and severe drought can significantly reduce the plant size, shoot numbers, and total biomass production of both plants, while flooding was shown to have less effect because both plants were reported to have a high tolerance to flooding [20]. Giant reed was found to be more tolerant to drought than miscanthus, while miscanthus had a slightly higher tolerance to flooding compared to giant reed [20].

Angelini et al. compared the changes of annual energy input during a long-term (12 years) cultivation of *M. × giganteus* and giant reed in a field experiment [28]. Since identical management methods were used, the energy input was the same for the two crops. More than half (17 GJ ha⁻¹) of the total energy input during the 12 years was used for the crop establishment during the 1st year, with over 70% attributed to tillage, nitrogen fertilizer, and harvest (Fig. 1). The annual energy input decreased to 12 GJ ha⁻¹ for the following 11 years (about 1 GJ ha⁻¹ for each year), since planting operations were no longer needed. Because a higher biomass yield was obtained from giant reed than from *M. × giganteus*, the total energy output and net energy output (potential outputs) of giant reed (650 ± 179 and 637 ± 180 GJ ha⁻¹ yr⁻¹, respectively) during the 12 years were higher than those of *M. × giganteus* (479 ± 168 and 467 ± 169 GJ ha⁻¹ yr⁻¹, respectively).

2.6. Environmental impacts

2.6.1. Invasive potential and controlling methods

The desired features for energy crops include a perennial plant with long canopy duration, rapid growth in spring to outcompete weeds, high water-use efficiency, and resistance to pests and diseases [38,39]. However, all of these advantages are also properties of invasive plant species, and, if not carefully controlled, the energy crop can outcompete native species, altering plant and animal communities, change fire cycles, and cause huge economic and ecological losses [40,41].

Giant reed (native to Asia) and most of miscanthus species are invasive or have invasive potential. However, *M. × giganteus* (native to Asia), a natural hybrid between *Miscanthus sinensis* (Anderss.) and *Miscanthus sacchariflorus* (Maxim.), is believed to be less invasive because it is an allopolyploid that does not produce viable seeds. Compared with *M. × giganteus*, giant reed has much higher invasive potential based on the Australian Weed Risk Assessment (WRA) system [38,40]. One reason is that giant reed already has an invasive history in the temperate southern United States, from California to Maryland, and has already become a serious invader in the southern hemisphere with tropical and warm environments (e.g. Australia) [41]. In Florida, USA, it is considered as “naturalized” but has not been rapidly spreading [42]. In contrast, there are no documented historical invasion events for *M. × giganteus* due to its relatively new genetic

Table 2
Biomass yield (above ground harvestable parts) of giant reed and different miscanthus species.

Species	Fall harvest (dry tonne ha ⁻¹)	Winter harvest (dry tonne ha ⁻¹)	Location	Ref.
Giant reed	15–41	21–49	Italy, USA	[7,29,36]
<i>M. giganteus</i>	11–51	7–30	Austria, Belgium, Denmark, France, Germany, Greece, USA (Illinois), Latvia, Portugal, Spain, The Netherlands, UK	[32]
<i>M. sinensis</i>	17–49	6–22	Denmark, France, Japan, Slovakia, Switzerland	[37]
<i>M. sacchariflorus</i>	27–40	14–17	Poland	[35]
<i>M. floridulus</i>	NA	28–38	Taiwan	[30]
<i>M. lutarioriparius</i> ^a	10–30	NA	Southern China	[31]

^a Obtained by model calculation. NA: not available.

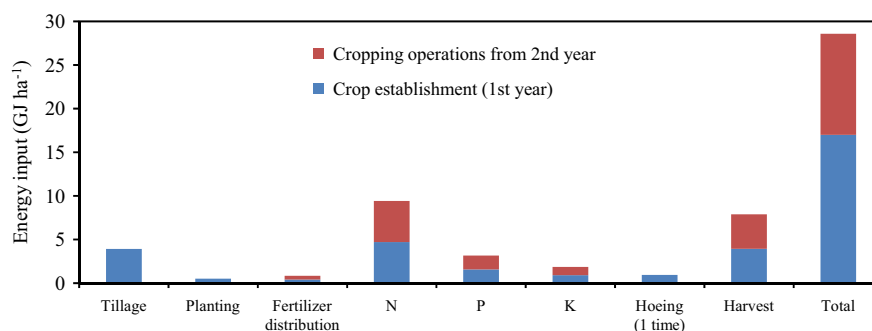


Fig. 1. Total energy input for the production of *M. x giganteus* and giant reed biomass with 20,000 plants ha⁻¹ from the crop establishment (1992) to the 12th year of growth [28].

modification and shorter cultivation history in new habitats [40]. However, concerns still arise that allopolyploidy does not guarantee continued sterility [43], and vegetative propagation can also enhance invasiveness [44,45]. For both species, additional concern also arises regarding large scale cultivation, which may shift the dispersal and colonization frequency of the plant and thus be more difficult to control [38].

Several ecological control methods have been shown to mitigate the invasive potential of both giant reed and miscanthus. Research in California, USA, found that giant reed is potentially more invasive at nitrogen rich sites, and dispersal of fragmented shoot and rhizome pieces of giant reed typically occurs during floods, which transport the plant to new locations [8,46]. Fast post-fire regrowth has also helped giant reed outcompete native species [47]. As a result, ecological control of giant reed invasion should include preventing flooding of its cultivation site, strict nutrient management in its surrounding areas, and removal of giant reed from riparian ecosystems adjacent to fire prone shrub lands [8,46,47]. For miscanthus, precautions should be taken if living (green) culms or rhizome fragments are removed from fields and transported through habitats containing either open water or abundant soil moisture in spring and summer. However, the whole culms and fragments of miscanthus cannot produce shoots and roots after fall and winter cutting [48].

