**Abstract**

As an herbaceous perennial, Miscanthus has attracted extensive attention in bioenergy refinery and ecological remediation due to its high yield and superior environmental adaptability. This review summarizes current research advances of Miscanthus in several aspects including biological properties, biofuels production, and phytoremediation of contaminated soil. Miscanthus has relatively high biomass yield, calorific value, and cellulose content compared with other lignocellulosic bioenergy crops, which make it one of the most promising feedstocks for the production of second-generation biofuels. Moreover, Miscanthus can endure soil pollutions caused by various heavy metals and survive in a variety of adverse environmental conditions. Therefore, it also has potential applications in ecological remediation of contaminated soil, and reclamation of polluted soil and water resources. Nevertheless, more endeavors are still needed in the genetic improvement and elite cultivar breeding, large-scale cultivation on marginal land, and efficient conversion to biofuels, when utilizing Miscanthus as a bioenergy crop. Furthermore, more efforts should also be undertaken to translate Miscanthus into a bioenergy crop with the phytoremediation potential.

**KEYWORDS**

bioenergy crop, bioethanol, biomass, environmental remediation, heavy metals, Miscanthus
1 | INTRODUCTION

Energy powers the households, industrial development, and global economy growth. The ever-increasing consumption of fossil fuels and the arising negative environmental impacts are currently driving a search for renewable alternatives that secures energy security and sustainability (Charles et al., 2007). To ensure energy independence and address environmental concerns, the production of renewable energy receives increasing global attention. Bioenergy is an important type of renewable energy supplementary to fossil fuels. According to the composition of energy carrier materials, bioenergy crops can be divided into three main categories: (a) starch and sugar crops that can be used in the production of fuel ethanol; (b) oil crops that can be catalyzed into biodiesel; (c) lignocellulosic crops, which are rich in cellulose, hemicelluloses, and lignin, can be converted to generate heat, electricity, biogas, and ethanol.

Ethanol derived from corn starch is currently one of the most important resources of biofuels, which accounts for 94% of the total bioethanol production in the United States. However, the increased demands for bioethanol will drive the surge of corn price and consequently endanger food security (Kocar & Civas, 2013). Therefore, it is preferable to use non-grain crops as feedstocks in the biofuels production. As an alternative, lignocellulosic biomass is a promising feedstock for bioethanol production. Recent years witness a growing interest in the utilization of perennial grasses as bioenergy crops in the United States and European countries. Several outstanding features that render perennial grasses attractive in bioenergy production include higher yield potential, high cellulose content, and positive environmental impacts (Lewandowski et al., 2003). In addition, marginal and abandoned land may be exploited for the cultivation of lignocellulosic crops, which can avoid the competition with farm land in biofuel feedstock production (Tulbure et al., 2012).

Miscanthus is a perennial rhizomatous C4 grass originated from East Asia. It belongs to the Poaceae that has about 17 species, including M. sinensis, M. floridulus, M. sacchariflorus, and M. lutarioriparius all over the world (Brosse et al., 2012). Miscanthus has several outstanding properties such as high photosynthesis efficiency, high nutrient and water use efficiency, and wide adaptability to various climates and soil types (Clifton-Brown et al., 2016). Meanwhile, Miscanthus has the potential application in environmental restoration. Thus, the use of environmentally friendly crops is deemed as a win–win strategy in the bioenergy feedstock production (Robertson et al., 2017). In this respect, this review systematically summarizes the current knowledge obtained for Miscanthus regarding its genetic breeding, cultivation, and its potential utilization in bioethanol conversion and environmental remediation.

2 | BIOLOGICAL CHARACTERISTICS

As a tall perennial grass, Miscanthus generally lives for 18–20 years or even up to 25 years. The height of Miscanthus plants varies from 1 to 7 m depending on different species and growth conditions. The photosynthetic efficiency of Miscanthus is high even at low temperatures (Tubeileh et al., 2016). The maximum conversion rate of solar radiation is estimated to be 4.1 g C/MJ, which is about 10 times higher than that of common agricultural crops (Heaton et al., 2008). Meanwhile, the water use efficiency of Miscanthus is up to 7.8–9.2 g/kg, which is significantly higher compared with other crops (McCalmont et al., 2017). With well-developed roots and underground rhizomes, Miscanthus has the capability to absorb nitrogen and water from the deep soil (Neukirchen et al., 1999). It is documented that Miscanthus can maintain normal growth in poor soil with little availability of nitrogen (N), phosphorus (P), and potassium (K) fertilization (McCalmont et al., 2017). In addition, Miscanthus exhibits prominent tolerance to drought, heat, cold, salt and alkali stresses, and broad resistance to a variety of diseases and insects. Due to its outstanding ecological adaptability, Miscanthus is widely distributed in various soil types in tropical, subtropical, and temperate regions (Chung & Kim, 2012). From the third year of cultivation, Miscanthus usually achieves the maximum biomass yield. For example, the aboveground biomass yield of M. giganteus and M. lutarioriparius reaches 30 t/hm at the third year after the plantation (Brosse et al., 2012).

