



The Potential Application of Giant Reed (*Arundo donax*) in Ecological Remediation

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Giant reed is known as one of the most important energy plants as a consequence of its huge dry biomass production. It can be used for bioenergy or biopolymer production. Thus, it can replace maize and reduce the production cost of biomass and electricity. Giant reed and its products have different uses in industry. The use of giant reed as a raw material to obtain cellulose past for the production of rayon viscose and paper. Thanks to the flexible and strong of the material, giant reed can be used in the manufacture of fishing rods, brass musical instruments, canes and construction supplies. One of the most important characteristics of giant reed is that it shows strong growth capability in different soils with wide ranges of pH, salinity and high heavy metal contents and can be used for ecological remediation. Giant reed was able not only to decontaminate polluted soils with heavy metals, but also to purify the wastewater and decrease the pH and make red mud safer. Here, we review the available evidence regarding the utilization of giant reed in the field of phytoremediation and discuss the potential application of giant reed combined with advanced remediation technologies in ecological remediation.

Keywords: ecological remediation, economic and ecological value, phytoremediation, heavy metal pollution, giant reed

INTRODUCTION

With the coming of the industrial revolution, humans were able to advance further into the 21st century. At present, the industry is a critical component of the world's economy. However, at the same time, the industrial processes also cause environmental pollution. It accounts for more than half of the total emissions of some key air pollutants and greenhouse gases, as well as other critical ecological impacts, including the release of pollutants to water and soil (Muradian and Martinez-Alier, 2001; Wang et al., 2019). Consequently, these pollutants can pose a health risk to humans and other organisms.

The discharge of excessive amount of heavy metals is one of the most severe environment pollutions. The toxicity of heavy metals is well documented for its impairment of plant growth and human health. Therefore, it is necessary to eliminate excessive amounts of heavy metals in soil and water to avoid negative consequences. Various conventional methods have been used to remove heavy metals, such as chemical precipitation, solvent extraction, membrane filtration, ion change, electrochemical removal and coagulation etc. (Burakov et al., 2018). However, questions have been raised to query these techniques in term of incomplete removal, low efficiency and costly disposal etc. Compared to conventional methods, phytoremediation has excellent potential to overcome those

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drawbacks, improving the treatment efficiency and cut the expense. It has been reported that some hyperaccumulator plants can accumulate a large number of heavy metals. For example, *Alyssum bertolonii* can accumulate Ni up to about $10,000 \mu\text{g g}^{-1}$ or 1% (Reeves et al., 2018). Soil salinization is another global environmental problem that could damage land quality and limit plant growth. It is estimated that over half of the irrigated farmlands are seriously impacted by soil salinization (Li et al., 2018). Although the use of chemical amendment, for example, use Ca to replace exchangeable Na, or apply organic amendments such as farm manure, poultry manure and plant ash to reduce the soil pH may be a practical strategy to improve soil remediation (Tejada et al., 2006; Dahlawi et al., 2018), the high cost and less efficiency of these methods were the main obstacles that limit their application (Nouri et al., 2017). Alternatively, halophytes are ideal plants for salt remediation of soil. For example, *Tecticornia indica* and *Suaeda fruticosa*, which can eliminate redundant salts from soil, and thus these plants are popularly used for the soil remediation (Rabhi et al., 2010). Water is essential for life on Earth. Any pollutants or contaminants which find their way into water will soon find their way into the bodies of plants and animals. Contaminated water is one of the most common forms of environmental pollution, not to mention one of the most damaging to the health of living organisms, entering bodies through drinking, contact, or uptake from roots. Water pollution can either be directly through the discharging of waste into a body of water such as a lake, river or the sea, or it can be indirect in that it is not deliberately disposed of into a watercourse but finds its way there. The most common cause of water pollution is human activity including industry, agriculture and livestock farming, rubbish and fecal water dumping. To abate water pollution, various treatments such as adsorption, biodegradation, coagulation, ion-exchange, and oxidation processes have been evaluated. However, the practice of these methods is very complexity (Jain et al., 2018; Shahid et al., 2019). Constructing wetlands to remediate wastewater is an efficient strategy because of its eco-friendly and low operational cost (Wang et al., 2018). This strategy mainly uses the plant-bacteria synergism to clean the organic matter, microorganisms, nitrogen, and phosphorus in the water.

Based on the above information, we can conclude that plants with excellent pollutant adsorption capacity have great potential in ecological remediation. In the following, we introduce the characterization of giant reed (*Arundo donax*) in the field of phytoremediation and discuss the potential application of giant reed combined with advanced remediation technologies in ecological remediation.

ORIGIN AND REPRODUCTION OF GIANT REED

Giant reed is a tall perennial rhizomatous grass that can reach 10 m in height (Barreca et al., 2019). Owing to its fast growth and great biomass, giant reed had been attracted the farmers and researchers attention to use for multi-purpose (Perdue, 1958; Bell, 1998). For a long time, the stem of the giant reed was used to

make paper (Perdue, 1958). In Italy, giant reed has been used in industry since 1930, when a company registered a trademark to obtain cellulose for producing rayon viscose and paper (Facchini, 1941). The European “Giant reed Network” has been established since January 1997. The project, within the framework of the FAIR Program, has been designed to generate information about this plant’s capacity to be brought into EU agriculture for energy and pulp production (Lewandowski et al., 2003). Due to its considerable growth capacity in different soils with wide ranges of pH, salinity, and trace metal contents, giant reed was used to absorb heavy metals and improve saline alkali soil in recent years (Herrera-Alamillo and Robert, 2012; Quinn et al., 2015). Giant reed is suitable for energy production because of the high biomass yield, which can reach to 37.7 t dry matter per ha and per year (Angelini et al., 2009). Among the different biomass crops for producing renewable energy to reduce greenhouse gas emissions due to fossil fuels, the giant reed is considered the best candidate (Di Mola et al., 2018). It is an ideal plant for dealing with extreme situations of soil conditions and water availability (Figure 1).

Because of its vast economic value, giant reed is widely planted in subtropical regions of the world, such as Southern Europe, North Africa, Australia, and America (Guo and Miao, 2010). Giant reed does not produce seed in many areas because the further development of the embryo is restricted (Balogh et al., 2012; Nixhade and Makde, 2014; Alshaal et al., 2015). The propagation of giant reed can be divided into rhizomes or stem cuttings and *in vitro* biotechnology methods.