2.6.2. Improvement of soil quality

Different from many bioenergy crops (e.g., corn) that are suspected to exacerbate soil erosion problems during the cultivation process, both giant reed and miscanthus have the ability to grow on marginal land and help prevent soil erosion and nutrient run off, and to improve soil quality [49]. Giant reed was also found to better enhance the bacterial and fungal growth in soil, compared with other energy crops such as grass, corn, and sunflower. Experiments in pots showed that a 12 week cultivation of giant reed increased available nitrogen in the soil, and the activities of soil dehydrogenase, urease, and catalase were increased 3- to 7-fold [50]. In one study, giant reed was found to have a higher ability than miscanthus in increasing soil organic carbon accumulation [51]. Giant reed cultivation obtained an annual carbon gain of 1700 and 63 kg C ha⁻¹ yr⁻¹ in the upper layer (0–0.2 m) and lower layer (0.2–0.4 m), respectively, of the soil, while miscanthus cultivation only obtained a 1178 kg C ha⁻¹ yr⁻¹ carbon gain in the upper soil layer, and –126 kg C ha⁻¹ yr⁻¹ in the lower layer. However, it is noteworthy that these numbers varied among different studies, due to differences of climate, annual precipitation, soil texture, and initial soil carbon content [52].

2.6.3. Phytoremediation

The use of energy crops for cost-effective remediation of contaminated soil, water, and sediments is a rapidly developing field [52]. Some features of giant reed and miscanthus, including the

extensive root systems, high biomass production, and tolerance to high trace element concentrations, make them highly suitable for phytoremediation [37,53–55]. The cultivations of giant reed and miscanthus in trace element-contaminated media have been extensively reviewed [37,53–55]. The data indicated that for both giant reed and miscanthus, trace element concentrations in the roots were only about 10% of those in the growing media. In addition, for both giant reed and miscanthus, trace elements were accumulated more in the belowground organs (roots, rhizomes, etc.) than in aboveground parts (stems and leaves), while the concentrations varied between different elements. The limited heavy metal concentrations in aboveground tissues make it easier for further biological conversion of the aboveground biomass of miscanthus and giant reed [37,55]. The cultivation of energy crops can also reduce the bioavailability of trace elements in the growing media. One reason might be the increased soil organic matter which binds with the trace elements and prevents them from being dissolved [54].

Currently there is no direct comparison between giant reed and miscanthus for their abilities to tolerate, extract, or immobilize trace elements in contaminated media. However, giant reed is likely to have a better ability for trace element removal due to its higher biomass yield. Research conducted on phytoremediation in constructed wetlands found that giant reed achieved the highest average dry biomass production (50 t ha⁻¹) among different energy crops, which was more than two times of that of *M. x giganteus* (24 t ha⁻¹) [56]. The N and P phyto-uptake of giant reed was 88.87 and 5.18 g m⁻² of wetland, which were also significantly higher than other plants [57].

3. Biomass conversion to bioenergy and bioproducts

3.1. Composition and energy potential

For bioenergy production, the preferred features of a biomass feedstock depend on the end-use. Each conversion technology, e.g., combustion, gasification, pyrolysis, fermentation, and anaerobic digestion (AD), has different requirements for the heating value, ash content, moisture content, sugar yield, digestibility, and other characteristics of the feedstock. The contents of minor elements, such as nitrogen (N), sulfur (S), and chloride (Cl) should also be considered, due to their influence on gas emissions, water discharge, and solid waste disposal [58,59]. The major components of giant reed and miscanthus are compared in Table 3, and their influences on different bioenergy production methods are discussed.

Biological conversion of energy crops to ethanol, butanol, methane, or hydrogen favors feedstocks with high cellulose content. Some microbial species can also utilize hemicellulose for ethanol production, and microbes in AD can utilize a wider range of organic compounds, including hemicellulose, extractives, lipids,

Table 3

Heating value and composition of harvestable above ground biomass of giant reed and *M. × giganteus*.

Properties	Giant reed	Ref.	<i>Miscanthus</i>	Ref.
Bulk density (t m^{-3})	0.1	[27]	0.04	[27]
Moisture content (%)	35–52	[60]	46–79	[61,62]
Heating value (MJ kg^{-1}) ^a	17–24	[63,64]	16–19	[61,62]
Ash (% DW)	3–8	[64]	2.0	[61]
Lignin (% DW)	8–34	[63,65]	9–11	[61,66]
Cellulose (% DW)	21–42	[65,67]	43–58	[61,66]
Hemicellulose (% DW)	7–23	[65,67]	16–34	[61,66]
Extractives (% DW)	19–22	[65,68]	9–17	[69]
Crude protein (% DW)	4–8	[65]	3–7	[69]
C (% DW)	42.8–49.4	[63,64,67]	44.7–47.4	[62,67]
N (% DW)	0.2–0.3	[63,67]	0.3–2.1	[61,62]
H (% DW)	6.0–6.4	[63,64,67]	5.9–6.0	[62]
O (% DW)	42.0–45.1	[63,64,67]	39.8–43.6	[61,62]

^a Based on dry biomass. DW: Dry weight.

and proteins, but the lignin primarily remains intact [70]. However, a high content of extractives, protein, or lipids can produce inhibitors in AD thus need to be carefully controlled [71,72]. The yields of ethanol, butanol, and methane of giant reed and miscanthus are reviewed in Section 3.2.