M. sinensis is a diploid (2n = 38), while various types of ploidy, including diploid, triploid, or tetraploid, are discovered for M. sacchariflorus. In addition, the polyploidy is either homo- or hetero-polyploidy depending on the intra- or inter-species hybridization (Hodkinson et al., 2014). Despite that Miscanthus is self-incompatible, hybrid plants derived from the intra- and inter-species have remarkably high seed setting rate. As a triploid (3n = 57), Miscanthus × giganteus (M × g) is a natural hybrid between M. sinensis (diploid) and M. sacchariflorus (tetraploid). Due to its larger stature and vigorous growth property compared with its parents, M × g is currently the dominant species cultivated in several European countries and the United States (Rayburn et al., 2009).

3 | POTENTIAL FEEDSTOCK FOR BIOFUEL

3.1 | Components of Miscanthus biomass

Similar to other plant biomass, the biomass of Miscanthus consists mostly of plant cell walls, containing cellulose, hemicelluloses, and lignin. Hemicellulose is a mixture of heteropolysaccharides mainly composed of xylan and
arabinoxylan. It is present in both primary and secondary cell walls, and cross-linked together with cellulose microfibrils. Lignin strengthens cell wall structure by forming a protective layer coating with cellulose microfibrils. According to previous studies, Miscanthus lignocellulose contains 32.7%–49.5% cellulose, 21%–34.8% hemicellulose, and 17.8%–27.7% lignin (Lee & Kuan, 2015). The main bottleneck restricting the use of lignocellulose material is the recalcitrance of plant cell walls to efficient degradation into fermentable sugars (Pauly & Keegstra, 2008). To enhance biomass yield and biofuels production, a systematic understanding of the composition and structure of Miscanthus cell walls is required, as both features have significant effects on plant growth and biofuels conversion (Der Weijde et al., 2017; Wang et al., 2016). Generally, higher cellulose and hemicellulose levels have a positive effect on enzymatic saccharification and fermentation of lignocellulose to biofuels (Costa et al., 2019; Der Weijde et al., 2017). In contrast, higher lignin content negatively impacts the conversion efficiency. Other cell wall features, such as polysaccharide cross-linking and cellulose crystallinity indices, have also been shown to affect biofuels conversion (Biswal et al., 2018; Wang et al., 2016).

Analysis of the Miscanthus lignocellulose components is mainly focused on four species: *M. sacchariflorus*, *M. sinensis*, *M. floridulus*, and *M × g*. According to the various reports in literature, the cellulose content of *M × g* (approximately 41%) is slightly higher than others while there is no significant difference in hemicellulose content among the four species (Tajana et al., 2017). The average cellulose content of *M. sacchariflorus*, *M. sinensis*, *M. floridulus*, and *M × g* are 38.9%, 37.6%, 37.2%, and 41.1%, respectively (Lee & Kuan, 2015). As for lignin, *M. sacchariflorus* has a relatively low content (16.7%), and *M. sinensis* has the highest (23.7%) while it is intermediate for *M. floridulus* and *M × g* (21.7%). Based on their average cellulose content, it is estimated that per gram of *M. floridulus*, *M. sinensis*, *M. sacchariflorus*, and *M × g* biomass could theoretically produce 0.211, 0.213, 0.221, and 0.233 g of bioethanol, respectively (Lee & Kuan, 2015).

Cultivation and screening of Miscanthus for enhanced biomass yield and biofuels production has been an important research topic. Tim et al. (2016) studied different Miscanthus genotypes growing in six locations to analyze the effect of genotypes, environmental conditions, and their interactions on lignocellulose compositions. These results indicate that environmental influence on biomass composition and quality is substantial. Therefore, it is of significant importance to select a genotype with superior and stable performance.