Planting time on stem cuttings has a significant influence on the survival rate of the giant reed. Tang (2000) used the stem of the giant reed as propagules about February or March, and the survival rate reached 97%. However, the survival rate of cutting with the lateral branches of giant reed is not high. Luo et al. (2018) used different types and concentrations of plant hormones to treat the lateral branches of giant reed, and the highest survival rate was only 50%. Rhizomes are easy to generate roots in wet environments and produce new plant clones. The propagation of giant reed is more commonly used fragments of rhizomes.

Compared with rhizomes or stem cuttings, the efficiency of *in vitro* biotechnology methods is higher. Gubišová et al. (2016) report that stem segments containing an axillary bud of the giant reed can produce about 700 rooted and acclimatized plants in one year starting from one axillary bud on Murashige and Skoog medium supplemented with 0.5 mg l^{-1} 6-benzyladenine or 0.2 mg l^{-1} thidiazuron. Marton and Czako (2002) suggest that the immature inflorescences of giant reed are sterilized and then cultured *in vitro* to produce totipotent tissue from which mass propagation of plantlets is possible. Herrera-Alamillo and Robert (2012) use axillary buds from the lateral stems cultured in liquid medium supplemented with indole 3-acetic acid and kinetin to produce 900 plants from a single mother plant in 4 months. Cavallaro et al. (2011) describe a protocol for the large-scale *in vitro* propagation of giant reed by adventitious bud formation. The technical system of callus induction, differentiation, and plant regeneration can significantly increase the reproduction coefficient of plants. Chen et al. (2016) report that Murashige and Skoog medium supplemented with 0.2 mg l^{-1} naphthaleneacetic

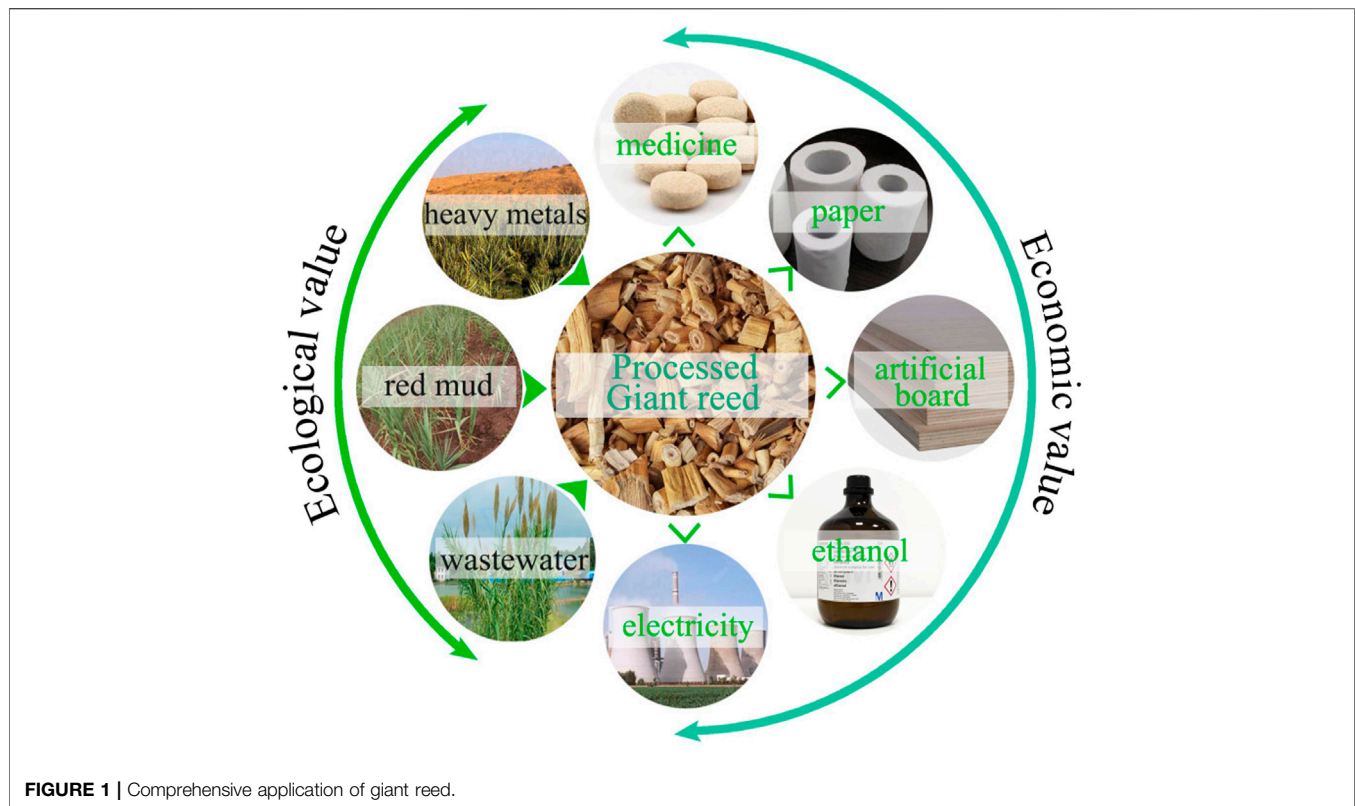


FIGURE 1 | Comprehensive application of giant reed.

acid and 2.0 mg l^{-1} 6-benzyladenine are used for the best callus differentiation medium in turn the bud differentiation stage reached 40.00%, while Yang et al. (2016) suggest that the callus (with an improved quality as well as an increased quantity) were transferred on the Murashige and Skoog medium with 0.5 mg l^{-1} kinetin and 1.0 mg l^{-1} 6-benzyladenine, on which both shoots and roots were simultaneously induced with a large quantity. The regenerated plants grow to more than 5.0 cm and transfer to Murashige and Skoog medium with 0.2 mg l^{-1} naphthaleneacetic acid and 1 g l^{-1} activated carbon. The rate of rooting was 100% for 7 days, and the average root number was four, and the length of the roots was 2–4 cm (Xian et al., 2018). The rooted seedlings, which with roots 2–3 cm, were transplanted from culturing seedlings to fine river sand, yellow soil or humus soil after one week-day's treatment. The survival percent reaches 98% after a month.

THE ECONOMIC VALUE OF GIANT REED

Giant Reed Used as an Energy Crop

Giant reed has a wide range of adaptations and can be planted in marginal areas where crops cannot grow (Roberto, 2012). It grows very fast and can grow to 6 m or even higher (Liao et al., 2017). The mature crop shows average annual production rates of $3 \text{ kg dry matter m}^{-2}$, with maximum values acquired in fertilized plots and during winter harvest time (Angelini et al., 2005). Giant reed is a very suitable source of biomass because of its low cost and high

productivity (Corno et al., 2014; Corno et al., 2015). Research shows that giant reed can replace maize and reduce the production cost of biomass and electricity (Corno et al., 2016). Giant reed stems can be transformed into useful, value-added reliable products through pyrolysis at appropriate conditions (Basso et al., 2005). Solid biofuels are conducive to preservation and transportation. Giant reed has good potential for biogas production through anaerobic digestion (AD). Among them, cellulose has the highest degradation rate and the most significant contribution to biogas production (Yang and Li, 2014).