Another pathway to convert giant reed and miscanthus to biofuels is through thermochemical conversion, where moisture content and mineral composition are two important factors [73]. High moisture content in harvested biomass reduces the heating value and increases the amount of flue gases, deteriorating the combustion quality [74]. Ash and mineral contents also impact combustion and thermochemical conversion. Perennial grasses generally contain higher ash-forming minerals, such as Cl, S, silicon (Si), phosphorus (P), potassium (K), sodium (Na), and calcium (Ca), compared to woody biomass [64]. Intrinsic alkali metals, such as K and Ca can react with Si from the residual soil to form alkali silicates and induce operational problems such as ‘slag’ formation [64]. Consequently, the K, Ca, and Si ratio should be taken into consideration in evaluating biomass quality for thermochemical conversion. The concern for N, S and Cl contents in biomass during thermochemical conversion include gas emissions (i.e. NO_x) and corrosion of equipment during power production [58,59]. However, S and Cl contents are relatively low in lignocellulosic biomass [75,76]. The thermochemical conversion of miscanthus and giant reed is reviewed in Section 3.3.

Harvest time is found to significantly influence the biomass composition and consequently alter its quality, thus managing harvest time can improve biomass quality for thermochemical or biological conversions. Important biomass characteristics that change with harvest time include the contents of moisture, nitrogen, minerals, and carbohydrates, and the recalcitrance of biomass for biodegradation. It was reported that the green miscanthus harvested in autumn contained more easily biodegradable components, such as 16.6% extractives and 6.8% protein, compared with 8.7% and 3.4%, respectively, in miscanthus harvested in spring. The carbon-to-nitrogen (C/N) ratio in miscanthus harvested in autumn was also substantially lower (45.7) than that harvested in spring (87.5) [69]. The hemicellulose content (340 g kg^{-1}) was found to be higher in the younger tissues than that of the mature parts (250 g kg^{-1}), while cellulose and lignin contents generally increased in mature tissues [77]. Harvest time was also reported to affect the recalcitrance of biomass for bioconversion [78].

Harvest time also affects the element compositions of miscanthus and giant reed, because both crops translocate nutrients, such as nitrogen, from the aboveground parts to rhizomes during late autumn and winter for the regrowth in the next year. Thus, the maturity of biomass and the loss of leaves during winter time

are two important reasons for the seasonal changes of element compositions [79,80]. The mineral composition of leaves and stems are substantially different. Various previous studies about energy crops suggested that leaves usually contain more N, Ca, P, S, Si, Na, aluminum (Al), iron (Fe), and magnesium (Mg) than stems, while stems are only slightly higher in K content than leaves [80]. The mineral content can be 2- to 4-fold higher in leaves than that in stems depending on the maturity [64,80]. As leaves count for about one third of the above ground biomass [79], the loss of leaves during winter will shift the composition of the total aboveground biomass [81].

3.2. Biological conversion

3.2.1. Pretreatment

Both giant reed and miscanthus are highly recalcitrant to enzymatic digestion, due to their considerable lignin content (Table 3) and the complex structure formed by the cell wall components. Thus, pretreatment is a required step prior to enzymatic hydrolysis to enhance the availability of polysaccharides to the hydrolytic enzymes. Several pretreatments have been studied for giant reed and miscanthus (Table 4), and most are performed in the presence of chemicals (e.g., acids, bases, salts, or solvents) and at high temperatures (usually higher than 100°C). Some of the pretreatments reduce the lignin content of the material, while others reduce the hemicellulose content or crystallinity of the cellulose, or simply disrupt the complex arrangement of the cell wall components, allowing the hydrolytic enzymes to access the cellulose.

Among the most efficient pretreatments are ammonia fiber expansion (AFEX) [82] and organosolv [83,84] for miscanthus, and cellulose solvent-based fractionation (CSLF) for both miscanthus and giant reed [85]. In general, better results have been found for miscanthus than for giant reed, with some pretreatment processes achieving sugar yields greater than 90% [82,83,86,87]. Using diluted oxalic acid pretreatment at the same severity factor, the glucose yield obtained for miscanthus was about 91% [87], while it was 68% for giant reed [88]. The lignin content of miscanthus and giant reed in these two studies were almost the same, which suggested that their difference in recalcitrance might be attributed to other factors [87,88]. When the CLSF pretreatment was performed for both miscanthus and giant reed, no statistical difference was found in the glucose yield based on the initial dry matter, but slightly better results were obtained for giant reed based on the initial cellulose content [85].

3.2.2. Liquid fuels

Bioethanol production is the most extensively studied approach in converting giant reed or miscanthus biomass to biofuels. Similar to bioconversion of other lignocellulosic materials, pretreatment is generally required to obtain high sugar yields from giant reed or miscanthus during the following enzymatic hydrolysis process. The ethanol fermentation step was usually conducted using baker yeast, *Saccharomyces cerevisiae*, which can only utilize glucose. As shown in Table 5, the final ethanol yields varied from 34% to 71% [83,85,88,101–105]. Currently, there is only one published report that compares ethanol production between giant reed and *M. × giganteus* using the same pretreatment and hydrolysis procedure. Higher ethanol yield was obtained from giant reed than from *M. × giganteus* mainly due to the higher sugar yield from giant reed than that from *M. × giganteus* [85]. For studies on ethanol production from giant reed, strains that can ferment both glucose and xylose have been used for ethanol fermentation. Therefore, higher ethanol yields of about 180 mg g^{-1} biomass were obtained, although the percentage yields were relatively low (42–57%) [105].