Peng et al. (2017) studied the biomass composition and degradability of four Miscanthus species (i.e., *M. sinensis*, *M. floridulus*, *M × g*, and *M. lutarioriparius*) at different growth stages. It was found that the biochemical methane potential (BMP) of Miscanthus is the highest when it is grown for 60 days and the BMP decreased with the extension of growth. As the BMP is positively correlated with cellulose degradability, it is justifiable to take into account of cellulose degradability apart from biomass yield when choosing the suitable harvest time.

### 3.2 | Pretreatment of Miscanthus biomass

The production of bioethanol and other fermentation products from lignocellulosic materials (i.e., Miscanthus biomass) involves a multi-step biochemical transformation process, which usually includes pretreatment, saccharification, and fermentation (Lee & Kuan, 2015). After the proper pretreatment, the polysaccharides in biomass can be converted into monosaccharide such as glucose and xylose via the enzymatic saccharification (Wang et al., 2016). Thereafter, monosaccharide can be fermented to produce fuel ethanol, organic acids, and other chemicals. The cellulose in lignocellulosic biomass can be modified through the pretreatment process, making it easier to be digested by cellulolytic enzymes. Methods for pretreatment include physical, chemical, and thermal chemical means, and various methods can be jointly utilized (Lee & Kuan, 2015). Currently, the commonly used pretreatment methods include mechanical, mineral acid, alkali, liquid hot water (LHW), organosolvent, wet oxidation, ozonolysis, CO₂ explosion, steam explosion, ammonia fiber explosion (AFEX), and ionic liquid (Chen et al., 2017; Kumar & Sharma, 2017).

The particle size of biomass usually needs to be reduced by mechanical processes such as chipping and grinding prior to other pretreatments. Reducing the particle size can reduce the crystallinity of cellulose and facilitate the binding of cellulase to the surface of cellulose. It has been proved that the crystallinity of cellulose decreases with the reduced particle size (Yoshida et al., 2008). It has also been proved that in the grinding process, the wet process (mixed water and biomass in a ratio of 2:1, homogenized at 9,000 RPM for 2 min, and then centrifuge at 2,600 RCF for 10 min) can obtain a higher cellulose content and a lower cellulose crystallinity than the dry method (the biomass was dried at 105°C for 24 hr, and then ground to particle), leading to a higher bioethanol productivity in the subsequent fermentation process (Boakyeboaten et al., 2016).

Physicochemical means include LHW, steam explosion, microwave chemical, and AFEX. When Miscanthus biomass is subjected to steam explosion at 200°C under 15 bar for 10 min, the xylooligosaccharide (XOS) yield of the initial xylan in the hydrolysate reaches 52% (Bhatia et al., 2019).

Chemical pretreatment refers to the pretreatment using acid, alkali, alcohol, organic acid, pH controlled LHW, or ionic liquid. Incubation of lignocellulosic raw materials with alkaline solutions (i.e., NaOH, KOH, Ca (OH)₂ and
ammonia) is effective to remove lignin and hemicelluloses, thus further improves the accessibility of cellulolytic enzymes
to cellulose. Compared with acidic pretreatment, alkaline
pretreatment can remove a large amount of lignin, thereby
resulting in highly digestible cellulose. For instance, the
removal rate of lignin can reach 84.6% after the pretreatment
with 1.5% NaOH on Miscanthus biomass (Jung et al., 2019).
Cerazywaliszewska et al. (2019) compared the ethanol pro-
duction efficiency of three Miscanthus species (i.e., \(M \times g, M. sinensis\), and \(M. sacchariflorus\)) by grinding biomass into
2.0 mm pieces and then subjected to 1.5% NaOH pretreat-
ment. The highest yield and efficiency of raw bioethanol
production are recorded for genotypes of \(M. sinensis\) (234–
253 g/kg DM, 83%–86%), followed by \(M. sacchariflorus\)
(207–237 g/kg DM, 76%–81%) and \(M \times g\) (185–222 g/kg
DM, 62%–76%) (Cerazywaliszewska et al., 2019).