Giant Reed Used as an Industrial Material

Its peculiar characteristics, such as its large diffusion on the territory, its stem's lightness combined with its adequate mechanical strength, and its high cellulose content, have allowed different industrial uses of giant reed (Perdue, 1958; Speck and Spatz, 2004; Barreca, 2012). Because of its advanced eco-friendly pulping and bleaching technology, giant reed has become an excellent substitute for wood fibers to meet pulp and paper products' rapid growth (Shatalov and Pereira, 2006). The fibers of giant reed possess high tensile strength and suitable raw material for particleboard production (Flores et al., 2011). The stem of the giant reed can be converted into activated carbon by various technologies, which shows excellent performance in wastewater treatment (Ahmed, 2016). In the Mediterranean region, giant reed has been traditionally employed to build fences and temporary shelters for men and animals, or as a prop for plants and as windbreak or shading barrier (Barreca and Fichera, 2013). Thanks to the lightness of the material, walls can

be erected even by farmers or breeders with modest tools (Barreca, 2012). Because of widespread and locally abundant, giant reed is widely used and has a greater diversity of uses in Cyprus's northwest. The culms are used to make baskets, tables, fishing equipment, musical instruments, candy bow, chandelier, distaff, heddle, knife, and fence (Barreca, 2012).

Giant Reed Used as Medicine

Modern pharmacological studies have proved the plants' role in treating diseases, reflected in current plant origin drug therapy. The use of medicinal plants to treat diseases has witnessed such treatments and increased awareness of the importance of using natural resources in the pharmaceutical industry (El Sheikha, 2017). Giant reed is considered as one of the medicinal plants. It was reported that aqueous extracts of the reed nodes, which contain the white hemicellulose membrane, and demonstrated a marked dose-dependent response for anti-biofilm activity, both in preventing MRSA biofilm formation and disrupting established biofilms (Quave et al., 2008). The antimicrobial effects of methanolic extracts of 14 medicinal plant species were examined comparing to conventional therapeutic antibiotics against standard bacterial strains (*Staphylococcus aureus*, *Micrococcus luteus*, *Klebsiella pneumoniae*, *Escherichia coli*, and *Pseudomonas eruginosa*). Among the four medicinal plants, the giant reed extract has the most significant effect on *Escherichia coli* and *Pseudomonas eruginosa* (Al-Snafi, 2015). Besides, the tender shoots can be used for the treatment of fever, wound suppuration, ear infection, typhoid, pneumonia and asthma (Sinha, 1996; Singh, 2003; Dhiren and Singh, 2015). Extractions of biologically active components from giant reed shoot is regarded as good anti-galactagogue, depurative, diaphoretic, emollient, hypertensive, hypotensive, and sudorific (Duke and Wain, 1981). In addition, the root of giant reed is also an alternative herbal medicine used as diaphoretic, emollient, diuretic, and cancer, dropsy, and headache (Mir et al., 2018).

PHYTOREMEDIATION POTENTIALS OF GIANT REED

Heavy Metal

With fast urbanization and industrialization, heavy metal pollution has become one of the utmost environmental severe issues that influence human health (Zhao et al., 2018). In the past 5 decades, more than 30,000 tons of Cr and 800,000 tons of Pb have been released into the environment around the world (Yang et al., 2018). Heavy metal pollution has an essential impact on crop yield and quality and affects the air and water environment and even human health. Many of them are toxic even at deficient concentrations, which are cytotoxic and carcinogenic, and mutagenic. Joint committee of World Health Organization (WHO) and Food and Agriculture Organization (FAO) on food additives (JCEFA) has set the maximum tolerable intake for As, Cd, Pb, and Cr as 2, 1, 6.03, and 3.32 $\mu\text{g}/\text{kg}$ body weight/day, respectively (Dubey et al., 2018). Excessive levels of heavy metals can cause health risks, for instance, 1) the concentrations