There are very few studies on butanol production from giant reed or miscanthus. Zhang and Ezeji studied butanol production

Table 4
Pretreatment of giant reed and miscanthus.

Pretreatment	Conditions	Results ^a	Ref.
Giant reed			
Diluted acid	1–2% H ₂ SO ₄ , 130–140 °C, 30–60 min.	65–70% sugar yield.	[89,90]
Diluted oxalic acid	170–190 °C, 15–40 min, 2–10% (w/w) oxalic acid.	37–68% glucose yield.	[88]
Steam explosion	190–210 °C, 3–5 min.	24–29% enzymatic digestibility.	[91]
Acid catalyzed steam explosion (ACSE)	1.4% H ₂ SO ₄ , 190 °C, 5 min.	68–86% enzymatic digestibility.	[91]
Cellulose solvent-based lignocellulosic fractionation (CSLF)	84% H ₃ PO ₄ , 50 °C, 45 min. Then mix with acetone.	89% glucose yield.	[85]
Two-stage microwave	First stage: 5% (w/v) of NaOH, 80 °C, 5 min. Second stage: 0.5% H ₂ SO ₄ , 180 °C, 30 min. (No enzymatic hydrolysis).	45% sugar yield, 61% glucose yield. ~100% delignification.	[92]
Two stages: diluted acid and alkaline	First stage: 1.1% of H ₂ SO ₄ , 121 °C, 30 min. Second stage: 0.5 M NaOH, 120 °C, 30 min.	52% enzymatic digestibility. 75% delignification. 85% hemicellulose reduction.	[93]
Miscanthus			
Diluted sulfuric acid	1% H ₂ SO ₄ , 160 °C, 10 min.	96% enzymatic digestibility.	[86]
Diluted sulfuric acid + wet explosion	Diluted acid pre-soaking: 0.75% of H ₂ SO ₄ , 100 °C, 14 h. Wet explosion: 5 min, 170 °C.	61% glucose yield. 95% xylose yield.	[94]
Diluted oxalic acid	150–190 °C, 10–40 min, 2–8% H ₂ C ₂ O ₄ (w/w).	46–91% glucose yield.	[87]
Hot water	200 °C, 30 min.	93% enzymatic digestibility.	[86]
Aqueous ammonia	5–30% NH ₄ OH, 150–160 °C, 5–60 min.	49% glucose yield. 53–72% enzymatic digestibility. 74% delignification.	[86, 95]
Ammonia fiber expansion (AFEX)	2:1 NH ₄ OH to biomass, 160 °C, 5 min.	96% glucose yield. 81% xylose yield.	[82]
Extrusion-Alkaline	12% NaOH, 70 °C, 4 h.	69% glucose yield. 55% sugar yield. 70% enzymatic digestibility. 77% delignification.	[96]
Alkaline hydrogen peroxide	0.2–2 M NaOH and 0.3–6 M H ₂ O ₂ , 30–70 °C, 3–21 h.	80–85% enzymatic digestibility.	[97]
Inorganic salt pretreatment	2% NH ₄ Cl or 0.5% FeCl ₃ , 200 °C, 15 min.	37–43% glucose yield. 40–72% enzymatic digestibility.	[98, 99]
Cellulose solvent-based lignocellulosic fractionation (CSLF)	84% H ₃ PO ₄ , 50 °C, 45 min. Then mix with acetone.	82% glucose yield.	[85]
Two-stage microwave	First stage: 1% of NH ₄ OH, 120 °C, 15 min. Second stage: 1.78% H ₃ PO ₄ , 140 °C, 30 min. (No enzymatic hydrolysis).	86% sugar yield. 95% glucose yield.	[100]
Organosolv	Solvents: ethanol, or formic and acetic (40%). 107–180 °C, 1–3 h.	64–93% glucose yield. 75–98% enzymatic digestibility. 80% delignification.	[83,84]
Fungal pretreatment	<i>Ceriporiopsis subvermisporea</i> , 28 °C, 28 days.	29% glucose yield. 30% enzymatic digestibility.	[69]

^a Enzymatic digestibility refers to the sugars liberated after enzymatic hydrolysis compared with the sugars present in the pretreated material. It is referred to as glucan in this table. Sugar yield refers to the sugars liberated at the end of the whole process (including enzymatic hydrolysis, if present) compared with the sugars present in the untreated feedstock. It can be referred to glucan (or glucose), xylan (or xylose), or the total sugar content.

Table 5
Comparison of ethanol yield from raw biomass between giant reed and *M. × giganteus*.