To obtain a higher saccharification yield, the above-
mentioned pretreatment methods are usually applied in
combination. For example, a two-step ferric chloride and
dilute alkaline pretreatment (F-ALP) is developed by
effectively recovering soluble sugars in the first ferric chlo-
ride pretreatment (FP) step and further removing lignin of
the FP sample in the second alkaline pretreatment (ALP)
step to improve Miscanthus biomass saccharification (Li
et al., 2020). As a result, the two-step process yields the
highest total sugar recovery (418.8 mg/g raw stalk) through
the whole process than FP/ALP process. Cayetano and
Kim (2018) pretreated biomass with the AFEX (120°C for
12 hr) and hot water (190°C for 90 min), glucan digestibility
approaches 95.3% and the recovery rate of xylan reaches
84.2%. In addition, the pretreatment combining hydrother-
mal method (190°C, 10 min or 195°C, 15 min) with NaOH
(300°C) has the most ideal depolymerization effect on lig-
nin (Jensen et al., 2018).

Moreover, adding catalyst in the pretreatment process
is also effective to improve sugar recovery. After pretreat-
ment by chloride/glycerol as solvent and silicotungstic acid
as catalyst under 120°C for 3 hr, the enzymatic digestibil-
ity efficiency reaches 97.3%. Approximately 80% glucose is
obtained within 12 hr, and 81.8% ethanol is produced after
the fermentation (Guo et al., 2019). Dąbkowska et al. (2019)
pretreated \(M \times g\) biomass with 1.25% \(H_2SO_4\) as the catalyst
and 80% glycerol as the organic solvent, which efficiently
prevents the conversion of sugars into furfural and organic
acids, resulting in a relatively high sugar recovery rate (dex-
tran > 98%, and xylan > 91%) and 60% removal of lignin.
When pretreated with dilute sulfuric acid (\(H_2SO_4\)), adding
0.08 mol/L MgO to the pretreatment liquid can neutralize the
acetic acid produced during the reaction, reduce glycolysis,
and eliminate the formation of inhibitors in downstream re-
actions (Liu et al., 2019).

Kashcheyeva et al. (2019) compared the enzymatic sac-
charification efficiency of Miscanthus biomass pretreated
by five different pretreatment methods: hydrothermobaric
treatment, single-stage treatments with dilute \(HNO_3\) or di-
lute \(NaOH\) solution, and two-stage combined treatment
with dilute \(HNO_3\) and \(NaOH\) solutions in direct and reverse
order. The results showed that except for the hydrothermal
pretreatment, all other pretreatment methods can produce
high-quality pretreated substrates. From a techno-economic
perspective, single-stage pretreatment methods are of choice.
When dilute \(HNO_3\) or dilute \(NaOH\) is used for single-stage
pretreatment, biomass digestibility is increased about seven
times and the yield of total reducing sugar reaches about 80%
on a substrate weight basis. From an ecological perspective,
hydrothermal and dilute acid pretreatments have the least
adverse impact on the environment while alkaline treatment
had the largest environmental impact (Lask et al., 2019).
Considering the greenhouse gas mitigation, dilute alkali of-
fers the smallest savings because of its upstream burdens,
whereas dilute acid and LHW have substantially higher re-
duction potentials. Based on a techno-economic analysis, the
cost of AFEX appears to be the lowest (0.61 US $/L), while
the cost of other pretreatments is between 0.75 and 0.93 US
$/L (Lee & Kuan, 2015).

In addition to chemical, physical, and thermal pretreat-
ments, Guo, Feng, et al. (2017) developed an effective bi-
ological pretreatment method with bacterial isolates. This
leads to decreased hemicellulose contents and cellulose
crystallinity in Miscanthus biomass and, thus, increased en-
zymatic saccharification by 31%–88%. Wright et al. (2018)
designed a new lignocellulosic biomass pretreatment reac-
tor. This reactor uses plasma and energy efficient micro-
bubbles for the pretreatment of Miscanthus biomass and
is expected to replace traditional pretreatment reactors.
However, the potential of the new reactor need to be ex-
plored further.