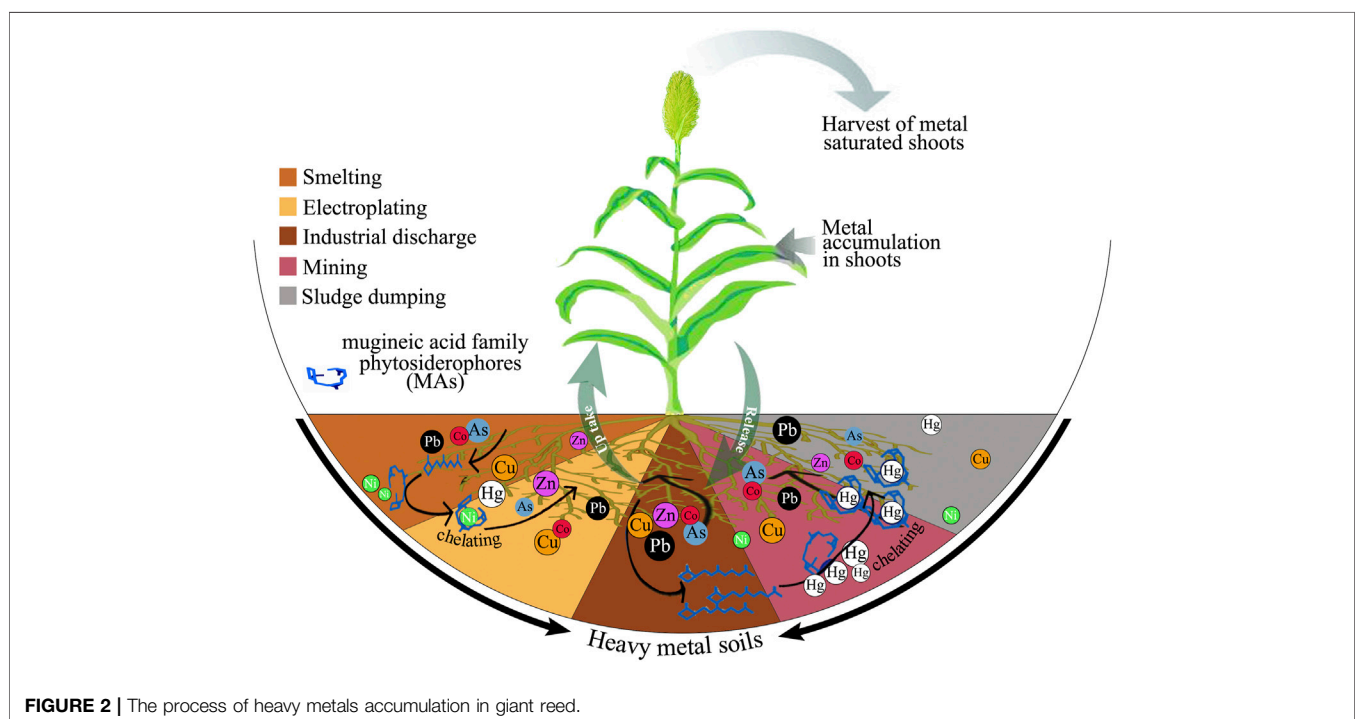
of Hg in whole blood reach 10 $\mu\text{g}/\text{L}$ may lead to lung damage; kidney damage, proteinuria, allergy, and amalgam disease, 2) the dietary intake of Cd reach 0.01 mg/kg/day can affect kidney functioning, 3) intaking of Ni from contaminated food reach 5 mg/kg/day can affect renal functioning, and so on (Rai et al., 2019). Accumulation of heavy metals on soil can cause direct or indirect reduction of plant growth by adversely affecting various physiological and molecular activities of plants (Tiwari and Lata, 2018). The current research suggests that the maximum soil concentration for different heavy metal (loids) were as follows: As ranged from a maximum of 11–34 mg/kg, Cd from 0.15 to 21.84 mg/kg, Cu from 16 to 713 mg/kg, Ni from 25 to 740 mg/kg, Pb from 25 to 2025 mg/kg, and Zn from 25 to 3,925 mg/kg (O'Connor et al., 2018). However, the tolerance of most plants for safe limits of heavy metals is not high. Guideline for safe limits of some heavy metal as follow: Cd from 3 to 6 mg/kg, Cu from 135 to 270 mg/kg, Pb from 250 to 500 mg/kg, Zn from 300 to 600 mg/kg, Ni from 75 to 150 mg/kg (Nagajyoti et al., 2010). In high concentrations, heavy metals negatively impact the growth, biomass, and photosynthesis of plants and compromise sustainable food production (Etesami, 2018). As a result of heavy metals have detrimental effects on plants and humans. Recently, the remediation of heavy metal pollution has aroused people's concern. So far, several efficient methods have been reviewed for the removal of heavy metals such as chemical precipitation, adsorption, ion exchange, reverse osmosis, phytoremediation, bioremediation, membrane technology, and electrochemical treatment, etc. (Dixit et al., 2015). They can be classified into two main groups, including physicochemical and biological techniques. Key factors influencing the applicability and selection of such technologies are capital investment and operational cost, plant flexibility, and reliability and environmental impact, etc. (Fu and Wang, 2011). Physicochemical approaches include chemical precipitation, adsorption, ion exchange, reverse osmosis, membrane technology, and electrochemical treatment. These techniques are rapid but inadequate, high cost, intensive labor, altered soil properties, and disturbance of soil native microflora (Ali et al., 2013). Moreover, most of these techniques are ineffective when the concentration of heavy metals is below 100 mg/L (Ahlwalia and Goyal, 2007). Compared with physicochemical, biological remediation has many advantages, such as natural process, environmentally friendly, low cost, and high public acceptance (Ullah et al., 2015). Biological remediation use microorganisms and plants to remove toxic contaminants from the environment (Singh et al., 2009). Living or dead microorganisms can be used for the remediation of heavy metals. Among these microorganisms, bacteria, fungi, and algae are most widely used, for example, bacteria can remediate Hg, Pb, Cr, Cu, Zn, and Cd, fungi can remediate Pb, Cr, Cu, Co, and Cd, algae can remediate Pb, Cr, Cu, and Cd (Yin et al., 2019). Phytoremediation is an emerging green technology used of metallophytes and related soil microorganisms to reduce the concentration or toxic effects of heavy metals in the environment. Remediation of a metal-contaminated climate by phytoremediation has received extensive attention because it is cost-effective, efficient, resource-conserving, and eco-friendly (Baker et al.,

1994; Sumiahadi and Acar, 2018). Heavy metal removal from contaminated sites using different phytoremediation methods has been initiated worldwide since the last decade, including phytoremediation of organic, inorganic and radionuclides. This sustainable and cheap process is rapidly evolving into a viable alternative to traditional remedies and most suitable for developing countries (Ghosh and Singh, 2005).

Recently, the accumulation of heavy metals by giant reed attracted more and more attention from various fields of science and engineering and became a hot researching spot (Borso et al., 2018; Coppa et al., 2020; Delplace et al., 2020). Giant reed has promising ability to uptake wide variety of metals viz. Pb, Cd, Mo, As, Zn, Cu, Ni, Co, Fe, Mn, Cr, Hg, Al etc. from the environment (Miao et al., 2012; Delplace et al., 2020; Danelli et al., 2021). It is a promising candidate for the phytoremediation of Zn-/Cr-contaminated soil (Li et al., 2014). Biomass obtained in Zn and Cr contaminated soils presented higher ash content and higher Zn/Cr content than biomass from non-contaminated soils (Barbosa et al., 2013; Barbosa et al., 2015). Pu et al. (2017) reported that despite the oxidative stress involved in the mechanism of Cd toxicity associated with the high transport of Cd in giant reed, its photosynthetic system was not harmed. When giant reed grown on surface soil and irrigated with mixed heavy metal solutions of Cd(II) and Ni(II), the examined parameters, namely, stem height and diameter, number of nodes, fresh and dry weight of leaves, and net photosynthesis (Pn) were not affected (Papazoglou et al., 2005). Mahmood (2010) report that giant reed can extract arsenic (As) and mercury (Hg) in sufficient amounts, and Cano-Ruiz et al. (2020) report that giant reed showed a broad tolerance to cadmium (0.5 mM), chromium (0.2 mM), cooper (2 mM), nickel (0.5 mM) and lead (1 mM). Guarino et al. (2020)

reported that giant reed can remove As through high and efficient volatilization. Biomass obtained in Pb contaminated soils presented higher ash content and lead content than biomass from non-contaminated soils (Sidella et al., 2013). Based on the findings of Domokos-Szabolcsy et al. (2018), giant reed can be identified as the first monocot hyperaccumulator of selenium. Some researchers find that the presence of chelating agent, organic fertilizer and mycorrhizal fungi have an impact on the ability to accumulate metals for giant reed. Atma et al. (2017) investigate that the addition of EDTA to the treatment increased plant uptake of arsenic. Other researchers also aimed at finding that compost fertilization and mycorrhizal fungi inoculations increase the metal uptake of giant reed (Fiorentino et al., 2013; Liu et al., 2017; Sarathambal et al., 2017).