Pretreatment	Simultaneous saccharification fermentation (SSF)	Crop	Strain for ethanol fermentation	Ethanol yield (% of theoretical)	Ref.
Alkaline	No	Giant reed	<i>Z. mobilis</i> ^a	42	[105]
		<i>M. × giganteus</i>	<i>S. cerevisiae</i>	71	[101]
H ₃ PO ₄ /acetone	No	Giant reed	<i>S. cerevisiae</i>	62	[85]
		<i>M. × giganteus</i>	<i>S. cerevisiae</i>	55	
Dilute H ₂ SO ₄	Yes	Giant reed	<i>S. cerevisiae</i>	34	[104]
		<i>M. × giganteus</i>	Active dry yeast	65	[102]

^a Fermentation of both glucose and xylose.

from *M. × giganteus* with *C. beijerinckii* using liquid hot water pretreatment [106]. During 60 h of fermentation, more than 8 g L⁻¹ of acetone–butanol–ethanol (ABE) (about 5 g L⁻¹ of butanol) was obtained using miscanthus hydrolysate, which contained 38.8 g L⁻¹ of glucose and 14.5 g L⁻¹ of xylose [106].

3.2.3. Gaseous fuels

Giant reed and miscanthus can be converted into biomethane by anaerobic digestion. Anaerobic digestion is a biological process in which anaerobic microbes convert organic matter into biogas, which is mainly composed of methane and carbon dioxide. Yields obtained for the production of biomethane by anaerobic digestion of miscanthus and giant reed have been similar (Table 6).

Harvest time of an energy crop can affect its total energy potential per hectare by altering both the methane yield per unit biomass and the total biomass yield per hectare. For giant reed with only one harvest per year, the highest biochemical methane

potential (BMP) was reached in giant reed harvested in early August, while late harvest reached the highest biomass production [60]. However, a double harvest in early summer and late autumn was reported to increase the methane yield per hectare by 20–35% compared to the most productive single harvest, due to both the higher BMP from the early harvest and the high total biomass production [60]. In contrast, recent work in miscanthus has shown that the harvest date had little effect on the methane yield (L kg⁻¹ VS_{feed}) [69,112], which implies that miscanthus can be harvested at any time during the harvest window if it is to be used for the production of biogas.

Giant reed and miscanthus can also be converted into biohydrogen via dark fermentation. Dark hydrogen fermentation is the process in which heterotrophic microorganisms degrade organic matter by oxidation under anaerobic conditions, producing hydrogen. However, biohydrogen production is not reviewed in this paper due to the limited available research on the production

of biohydrogen from giant reed and miscanthus, and the conditions for those experiments are not comparable [96,110,117,118].

3.3. Thermochemical conversion

With high temperature and controlled oxygen exposure, giant reed and miscanthus can also go through thermochemical conversion processes, such as gasification, pyrolysis, and liquefaction to produce syngas, bio-oil, and biochar, a solid residue [75]. Compared with miscanthus, studies about thermochemical conversion of giant reed are relatively limited. The product yields of giant reed and miscanthus through different thermochemical conversion methods are reviewed in Table 7. Although the yields of syngas, bio-oil, and bio-char varied among research, no significant difference was found between the two crops. Miscanthus appears to have higher bio-oil yield and lower gas yield, but no conclusion can be made with this limited data.

It is well accepted that the relative ratios of the main products (charcoal, condensation liquids, and gas) from a thermochemical conversion process are strongly influenced by the physical and chemical characteristics of the raw materials, and the reaction parameters [73]. Increasing the temperature and incubation time or reducing rate of temperature increase can substantially increase biomass conversion to gas and liquid fuels. The addition of a catalyst also increases the biomass conversion during thermochemical conversion. For example, when catalyst loading increased from 10% to 100% (by weight) of the raw material, the pyrolysis conversion of *M. × giganteus* increased from about 60% to

about 80% of the biomass, with the solid residue reduced to half, gas yield doubled, and oil yield slightly increased [120].

Harvest time was also found to influence the thermochemical conversion of giant reed and miscanthus (Table 7). Increasing moisture content and inorganic salts have been accepted to lower the conversion efficiency of biomass to oil, while increase char production [73]. At a biomass moisture content of close to 20% (wet basis), organic vapors could be lost when being condensed, reducing the quality of bio-oil and increasing gas production [122]. Although low moisture content is preferred in thermochemical conversion, drying feedstock will increase the overall energy requirement. Consequently, minimizing biomass moisture content through selecting harvest time might be a cost-effective option for improved bio-oil production.

The content of mineral salts also affects thermochemical conversion processes. Their presence can increase the char yield and, sometimes, the amount of light volatiles, increasing the chance of bio-oil phase separation and reducing its stability during long term storage [62]. One research found that the differences between giant reed and *M. sinensis* during pyrolysis was due to their different mineral salt contents, and after using HCl washing to remove the ash, their thermal decomposition became remarkably similar [73]. HCl washing was found to significantly reduce the amount of char production from giant reed and miscanthus, because it removed roughly 90% of the ash content, especially K, which has been found to be a major element that related to the formation of char [73]. In contrast, H_3PO_4 was used to enhance char yield of giant reed, and help to develop a porous structure with surface properties similar to those of activated carbons [63]. Water can also be used for ash removal, however, it also increases the biomass moisture content [74]. Thus, selection of harvest time or harvest method can be another option to reduce ash content that adversely affects pyrolysis products distribution, as discussed in Section 3.1. By delaying the harvest from December to February, concentrations of ash, nitrogen, potassium, and chlorine were found to be significantly reduced [123]. Thus, spring harvested biomass was found to obtain higher bio-oil yield and lower char production [62,120,121].

3.4. Bioproducts

Giant reed and miscanthus are promising not only as feedstocks for bioenergy production, but also as sources for bioproducts. Various types of products, including boards, paper, and chemicals, can be produced from whole biomass or certain

Table 6
Production of biomethane from giant reed and miscanthus.