### 3.3 | Enzymatic saccharification of Miscanthus biomass

After pretreatment, the remaining carbohydrates (cellulose
and a small amount of hemicelluloses) in the pretreated raw
materials are converted into fermentable sugars by a cock-
tail of enzymes (cellulolytic, hemicellulolytic, auxiliary/AA9)
and proteins (e.g., swollenin; Adsul et al., 2020; Payne
et al., 2015). In addition to enzyme and proteins, supple-
ment of surfactant (2% Tween-80 or 1% Silwet L-77) into
pretreated Miscanthus biomass has massive boosting effect
on hexoses yield (Sun et al., 2017, 2020). Lignin isolated
from the \(M \times g\) genotype contains a high proportion of \(\beta-O-
4\)-linkages, which may be more easily removed during pre-
treatment processes to efficiently reduce the lignin content
(Schafer et al., 2019). In addition to linkages, lignin com-
position can also affect biomass pretreatment and enzymatic
miscanthus with higher levels of guajacyl-lignin monolignol exhibits significantly increased enzymatic saccharification compared to those with higher levels of syringyl-lignin monolignol, whereas biomass samples with higher levels of hydroxyl-phenyllignin monolignol display only slightly increased saccharification yields (Li, Si, et al., 2014). Moreover, various products, such as soluble lignin compounds, derived from biomass pretreatment may also have a great influence on enzymatic saccharification efficiency (Hendriks & Zeeman, 2009). Costa et al. (2019) examined key variables between Miscanthus organs, genotypes, and saccharification performances and found that the cell wall composition and biomass quality are significantly different between plant organs, group of genotype and species, which affect the fine structure of the plant cell wall, and further impact saccharification efficiency performances. In particular, lignin has a predominant effect on the saccharification of Miscanthus stems, while polysaccharide cross-linking and/or modification in foliar biomass appear to have more determinant effects on saccharification (Costa et al., 2019). Hence, a holistic outlook of the cell wall is indispensable to improve biomass quality. Instead of defining a single Miscanthus biorefining ideotype, the development of a collection of varieties, taking into account target products, provides a more realistic and valuable approach (Costa et al., 2019).

Although pretreatment can deconstruct the tight cross-linking among cellulose, lignin, and hemicellulose, and make them easier for enzymatic saccharification, tailored-design of plant cell wall components and structure by genetic modification may make the enzymatic process even more efficient (Xie & Peng, 2011). Robust and effective in vitro regeneration techniques have been developed for M. sinensis, M. × g, and M. sacchariflorus species (Guo et al., 2013; Hwang et al., 2014; Rambaud et al., 2013; Ślusarkiewicz-Jarzina et al., 2017; Wang et al., 2011; Zhang et al., 2012). Yoo et al. (2018) generated transgenic M. sinensis lines with decreased lignin biosynthesis by knocking down the caffeic acid O-methyltransferase using antisense RNA technique. All these studies put forward new ideas to improve the enzymatic saccharification efficiency of Miscanthus biomass feedstock.

### 3.4 Production of cellulosic ethanol and other by-products

Cellulosic ethanol is commonly produced by yeast fermentation of the hydrolysate from enzymatic saccharification of Miscanthus biomass after pretreatment. Therefore, optimized feedstock and its pretreatment and saccharification processes are required for a cost-effective production of bioethanol (Mohapatra et al., 2017). The key issues concerning the fermentation process include (a) to improve microorganisms for high fermentation capacities, (b) to efficiently convert both hexoses and pentoses, and (c) to minimize the formation of fermentation inhibitors from pretreatment and saccharification. When a two-step procedure involving a dilute-acid pre-soaking step and an aqueous-ethanol organosolv treatment was applied, an efficient fractionation of \( M \times g \) biomass into cellulose-, lignin- and hemicelluloses-rich fractions was achieved, which allowed the hydrolysate to be fermented with S. cerevisiae to produce 70% ethanol within 48 hr (Brosse et al., 2009). Zhu et al. (2015) reported that the major fermentation inhibitory by-products from acidic and alkaline pretreatment of Miscanthus biomass include furfural and hydroxymethyl furfural. Using microwave-assisted mild alkaline- and acidic-pretreatment of Miscanthus biomass, an increased sugar yield was obtained with relatively low levels of fermentation inhibitors (Zhu et al., 2015).

To gain more economic benefits in the production of cellulosic ethanol, the maximum and effective utilization of lignin and hemicellulose by-products is also necessary (Hahn-Hagerdal et al., 2006). Lignin is a commercial product that can be used as a polymer modifier, binder, resin, etc. Hemicellulose extract can be used to produce other value-added products, such as xylitol and XOSs. During autohydrolysis of \( M \times g \) biomass at 180°C for 20 min, 63% of xylan was converted into XOS and xylose (Chen et al., 2015). XOSs are oligosaccharides containing 2–7 xylose molecules linked with \( \beta-(1,4) \) bonds and are generally considered to be prebiotics. The pretreated xylan extracts can be degraded to XOSs by endo-xylanases. Otieno and Ahring (2012) prepared XOSs from Miscanthus biomass by pretreatment with 0.1% \( H_2SO_4 \) at 60°C for 12 hr. The residuals are then heat treated with dry steam, and the resulting liquid contains xylose oligomers at a concentration of 65% (Otieno & Ahring, 2012). In addition, xylan residues released in the pretreatment can be completely hydrolyzed to xylose by xylanases, which can be further converted to by microbial fermentation of the resulting xylose (Li, Liu, et al., 2014).