The remediation mechanism from plants is distinct. According to growth potential in HM-contaminated sites, they can be classified into five main groups including plant extraction, plant degradation, plant stabilization, plant volatilization and rhizosphere filtration (Mukhopadhyay and Maiti, 2010; Ali et al., 2013; Thakur et al., 2016; Saxena et al., 2019). Recent studies show that giant reed shows good phytostabilization capability in the short-term while long-term can be used in phytoextraction processes (Cristaldi et al., 2020). The pH of the soil and the presence of chelating agents like mugineic acid family phytosiderophores (MAs) can mobilize metal ions into the soil solution. Metal ions can be taken up by the root of giant reed and come in contact with the cell wall. Giant reed can translocate the heavy metals to above-ground shoots or leaves and produce a large quantity of plant biomass that can be easily harvested (Figure 2). Various kinds of heavy metals can be extracted and accumulated in various organs (e.g., root, stem, leaf) by giant reed. Numerous studies have shown that the root is



the highest concentration organ, and the stem is the lowest concentration organ (Table 1). However, the most inferior concentration organ is still a matter of debate that leaf can be the most deficient concentration organ when heavy metals in soil are out of threshold limit value (Cristaldi et al., 2020). It can become hyperaccumulator plants and absorb metal contaminants from the ground and translocate them to aerial plant parts (Baker et al., 2000). In general, heavy metals exert multiple inhibitory effects on photosynthesis at several structural and metabolic levels (Clijsters and Van Assche, 1985). However, giant reed does not die after exposure to metal and show no visible signs of stress, and the photosynthetic rate of giant reed is not affected by heavy metals (Papazoglou et al., 2005). The phytoextraction process has a significant advantage for giant reed because most heavy metals are accumulated in the roots. In this way, the use of the upper parts (e.g., shoots and leaves) of giant reed is not affected, and the concentration of heavy metals in the soil can be reduced by collecting the roots of giant reed.

Previous research reported the mechanized harvest of the upper parts of giant reed. Curt et al. (2013) report that the strategy of two-step harvesting: stalk cutting and crushing and biomass collection and baling with this specific machinery is feasible. Assirelli et al. (2019) provide good results using a

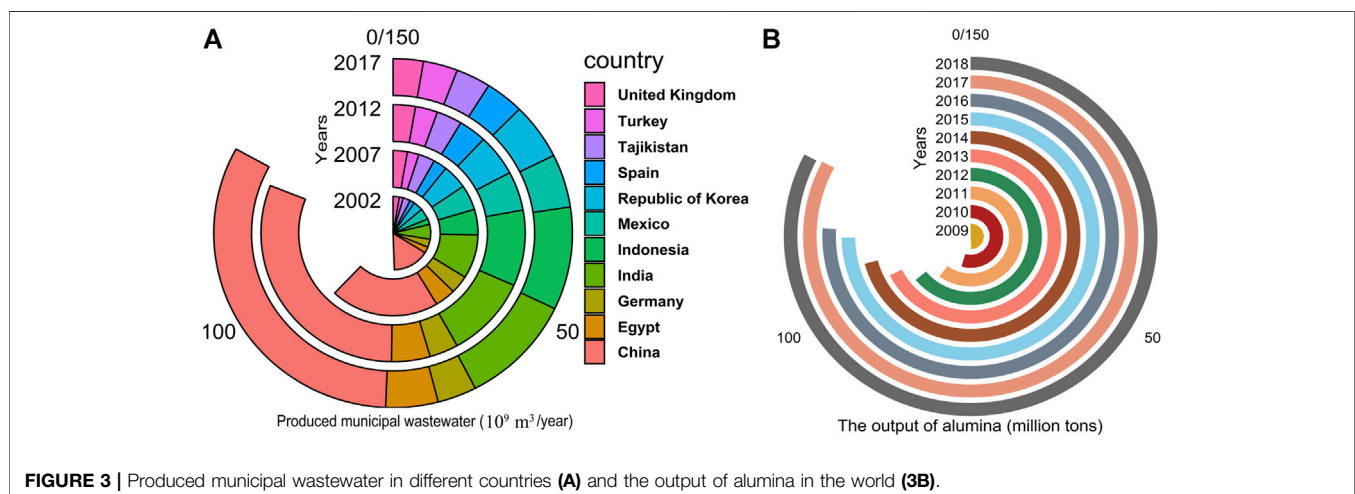
shredding machine for giant reed harvesting. Comparing to the mechanized harvest of the upper parts of giant reed, the roots of giant reed collecting are still a difficult task. Assirelli et al. (2013) use a modified stump grinder for *in situ* rhizome extraction. However, this method obtains most of the rhizomes with variable length, ranging between 4.4 and 6.4 cm, and most of the rhizomes were not excavated in the soil. It is an excellent way to digging rhizomes with a Noble sweep plow to a 0.30 m depth (San Martín et al., 2019). Because the rhizome depth of giant reed is 5–30 cm under the soil surface, this method can obtain almost entirely of rhizomes. Due to the low volatility of heavy metals, pyrolysis is an excellent way to extract heavy metals from the roots of giant reed. Grottola et al. (2019) report that the metals recovery is in the temperature range 653–873 K under steam assisted slow pyrolysis conditions.

Water Treatment

Water is one of the major issues humanity must tackle to achieve human society's sustainable development (Zhang et al., 2018). Although the total amount of water is enough on the Earth, the amount of drinkable water is limited. Surface and groundwater in many parts of the world are contaminated and not suitable for drinking (Gupta et al., 2012). The primary sources of water

TABLE 1 | Types and locations of giant reed accumulating heavy metals.