Biomass and pretreatment	CH ₄ yield (L kg ⁻¹ VS _{feed})	Ref.
Giant reed		
Raw biomass	151–391	[60,65,107–109]
Steam cooking	283–337	[108]
NaOH pretreatment	216–246	[109]
Separated leaves, HCl pretreatment	200	[110]
Ensilage with NH ₃ addition	173	[68]
Miscanthus		
Raw biomass	175–333	[69,111,112]
Steam-exploded 220 °C, 10 min	345–374	[113,114]
Ensilaged	190–280	[115,116]
Ammonia soaking 32% w/w, 25 °C, 3 d	310	[111]
Fungal pretreatment 28 d, 28 °C, <i>Ceriporiopsis subvermispora</i> (<i>M. sinensis</i>)	218	[69]

Table 7
Thermochemical conversion of giant reed and miscanthus.

Biomass	Heating value (MJ kg ⁻¹)	Gas (%)	Bio-oil (%)	Char (%)	Process	Ref.
Giant reed						
Raw biomass	17	34	22	24–44	Up to 300–900 °C, 1–2 h, heat rates 10–70 °C min ⁻¹	[63,73,119]
HCl washed		22	52	15	Up to 900 °C, 1–2 h, heating rate 70 °C min ⁻¹	[73]
H ₃ PO ₄ treated	17			41	Up to 500 °C, 1–2 h, heating rate 10 °C min ⁻¹	[63]
<i>M. × giganteus</i>						
Raw biomass		12–32	47–51	21–40	550 °C, Al ₂ O ₃ catalyst, heating rates 10–50 °C min ⁻¹	[120]
Summer harvest	15–18	14–15	41–50	26–34	490–525 °C, 1.5–2 h, fast pyrolysis	[62,121]
Fall harvest	15–18	15–18	46–60	16–34	490–525 °C, 1.5–2 h, fast pyrolysis	[62,121]
Spring harvest	17–19	6–12	51–63	14–34	490–525 °C, 1.5–2 h, fast pyrolysis	[62,121]
<i>M. sinensis</i>						
HCl washed		23–36	29–35	9–22	380–900 °C, 0.25–2 h, 0–10 Mpa	[67,73]

[73]: Total gas production is calculated by adding up CO₂, CO, and light volatile organic products, and bio-oil (tar) is calculated by mass balance

components, such as cellulose, hemicellulose, lignin, and extractives of giant reed and miscanthus.

3.4.1. Particle board

Particle board is a panel product made from particles of lignocellulosic fibrous materials mixed with a binder and subjected to high pressure and temperature. It has been widely used for furniture, floor underlayment, and wall and ceiling panels. Woods are the most common material used in the particle board industry, while non-wood lignocellulosic materials have also been studied as a partial or complete substitute for wood in manufacturing particle board. Currently, few studies have been found on particle board production from giant reed and miscanthus biomass. García-Ortuño et al. [124] and Flores et al. [125] used particles from giant reed culms with different particle sizes as a raw material for particle board panels, and suggested that producing high-quality giant reed-based particle board is feasible. Particle size was found to be crucial to the properties of urea-formaldehyde-bounded giant reed particle boards, and particle size of 2–4 mm was recommended for a desirable quality. Park et al. [126] studied the manufacture of particle board using *M. sacchariflorus* straw retained on 2 mm sieves. Low internal bonding and high thickness swell values were observed, and combination with wood particles was necessary to improve the quality of the board. Currently, there have been no reports on particle boards made of other miscanthus species, such as *M. × giganteus*. Compared to *M. sacchariflorus*-based particle board, the giant reed-based particle board was manufactured at a lower temperature and pressure with a shorter press time, but showed higher qualities in many aspects, such as internal bonding, thickness swelling, modulus of rupture, and modulus of elasticity.

Interestingly, the physical properties (such as internal bonding, thickness swelling, modulus of rupture, and elastic modulus) of giant reed-based particle board were even better than those of wood-based particle board [125]. However, the modulus of elasticity (MOE) (up to 1362 N mm⁻²) and modulus of rupture (MOR) (up to 10.3 N mm⁻²) of giant reed particle board still did not meet the UNE 312-4 thresholds (MOE of 1600 and MOR of 13 N mm⁻²), necessitating further investigations for improving its mechanical properties [125]. In addition, García-Ortuño et al. [127] used giant reed particle board to manufacture trays as containers for storage, transportation, distribution, and marketing of vegetables and fruits. Their results suggested that giant reed containers did not have negative effects on the shelf life and quality of foods.