Besides the by-products derived from the fermentation process, hydrogen energy can also be produced by electrolyzing the extracts of cellulose and lignin isolated from Miscanthus biomass (Ito et al., 2018). Sahoo and Mani (2019) produced compressed natural gas from Miscanthus lignocellulose. A yield of 75%–82% of succinic acid is obtained when the polysaccharide mixture is fermented with Actinobacillus succinogenes (Dąbkowska et al., 2019). The transition metal chromium and tin combined with \( \beta \) zeolite can catalyze the conversion of Miscanthus lignocellulose to lactic acid with a yield of 33.4% and a selectivity of 53.2% (Xia et al., 2019). The production of these value-added products will eventually lower the cost of cellulosic ethanol production, allowing large-scale production of cellulosic ethanol. This will offer new income opportunities to farmers and create new jobs in rural areas as well as protect environment.
4 | ENVIRONMENTAL IMPACT

4.1 | Remediation of heavy metal polluted soil

4.1.1 | Tolerance to heavy metals

Miscanthus has the capacity to absorb and fix heavy metals, remove organic pollutants, promote carbon deposition, improve soil physicochemical properties, and prevent soil erosion. It is of great ecological and economic significance to remediate heavy metals contaminated soil by planting Miscanthus, especially for soils of mining wasteland. Wilkins (1997) verified that \( M \times g \) can grow normally on soils heavily contaminated with copper (Cu), arsenic (As), and zinc (Zn). Wu et al. (2017) summarized several specific characteristics that is distinctive for the excellent heavy metal tolerance of Miscanthus: (a) Miscanthus can tolerate high concentrations of single heavy metal as well as mixed heavy metals; (b) The tolerance to heavy metals varies substantially among different Miscanthus varieties; (c) Heavy metals are mainly accumulated in the underground parts of Miscanthus; and (d) While Miscanthus is not considered a super-accumulation plant for heavy metals, it has a relatively strong absorption and transport capacity for Zn, As, lead (Pb), and chrome (Cr).

Current literature reports indicate that the heavy metal tolerance of Miscanthus is mainly attributed to the following three aspects:

1. Vigorous metabolism in the underground root and rhizome system. Miscanthus has a large and well-developed root and/or rhizome system. For example, \( M \times g \) can accumulate 11–20 t/hm\(^2\) underground dry mass and 7.5–10 t/hm carbon stocks per year (Amougou et al., 2011). Meanwhile, Miscanthus returns a large amount of root residues to the soil every year, and the total sugar and lignin in these root systems are as high as 68.1% and 20.4%, respectively. On the one hand, the returned carbon-containing compounds provide nutrients for soil microorganisms. On the other hand, they can chelate heavy metal ions in the rhizosphere. Zgorelec et al. (2020) observed that 59% of the total Hg was chelated with organic ligands after Miscanthus planting. Besides, the root system of Miscanthus exhibits intense respiration and secretion capability. Ladislav et al. (2010) found that \( M \times g \) roots secrete 17 amino acids including aspartic acid, histidine, arginine, and alanine. Under Cu stress, most Cu is sequestered around the root surface/epidermis, primarily forming Cu alginate-like species as a Cu-tolerance mechanism (Cui et al., 2019). Under Cd stress, the malate (MA) content is significantly increased in root exudates of \( M. \) sacchariflorus (Guo, Wu, et al., 2017). The results indicate that Cd-induced MA synthesis and secretion efficiently alleviate Cd toxicity by reducing Cd influx in \( M. \) sacchariflorus.

2. Miscanthus has superior antioxidant and photosynthetic capability. The antioxidant defense system of plants, if normally activated, can help alleviate damages caused by heavy metal stress and improve the tolerance to heavy metals. For Miscanthus, hormesis effect is the main trend under Cd/As stress. Cr stress leads to a surge in the contents of malondialdehyde (Jiang et al., 2018). Alterations in the expression of 31 genes associated with antioxidant, photosynthesis, and cell growth are observed in \( M. \) sinensis roots and leaves under antimony (Sb) stress (Xue et al., 2015). In particular, significant upregulation is observed in the expression of antioxidant-related enzymes, such as ascorbate peroxidase, guaiacol peroxidase (POD), and glutathione S-transferase. These results suggest that the antioxidant defense system and photosynthetic machinery play a crucial role in the tolerance of Miscanthus to heavy metal stress.