Metal type	Concentration organs	Highest concentration organ	Lowest concentration organ	References
Hg	Root, stem, leaf	Root	Leaf	Cristaldi et al. (2020)
Cd	Root, stem, leaf	Root	Stem	Guo and Miao (2010)
Cu	Root, stem, leaf	Root	Stem	Han and Wang (2007)
Pb	Root, stem, leaf	Root	Stem	Guo and Miao (2010)
Fe	Root, stem, leaf	Root	Stem	Castaldi et al. (2018)
Ni	Root, stem, leaf	Root	Stem	Bonanno (2012), Mabhungu et al. (2019)
Al	Root, stem, leaf	Root	Stem	
As	Root, stem, leaf	Root	Stem	
Cr	Root, stem, leaf	Root	Stem	
Mn	Root, stem, leaf	Root	Stem	
Zn	Root, stem, leaf	Root	Stem	



pollution come from industry, household, agricultural activities, and environmental and global changes. From 2002 to 2017, the total amount of municipal wastewater discharge in different countries uptrend (Figure 3A). In some developing countries, such as China, India, Indonesia, these countries produce much industrial wastewater and need to spend much money to treat this wastewater (This figure results from global information system on water and agriculture: <http://www.fao.org/aquastat/statistics/query/results.html>). Wastewater treatment had been a concern in the Bronze Age (ca 3,200–1100 BC) in Crete, Aegean Islands, and Indus Valley civilizations (Salgot and Folch, 2018). Since the 1950s, wetlands had been used for water purification around the world. Emergency assessment, a measure of the environmental and human economic resource utilization, showed that wetland systems used much fewer materials than conventional wastewater treatment. Wetland systems can rely on microbes and plants' ecological action for their efficacy and improve energy independence (Nelson et al., 2001). Wetlands are divided into natural and constructed wetlands. Because of environmental issues, natural wetlands are not always available where treatment is needed (Jenssen et al., 1993). Using constructed wetlands (CW), ecological concerns are reduced, and systems can be built on-site and more easily customized to facilitate specific treatment needs. In constructed wetlands, plants can stabilize the bed's surface, provide the right physical filtration conditions, transport gases, release oxygen to the rhizosphere, absorb inorganic compounds, organic pollutants, and plant metabolites, and release organic compounds (Stottmeister et al., 2003). Of course, not all plants are suitable for use in constructed wetlands. Plants need to meet the general requirements: 1) not causing significant weed or disease risks or risking to the ecological or genetic integrity of the surrounding natural ecosystems; 2) are well tolerant to local growing environments, pests, and diseases; 3) growing fast and having high biomass productivity; 4) removing of contaminants through direct assimilation and storage, or by enhancement of microbial transformations such as nitrification (through oxygen release from the root zone) and denitrification (by the production of carbon substrates) (Tanner, 1996).

Giant reed is an excellent plant for water purification. Wang et al. (2008) tested the removal efficiency of chemical oxygen demand (COD), total nitrogen (TN), and total phosphorus (TP) in rural domestic sewage by seven kinds of aquatic plants (*Arundo donax*, *Triarrhena sacchariflora*, *Acorus calamus*, *Phragmites communis*, *Iris pseudacorus*, *Lythrum salicaria*, and *Sagittaria trifolia*), and the result shows that giant reed has the strongest purification ability. Giant reed has higher removal rates for total suspended solids (TSS) than some aquatic plants (Toscano et al., 2015). The planted filter of giant reed allows better elimination of *Escherichia coli* (*E. coli*) than *Pennisetum purpureum* Schumacher (Fidele and Audra, 2020) and previous study has shown that giant reed planted in gravel-based constructed wetlands (CWs) can remove up virtually 100% of *E. coli* (Idris et al., 2012a). It shows excellent organic pollutant removal, macronutrient, removal microbiological removal, and heavy metal (Leto et al., 2013; Jesus et al., 2017; Pu et al., 2018), giant reed can be used to treat various polluted waters (Liao et al., 2017). Giant reed shows

excellent purification efficiency when used to treat micro-polluted river water, secondary municipal wastewaters for crop irrigation, dairy factory stormwater, and winery wastewater (salinity up to 9 dS/m) (Williams et al., 2008, 2009; Idris et al., 2012b; Xie et al., 2012; Barbagallo et al., 2014). Moreover, giant reed can be used as a source of biomass production when it is used to treat polluted waters. Mavrogianopoulos et al. (2002) report that giant reed stem biomass production in pig's waste is higher than the ordinary production in the soil. Irrigation with urban wastewater increased the biomass yield of three energy crops (*Typha latifolia*, *Arundo donax*, and *Phragmites australis*) and the biomass productivity of giant reed was much higher than those of *T. latifolia* and *P. australis* (Czakó and Márton, 2011; Zema et al., 2012). Giant reed can uptake pollutants from wastewater and accumulate pollutants in different parts. Cui and Wang (2013) got the nitrogen and phosphorus content of different parts of giant reed. There is a quantitative relationship of stem < root < leaves and root < stem < leaves, respectively, for the total nitrogen content and the total phosphorus content in the plant. Previous study reports the potential of giant reed for phytoextraction of heavy metals from synthetic wastewater and traces element concentrations decreased according to the pattern of root > leaf > stem (Mirza et al., 2010; Bonanno, 2012). Pollutants can be removed from wastewater by harvesting giant reed. The harvested giant reed can also be used to produce biomethane for energy and digestate for plant nutrition through anaerobic digestion process (Shilpi et al., 2019). A major barrier to the use of giant reed for water purification is its invasive properties in riparian ecosystems. Because giant reed hardly produces viable seed and its clumping rhizome growth habit, its ability to spread is limited. Giant reed's rapid clonal spread can be attributed to flood dispersal of rhizome and culm fragments. It is necessary to avoid the use of giant reed for treatment polluted rivers that are subject to flooding.

Red Mud Improvement

As the name implies, the red mud is brick red in color and slimy, with an average particle size of fewer than 10 μm , and a few particles larger than 20 μm can also be available (Paramguru et al., 2004). Red mud is the primary waste material produced during alumina production following the Bayer's process. Depending on the quality of the raw material processed, 1–2.5 tons of red mud is generated per ton of alumina produced (Paramguru et al., 2004). From 2009 to 2018, the output of alumina has nearly 40% growth in the world (An, 2019) (Figure 3B). China has become the leader in aluminum production and use (Hu et al., 2018). It causes the production of red mud to increase dramatically. Although many methods having been used to neutralize bauxite residues, cost remains an important consideration. Nowadays, dry stacking is one of the most popular disposal practices for red mud (Khairul et al., 2019). The main environmental impacts of red mud are its high alkalinity, salinity, and sodicity. Besides, the high alkalinity, salinity, and sodicity may be an immediate risk to plant growth. The pH of red mud can be up to 11 or more, due to presence of NaOH and Na_2CO_3 (1–6%, w/w) (Brunori et al., 2005; Sahu et al., 2010). The selected plant species should survive high salinity and alkalinity conditions to build vegetation on the residue. However,

very few plant species are able to survive on substrates with high pH, EC, and Na concentrations (Xue et al., 2016).