3.4.2. Paper

Wood plants are the conventional raw materials used in pulping for paper production. However, the shortage of wood resources and increasing demand for paper products make non-wood plants, such as giant reed and miscanthus, attractive as alternative sources for paper production [128]. Non-wood plants have shorter growth cycles and lower lignin content than wood plants, which can reduce the energy and chemical input during pulping [128]. Ververis et al. [128] examined the suitability and potential of giant reed and *M. × giganteus* for paper production compared to traditional wood materials, including softwoods and hardwoods. Internodes of giant reed showed excellent derived values that are comparable to several softwoods and most hardwood species. This is consistent to the results obtained by Shatalov and Pereira [129] who carried out pulping experiments using giant reeds stems and observed comparable papermaking properties to those of hardwood. *M. × giganteus* has satisfactory slenderness ratios but poor flexibility and Runkel ratios due to its shorter fibers. Besides, giant reed has lower lignin content than *M. × giganteus*, which could result in shorter pulping time and less chemical requirement [128]. According to the results obtained by

Cappelletto et al. [130], the tensile index and burst index of chemi-thermo-mechanical *M. × giganteus* pulp were better than those of giant reed, but the tear index was still poor compared to that of giant reed pulp reported by Shatalov and Pereira [129]. Alkaline treatment is generally used in the pulping process to remove lignin. Caparrós et al. [131] investigated paper production from giant reed using an ethanol-water pulping method, and obtained paper with a tensile index of 33–39 kN m kg⁻¹, burst index of 1.5–2 kN g⁻¹, and tear index of up to 2.5 kN m² g⁻¹ after the refining process. The burst index values were higher than those for vine shoots (0.99 kN g⁻¹), similar to those for sunflower stalks (1.62–3.22 kN g⁻¹), while lower than those for cotton plants (2.09–4.15 kN g⁻¹) and sorghum stalks (4.2–5.3 kN g⁻¹). The tear index values were higher than those for vine shoots (1.50–2.49 kN m² g⁻¹), and lower than those for sunflower (5.55–6.39 kN m² g⁻¹), cotton plants (7.02–4.05 kN m² g⁻¹) and sorghum stalks (5.2–8.5 kN m² g⁻¹).

3.4.3. Xylo-oligosaccharides

Xylo-oligosaccharides (XOS) have recently been recognized as emerging prebiotics that may have comparable or better properties than commercial oligosaccharides, which are used for maintaining a healthy digestive system. The XOS are high-value products with a market price of up to \$55 per kg [132]. Hemicellulose, one of the major components of lignocellulosic biomass, is a promising source of xylan for XOS production. Utilization of xylan in giant reed and miscanthus for XOS production could significantly improve the economical sustainability of energy production from these energy crops. Lignocellulose-based XOS production generally has two steps, pretreatment for hemicellulose extraction and hydrolysis of xylan. Various pretreatment methods have been studied, but only hydrothermal pretreatment has been used for XOS production from giant reed and *M. × giganteus* [133,134]. The reported yield of XOS from giant reed was 145 g kg⁻¹ dry initial biomass, higher than that (about 90 g kg⁻¹ dry initial biomass) from *M. × giganteus* [133,134].

3.4.4. Humic substrates

Humic substrates as well as humic-like substrates have positive effects on plant growth and physiology, such as nutrient uptake, photosynthesis, and root development. Lignin has been recognized as a plant growth promoter due to its hormone-like effects. Savy [135] isolated water-soluble lignin fragments from giant reed and *M. × giganteus* using alkaline oxidative hydrolysis, and tested their physical-chemical characteristics and humic effects on the early stage of maize growth. Both of the lignin fragments were extensively depolymerized and largely oxidized with high water-solubility and molecular weight lower than 3,000 Da [135]. Although none of these properties affect maize germination, both of them showed a positive biological activity on maize seedlings [135]. Lignin from *M. × giganteus* enhanced primary root, lateral root, and shoot development with increasing doses, and caused about a 2-fold increase at a phenol-derived organic carbon concentration of 10 ppm [135]. Lignin from giant reed positively affected both primary and lateral root development by about 1.5-fold at 10 ppm of phenol-derived organic carbon, while it did not significantly improve the shoot length at 0–100 ppm of phenol-derived organic carbon [135].

3.4.5. Potential products from lipophilic extractives

Lipophilic extractives are a diverse group of compounds that are dissolvable in organic solvents, such as acetone and dichloromethane. Lipophilic extractives in lignocellulosic biomass mainly contain fatty and resin acids, fatty acid esters, and neutral compounds, such as fatty alcohols, sterols, and sterol glycosides [136]. Although the amount of lipophilic extractives from lignocellulosic

Table 8

Comparison of bioproducts production between giant reed and miscanthus.

Products	Crops	Conditions	Performance	References
Whole biomass				
Particle boards	GR	120 °C, 3.5 N mm ⁻² , 6 min	High quality	[124,125]
	MS	180 °C, 3.4 N mm ⁻² , 9 min	Low quality	[126]
Cellulose				
Paper	GR	200 °C, ethanol/water, 130 min	Excellent	[131]
		175 °C, alkaline, 90 min	Excellent	[129]
	MG	120 °C, alkaline, 30 min	Excellent except for the poor tear index	[130]
Hemicellulose				
XOS	GR	Pretreatment: 180 °C, water, 42 min	Yield: 145 g kg ⁻¹	[133]
	MG	Pretreatment: 160 °C, water, 60 min	Yield: ~90 g kg ⁻¹	[134]
Lignin				
Humic substrates	GR	Pretreatment: 50 °C, 2% H ₂ O ₂ (v/v), pH 11.5, 24 h	Improve maize root development by ~1.5-fold	[135]
	MG	Pretreatment: 50 °C, 2% H ₂ O ₂ (v/v), pH 11.5, 24 h	Improve maize root and shoot development by ~2-fold	[135]
Lipophilic extractives				
Phytosterols	GR	N/A	Fatty acids > sterols > monoglyceride	[137]
	MG	N/A	sterols > aromatics > fatty acids	[138]

GR: giant reed; MG: *M. × giganteus*; MS: *M. sacchariflorus*.