To cope with heavy metal stress, \( M. \) floridulus and \( M. \) sacchariflorus reconcile their photosynthetic efficiency and antioxidant capability to varying degrees. For example, the chlorophyll content and activities of superoxide dismutase and POD are significantly increased under the stress from low concentrations of Pb, Zn, or Cd (Zhang et al., 2015).

3. A variety of beneficial microorganisms are available in the rhizosphere of Miscanthus. Most of these microorganisms are parasitic on the root system and can assist Miscanthus to absorb nutrients, secrete organic acids to passivate heavy metals in the rhizosphere, or promote the non-toxic absorption of heavy metals by Miscanthus roots. All these processes are beneficial to the survival of Miscanthus plants in heavy metal-polluted soil. For example, \( Chaetomium cupreum \) can induce Miscanthus to produce chlorogenic acid and meanwhile produce oospore protein by itself, both of which can reduce the accumulation of Al in the cell wall (Haruna et al., 2019). Inoculation of exogenous microorganisms into the rhizosphere of Miscanthus significantly improves its tolerance to heavy metals. For example, the growth of Miscanthus is promoted by inoculating bacteria or fungi originating from other Miscanthus on heavy-metal-polluted soils (Schmidt et al., 2018). Firmin et al. (2015) found that inoculating \( Funneliformis mosseae \) can improve the antioxidant capability of \( M \times g \), reduce the deleterious oxidation damage induced by heavy metal stress, and promote the growth of \( M \times g \) plants in heavy metal polluted soil. Moreover, Miscanthus planting in mercury-contaminated soil can also enrich the diversity and abundance of microbes in soil (Zhao et al., 2019).

It is noteworthy that \( M \times g \) grown in heavy metal contaminated soil over a long period of time would suffer from early aging of leaves, retarded growth, and lower biomass yield. Fortunately, the application of mineral fertilizers
Cu, 77.5 × 10³ kg Mn, 3.1 × 10³ kg Pb, and 95.9 × 10³ kg Zn

M. sacchariflorus quantities of heavy metals accumulated in respectively, under certain conditions (Bang et al., 2015). The average

61.0%, 56.2%, and 42.9% of Cu, Pb, Ni, Cd, and Zn, respectively, could remove up to 97.7% of As in soil, and 86.4%, 77.5%,

307 mg Zn per square meter in Dongting Lake wetlands (Yao et al., 2018). It is estimated that 0.7 × 10³ kg Cd, 22.9 × 10³ kg

0.06 and 0.29 fold relative to the transplanting stage. In contrast, the ion exchange state of Pb is 10 times relative to the vegetation prior to the restoration, is 14.79 and 9.33 times

removing capability of Zn and Pb is much higher than the control plant Sida hermaphrodita.

The removal capacity of heavy metals is closely associated with the vegetation coverage of plants. Generally, the higher the vegetation coverage is, the more drastic reduction in heavy metal is expected. For instance, the content of organic bound Pb and Zn in soil is 14.79 and 9.33 times higher in M. floridulus at the mature stage compared to the transplanting stage. In contrast, the ion exchange state of Pb and Zn in soil is significantly declined at the mature stage, which is only 0.06 and 0.29 fold relative to the transplanting stage (Ezaki et al., 2008). Therefore, it can be concluded that Miscanthus has a relatively strong heavy metal removing capability from contaminated soil. With this respect, large-scale M × g plantation for the restoration of sludge and soil contaminated by heavy metals have been implemented in Slovakia, Poland, and other countries. Short-term pilot experiment has achieved a rather satisfactory effect. As estimated conservatively, M × g can absorb 55 g Cd, 85 g Pb, and 720 g Zn per hectare per year in the wasteland (Pidlisnyuk et al., 2018, 2019). It is noteworthy that in addition to tailings, municipal sewage sludge constitutes a potential source of heavy metals in soil, which can be partially removed by the cultivation of Miscanthus (Antonkiewicz et al., 2016).