Without human intervention, the phytoremediation of red mud deposits is a slow process (Mishra and Pandey, 2019). Planting potentially successful plant species can accelerate ecological succession and restore soil fertility. Halophytes show the greatest potential to ameliorate bauxite residues (Xue et al., 2016). At present, giant reed is not considered to be a halophyte because it mainly invades freshwater habitats, but its salt tolerance has been confirmed (Pompeiano et al., 2017; Sánchez et al., 2017; Di Mola et al., 2018). Giant reed exhibits high tolerance to saline conditions and significant adaptability to salt accumulation in the soil (Verslues et al., 2006). Giant reed can maintain adequate K^+ and Ca^{2+} to counteract high salinity influence. The accumulation of Na^+ in leaf tissues under Na + stress was lower than that in roots during the experiment, and Na^+ decreased under leaf/root salinity (Balogh et al., 2012). However, in consideration of the accumulation of Na^+ and Cl^- in the leaves, the compartmentalization mechanism (for instance, vacuole storage) is likely to assist giant reed after exposure to salt toxicity once Na^+ and Cl^- have been inevitably absorbed and translocated to the leaf tissues (Pompeiano et al., 2017). The results of biomass production, nutrient removal, salt tolerance, weed risk, and carbon sequestration with saline brewery wastewater show that giant reed is suitable for growing on saline soil (Williams et al., 2008). More importantly, giant reed can still grow well in the alkaline soils of pH9-10 and reduce alkaline soils' pH. Giant reed has phytoremediation potential to grow in red mud containing high pH, EC, and trace metals. Red mud and red mud control soil in a 1:1 ratio positively affect on the height and biomass of reeds (Alshaal et al., 2013).

CONCLUSION AND FUTURE CHALLENGES

This paper reviews the application of giant reed in production and ecological remediation. It can absorb heavy metals, treat wastewater, improve red mud, and is a valuable raw material for many products. Genetic diversity has low among populations of giant reed that originated from different territories due to asexual reproduction (Antal et al., 2018). Therefore, it is of great significance to directly modify the expression of specific genes, making giant reed even more competitive than other energy crops.

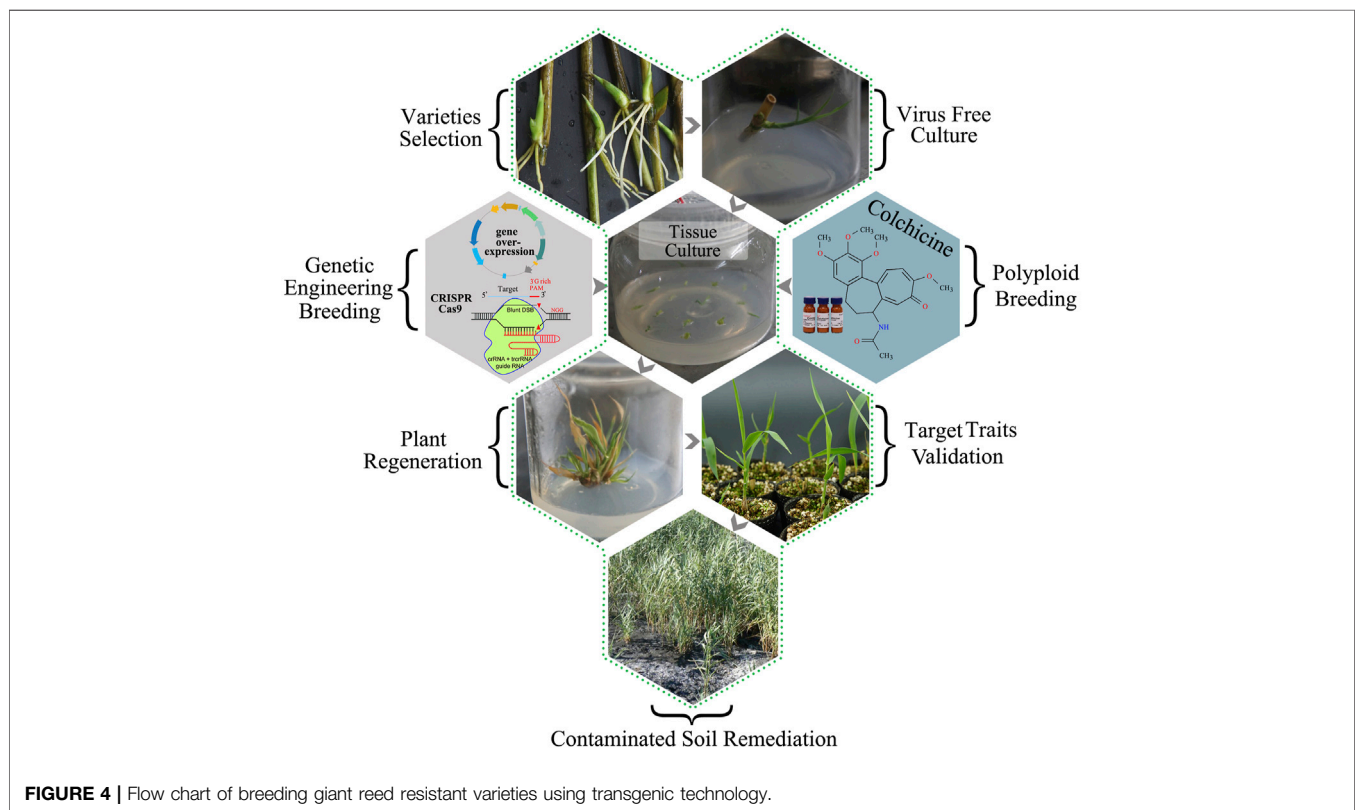
Plant breeding can be considered a coevolution between humans and plants. People caused changes in the plants that were used for production and life. In turn, those new plant types allowed changes in human populations to take place. The core of plant breeding is to choose a better type among the varieties, yield, and quality of the edible portion; easy to grow, harvest, and process; resistance to environmental stress; and insect resistance (Brescghello and Coelho, 2013). Standard breeding methods include hybrid breeding, mutation breeding, haploid (polyploid) breeding, genetic engineering breeding. Among them, hybrid breeding is the preferred breeding method for many crops (Kempe and Gils, 2011). Hybrid breeding is a

remarkable success story in maize, sunflower, sorghum, beets, and rye (Longin et al., 2012). As DNA's understanding has expanded and its importance for plant characteristics, breeders have taken matters into their own hands. Instead of waiting for spontaneous mutations to occur in DNA, they began mutation breeding in the 1930s (Bradshaw, 2017). Through this breeding, changes to plant DNA can be applied at a much higher frequency. Mutation breeding is an essential method for improving crops, with more than 3,200 mutant cultivars produced worldwide thus far (FAO/IAEA Mutant Variety Database) (Yamaguchi, 2018). Polyploidy is an intriguing phenomenon in plants that have provided an essential pathway for evolution and speciation (Bukhari and Kour, 2019). Polyploidy breeding can be used as a critical tool for developing new crop species, producing larger fruit or other parts to obtain more yield and profits, improving the resistance of plant organisms and abiotic organisms.