biomass is usually very low, they can potentially be used as a highly valuable source for phytochemicals, providing a significant contribution to the valorization of lignocellulosic biomass [136]. Coelho et al. [137] and Villaverde et al. [138] studied the chemical composition of the lipophilic extractives from giant reed and *M. × giganteus*, respectively. It was found that giant reed extractives are rich in fatty acids (1.138 g kg⁻¹ dry biomass), sterols (0.528 g kg⁻¹ dry biomass), and monoglyceride (0.368 g kg⁻¹ dry biomass), while *M. × giganteus* extractives mainly contain sterols (0.275–0.949 g kg⁻¹ dry biomass), aromatic compounds (0.521–0.829 g kg⁻¹ dry biomass), and fatty acids (0.393–0.453 g kg⁻¹ dry biomass) [137,138]. Many studies have suggested that phytosterols are helpful in reducing blood cholesterol. Sterols in lipophilic extractives from giant reed and miscanthus could potentially be used as ingredients in functional foods.

Table 8 summarizes the conditions and performance of bio-product production from giant reed and miscanthus. Giant reed showed better performance than miscanthus in production of particle boards, paper and XOS, but its lignin had a lower effectiveness than that of miscanthus as a humic substrate. Besides, the profile of lipophilic extractives for giant reed was different from that for miscanthus, indicating that their lipophilic extractives could be used for different purposes. It should be noted that some performances were obtained under different conditions between giant reed and miscanthus. However, it is evident that giant reed has great potential in producing these bioproducts compared with miscanthus, and future researches are needed for more side-by-side comparisons.

4. Current challenges and future research

There are several challenges which may hinder the commercial scale cultivation of giant reed for the production of biofuel and bioproducts.

1. Propagation, planting, and harvesting methods of giant reed have not been as well studied as those of miscanthus. As mentioned in Section 2, established methods for cultivation of miscanthus (or traditional crops) cannot be directly transferred to giant reed. For future studies, improvement of micro-propagation of giant reed is expected to further reduce

production costs. More efforts are needed to develop or adapt equipment and methods that are suitable for mechanical planting and harvesting of giant reed. Also, the potential of multiple harvesting of giant reed, which constitutes an advantage over miscanthus, has not been properly evaluated. If the crop can be effectively harvested and re-grown several times each year, this practice can help increase the biomass yields and reduce the storage expenses for biorefineries.

2. Cultivation of giant reed in non-native environments is always a controversial issue due to its potential environmental impacts both in the short and long term. The major concern comes from its potential to be highly invasive to the local ecosystem due to its fast growth and strong adaptability, although these features also lead to beneficial applications, such as erosion control and phytoremediation of trace elements contamination. Continuous efforts should be devoted to exploit the environmental benefits of giant reed while reducing the potential hazards.
3. Pretreatment is generally required in order to improve sugar yield from giant reed for sequential biofuel production. There is a trade-off between low pretreatment cost and high sugar yield. For example, the reported sugar yields from giant reed were normally lower than 70% when using low-cost chemicals, such as sulfuric acid and sodium hydroxide. The highest glucose yield from giant reed was obtained by using the CSLF method, which typically requires expensive organic solvents and phosphoric acid (Table 4). Some pretreatment technologies, such as the AFEX method, appeared to be more effective than others for obtaining higher sugar yield from miscanthus, but this difference may not be accurate as research on pretreatment of giant reed is limited (Table 4). Therefore, it is worthy to evaluate the potential of these pretreatment technologies for improving sugar yield from giant reed.
4. Although giant reed has the potential for production of various biofuels and bioproducts with comparable or better performance than miscanthus, the available data are limited. Different processes for producing different bioenergy/bioproducts can be integrated for enhanced economic feasibility, but this strategy has not been studied using giant reed. Recently, a bio-refinery concept has been proposed for utilization of giant reed biomass for producing various products, which indicates another promising approach for future study.
5. The efficiency and energy inputs of converting giant reed to bioenergy and bioproducts are significantly influenced by the

characteristics of the biomass, such as the moisture content, mineral contents, cellulose content, and recalcitrance. Studies on the effect of harvest time, methods, and other management practices on the characteristics of giant reed and on the following biological and thermochemical conversions are needed, so that the production system can be optimized to reduce the cost of producing bioenergy and bioproducts from giant reed.

5. Conclusion

Giant reed is a C3 plant that can be competitive with miscanthus, a C4 plant and a well-known energy crop, in terms of biomass production and biomass conversion to bioenergy and bioproducts. Giant reed can adapt to a broader range of environments than miscanthus. Although giant reed may require more energy inputs for planting, it can achieve higher biomass yields than miscanthus, especially considering that giant reed has the potential for multiple harvests per year which is not recommended for miscanthus. Ecological control is critical for giant reed due to its high invasive potential. Compared with miscanthus, giant reed generally showed comparable yields in production of bioenergy, such as bioethanol and biomethane. However, giant reed achieved better performance than miscanthus in production of several bioproducts, such as particle boards, paper, and xylo-oligosaccharides. In order to commercialize cultivation of giant reed and production of biofuel and bioproducts from its biomass, more efforts are needed in the following aspects: (1) evaluation of multiple harvests per year, (2) assessment of environmental benefits and reduction of potential hazards, (3) evaluation of advanced pretreatment technologies, (4) integration of processes for production of different bioenergy and bioproducts, and (5) investigation of effects of management practices on the production of biofuels and bioproducts.

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