Despite that Miscanthus has the capability to restore heavy metal contaminated soils, it should be noted that heavy metals are mainly deposited in its underground organs. If such organs are not completely removed from the land, the accumulated heavy metals still remain in the soil and continue to threaten the safety of the environment and biological chain. Notably, the removal capacity of heavy metals

M. sinensis masson pine, and bamboo, among which M. sinensis plays a leading role. After 3 years of cultivation, the abundance of the mixed vegetation is 10 times relative to the vegetation prior to the restoration, and the microflora in the restored soil is considerably larger than the control soil (Zhang, Liu, et al., 2020).

Due to the wide adaptability of Miscanthus to various harsh environment conditions, it can be taken for granted that Miscanthus species serves as a pioneer plant in the ecological restoration. Zhang, Liu, et al. (2020) phytoremediate a mining area by mixed planting of Miscanthus, masson pine, and bamboo, among which M. sinensis plays a leading role. After 3 years of cultivation, the abundance of the mixed vegetation is 10 times relative to the vegetation prior to the restoration, and the microflora in the restored soil is considerably larger than the control soil (Zhang, Liu, et al., 2020).

In the barren Loess Plateau of China, the vegetation coverage of arable land, grassland, and scrub is extremely low. Miscanthus planting significantly reduces the release of N₂O and increase the absorbing capacity of CH₄ in soil. The net release of three primary greenhouse gases (N₂O, CH₄, and CO₂) is estimated to reduce to an extent of 4.08 t CO₂-eq per hectare per year (Mi et al., 2018). If we divert to grow Miscanthus on the grassland, soil carbon sequestration would be of significant difference in the long run (Holder et al., 2019). In one life cycle (15 years), it is estimated that Miscanthus will release twice amount of greenhouse gas compared to the current habituated grasses. Meanwhile, compared to the grassland soils, the surface soils of the Miscanthus fields tend to have a risk of acidification due to the higher concentrations of P and K (Hu et al., 2018). Therefore, when evaluating the impacts of Miscanthus cultivation on current and future land use changes in the long run, soil characteristics and soil organic carbon stability should be included in the evaluation.

4.2 | The effect of Miscanthus on the environment

Miscanthus planting in wasteland has been revealed to increase soil carbon input, enhance soil aggregate stability, and water-holding capacity. The improving effect of Miscanthus on soil physicochemical properties of wasteland is mainly attributed to the decomposition of underground organs and litter of root residuals in soil. McCalmont et al. (2017) showed that the decomposition of litter and underground organs of Miscanthus provide a large amount of organic carbon to the soil, which increases the soil organic matter, promotes soil nutrient cycling, improves the texture, structure, and water-holding capacity of soil, and reduces soil nutrient (especially N) loss. Therefore, Miscanthus planting could help to improve the soil organic matter and soil properties. Miscanthus planting accompanied by biochar and biosolid application, significantly enhanced the abundance of humus and mycorrhizal fungi, and improves soil fertility and hydraulic properties, with biosolid exerting the most pronounced effect among them (Allami et al., 2019).

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5 | PROSPECT

The lignocellulosic biomass of Miscanthus is deemed as a promising feedstock for cellulosic ethanol production due to its high cellulose content. As a perennial C4 grass, Miscanthus can maintain high biomass yield for up to 25 years once established. Extensive studies have shown that genotype, climatic condition, seasonal change, and harvesting time all have an impact on the cellulose content of Miscanthus. Therefore, screening and breeding of Miscanthus cultivars that has wide environmental adaptability can produce higher yield of biomass with optimum lignocellullose compositions.

Phytoremediation by Miscanthus is a very promising eco-friendly and cost-effective technology that is also expected to be commercially feasible in the near future. Phytoremediation activities can also help in ecological recycling of heavy metals and metalloids. Energy plantations established on marginal land provide environmentally and economically beneficial treatment of soil and do not compete with food production. Therefore, coupling bioenergy production with phytoremediation could thus play an important role in energy self-sufficiency and environmental remediation of polluted land. In addition, compared with other crops, the mechanisms underlying heavy metal tolerance of Miscanthus remain largely unknown. Many issues regarding heavy metal tolerance of Miscanthus have not been fully investigated or clarified. For example, how does Miscanthus activate its robust antioxidant system? Alternatively, are there unique proteins that are responsible for the absorption and transportation of heavy metals in Miscanthus? In-depth analysis of these issues is necessary to further maximize the potential of Miscanthus in the remediation of heavy metal contaminated soil. This highlights the tremendous potential for further studies focusing on the molecular breeding of Miscanthus.

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DATA AVAILABILITY STATEMENT

Data sharing not applicable—No new data generated or the article describes entirely theoretical research.

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