In the past 20 years, genetically engineered development has improved transgenic plants' speed and accuracy compared to traditional plant breeding. The knowledge of the essential genes transferred by transgenic plants is higher than that of conventional breeding. Transgenic technologies to develop cassava with enhanced resistance to viral diseases and insect pests improved nutritional content, modified and increased starch metabolism, and reduced cyanogenic content of processed roots (Taylor et al., 2004). Tobacco and *Arabidopsis* plants transformed with *Escherichia coli mtlD* encoding a mannitol-1-phosphate dehydrogenase accumulated mannitol. These plants have increased tolerance to high salinities than control plants (Bajaj et al., 1999). Liu et al. (2013) transferred the *ScNHX1* (encoding vacuolar membrane Na^+/H^+ antiporter from *Suaeda corniculata*) and *ScVP* (encoding vacuolar H + -PPase from *S. corniculata*) genes into alfalfa plants, and the results showed that transgenic alfalfa plants co-expressing *ScVP/ScNHX1* showed higher salt and saline-alkali tolerance compared with wild-type plants. Di et al. (2015) introduced the gene encoding the betaine aldehyde dehydrogenase from *Atriplex micrantha* into the maize inbred lines Zheng58 and Qi319 by *Agrobacterium*-mediated transformation. The maize ubiquitin promoter controlled them. The transgenic maize plants showed higher betaine aldehyde dehydrogenase activity and grew better than wild-type plants under NaCl stress. Compared with wild type, transgenic plants have higher fresh weight under salt stress, lower malondialdehyde content, lower relative conductivity, higher chlorophyll content, higher plant height, and higher grain. It is indicated that the expression of BADH gene in maize seedlings enhances these plants' salt tolerance. Zhang and Liu (2011) transferred a gene that simultaneously expressed human *CYP2E1* and *glutathione S-transferase (GST)* into alfalfa plants from hypocotyl segments by using an *Agrobacterium* transformation system. The *pKHCG* transgenic alfalfa plants' resistance to mixed contaminants (heavy metal-organic compounds) was significantly increased compared to the transgenic alfalfa plants expressing a single gene (*GST* or *CYP2E1*) and the non-transgenic control plants. The *pKHCG* alfalfa plants showed strong resistance to the mixtures of cadmium (Cd) and trichloroethylene (TCE), and these mixtures were metabolized

TABLE 2 | Giant reed and hyperaccumulator plants differ in accumulating heavy metal.

	Ni (mg/kg)	Pb (mg/kg)	Cd (mg/kg)	As (mg/kg)	Zn (mg/kg)	Cr (mg/kg)
Giant reed ^{a-d}	<193	<515	<64.12	<61.96	<118	<34
Hyperaccumulator plants ^e	>1,000	>1,000	>100	>1,000	>3,000	>300

^aAlshaal et al. (2013)^bGuo and Miao (2010)^cBarbosa et al. (2015)^dSidella et al. (2017)^eReeves et al. (2018)**FIGURE 4** | Flow chart of breeding giant reed resistant varieties using transgenic technology.

by the combination of introduced *GST* and *CYP2E1*. He et al. (2001) introduced the bacterial mercuric reductase (*merA*) into tobacco and the transgenic tobacco plants were resistant to high levels of mercuric chloride and removed mercury from water solutions and soil by volatilization. Czako et al. (2006) co-introduced the bacterial mercuric reductase (*merA*) and organomercurial lyase (*merB*) genes into the saltmarsh cordgrass (*Spartina alterniflora*) by *Agrobacterium*-mediated transformation and the resultant heavy metal resistant transgenic tissue showed enhanced tolerance to both mercuric and phenylmercuric salts. Kim et al. (2011) transferred the *MuSI* gene into tobacco, and *Escherichia coli* cells overexpressing *MuSI* were more resistant to Cd than wild-type cells transfected with vector alone. *MuSI* transgenic plants were also more resistant to Cd. *MuSI* transgenic tobacco plants absorbed less Cd than wild type plants. In transgenic plants, cadmium transport from root to shoot was reduced, thereby avoiding the toxicity of cadmium. These results indicated that *MuSI* transgenic tobacco plants

tolerate Cd by reduced translocation from roots to shoots and reduced uptake and/or increased immobilization of Cd in the roots. Peng et al. (2018) isolated a *TpNRAMP5* from dwarf Polish wheat (DPW, *Triticum polonicum* L.) and transferred it to *Arabidopsis thaliana*. The expression of *TpNRAMP5* in *Arabidopsis* significantly increased the content of Cd, Co, and Mn in roots, stems, and whole plants but did not affect the content of Fe and Zn. These results indicate that *TpNRAMP5* is a metal transporter that enhances Cd, Co, and Mn accumulation but does not enhance the accumulation of Zn and Fe. With the continuous advancement of biotechnology, it is an excellent way to improve the ecological environment by cultivating plants through genetically modified technology.

The use of plants to remove contaminants from contaminated water and soil may be a promising strategy. Giant reed can absorb heavy metals, reduce the pH of the saline soil and purify the water. It should be mentioned that some disadvantages of giant reed cannot be overlooked. There is still a gap between giant reed and

hyperaccumulator plants accumulating most of heavy metal (Table 2). Although recent studies report giant reed as moderately tolerant to salt stress and biomass yield was not decreased, surprisingly, high salt stress caused yield heavy losses (Di Mola et al., 2018). There is an urgent need, but it is still a significant challenge for giant reed breeding because giant reed seeds cannot breed in most areas. The reproduction only occurs by the vegetative growth of rhizomes and of stem nodes of broken canes. Because of this, the genotypic diversity among clonal populations is expected to be very low (Sicilia et al., 2019). Considering the chromosome number of giant reed is diverse and ploidy levels of giant reed may depend on the different territory in which the plant has grown and may depend on its evolutionary history, polyploidy breeding in giant reed is an excellent choice (Corno et al., 2014). As the regeneration system of giant reed has been published so far, and an optimized particle bombardment protocol for gene transfer with embryogenic calli was recently reported in giant reed (Takahashi and Takamizo, 2012), genetic engineering could represent a feasible option for giant improvement reed (Figure 4). Biotic and abiotic stress tolerance is the minimum required trait, which is not tricky in

molecular breeding. These traits and candidate target genes are reviewed in front of this article.

AUTHOR CONTRIBUTIONS

SH, JL conceived the original structure of the review. QJ, DL helped with literature data collection. DZ prepared the manuscript. All authors have read and agreed to the published version of the manuscript.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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