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Review

Invasive plants as potential sustainable feedstocks for biochar production and multiple applications: A review

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ABSTRACT

Invasive plants harm ecosystems and human health due to their strong environmental adaptability, fast reproduction and spreading capabilities. Management of invasive plants, therefore, attracted more and more attention recently. Biochar is a carbon-rich solid substance formed by pyrolyzing organic substances under low or limited oxygen conditions. It has high aromaticity and strong resistance to decomposition and is widely used in agriculture, environment, energy, and other fields. As a special raw material, the high diversity and wide distribution make invasive plants ideal feedstocks for biochar production. Pyrolysis of invasive plants to prepare biochar not only realizes the protection of ecosystemsbut also benefits human health. In addition, compared with traditional biochar, invasive plant-derived biochar (IP-DB) showed significant differences in structure, composition, and adsorption performance. As an economical and easily available adsorbent, IP-DB has been gradually used in environmental remediation and agricultural soil amendment, but there are relatively few reports compared with other types of biochar, and the research is scattered. Therefore, it is necessary to review the potential of invasive plants to prepare biochar and its application value. Here we make a review on current research status of invasive plants, focusing on their potential for biochar productions and applications. Based on these reviews, we proposed possible future development in this research field, which could serve as theoretical basis for further researches.

1. Introduction

Biological invasion refers to a kind of species with a certain distribution and abundance in countries or regions outside its origin, capable of breeding offspring, and causing damage to natural communities and ecosystems in the invaded areas (Souto et al., 2000). Plant invasion is a typical biological invasion. Invasive plants have strong adaptability, fast reproduction and spreading capabilities, which not only cause damage to natural ecosystems but also pose a serious threat to human health (Eviner et al., 2012; Olszańska et al., 2016; Wan et al., 2010; Wilgen et al., 2008; Zhang et al., 2019). Therefore, it is necessary to find effective approaches to combat their invasion. Currently, the management mainly includes manual eradication, chemical control (using herbicides), biological control (introducing natural enemies), and alternative control (Barreto and Evans, 1995; Hua et al., 2015; Poovey and Getsinger, 2005; Sun et al., 2015). Despite some certain effects, these methods involve huge human and financial resources, yet with limited sustainable value. Besides, these treatments may adversely affect native species. To eradicate the plants, some researchers proposed the way of resource utilization recently (Cheng et al., 2017; Lu et al., 2020; Zheng et al., 2014). The pyrolysis of invasive plants to produce biochar is considered to be an effective way, which has ecological and economic benefits because this treatment not only controls the expansion of noxious plants but also realizes the efficient use of waste (Du et al., 2018; Zhang et al., 2018).

Biochar is a carbon-rich solid material formed by pyrolysis and carbonization of biomass waste such as crop straw, animal manure, sludge, and other organic materials at low or limited oxygen conditions (Sohi, 2012; Wang et al., 2018c; Wang et al., 2015; Wang et al., 2018d; Zheng et al., 2019). It has the characteristics of high aromatization, stable properties and high carbon content, and has been widely used in agriculture, environment, energy and other applications (Field et al.,

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2013; Kim et al., 2019; Lee et al., 2018; Wang et al., 2019; Yang et al., 2017). Biochar can not only be used as a carbon sink material (Nan et al., 2020), but also improve soil environment (Basso et al., 2013; Cornelissen et al., 2013; Jeffery et al., 2011; Pandit et al., 2018). Besides, biochar can remove organic and inorganic pollutants from the environment and is a significant adsorbent (Cho et al., 2019; Heo et al., 2019; Liang et al., 2019; Wu et al., 2019). However, its physicochemical properties are greatly affected by pyrolysis conditions and feedstocks (Al-Wabel et al., 2013; Han et al., 2017; Sun et al., 2014; Wang et al., 2016a). Also, the production cost of biochar is a key indicator that limits its large-scale promotion and application. Therefore, research and development of low-cost and high-efficiency biochar is an inevitable development trend in this research field. Invasive plants are various in types, widely distributed, and renewable. Use of these plants as biochar feedstocks are more economical and easily available compared to other biomass waste. Moreover, studies have found that significant differences existed in structure, composition and adsorption performance between biochar prepared by invasive plants and other raw materials (Fan et al., 2020a; Yakkala et al., 2013; Yang et al., 2014). Therefore, it is necessary to summarize the application potential and value of invasive plant-derived biochar (IP-DB).

At present, the application research of IP-DB mainly focuses on environmental remediation and agricultural soil improvement (Cornelissen et al., 2013; Zheng et al., 2018). Although there have been already some studies on IP-DB, the conclusions are scattered. Up to now, there has been no relevant review to systematically analyze and research the advantages, disadvantages, and application potentials of IP-DB. As a new type of adsorbent, the adsorption mechanism of IP-DB on pollutants is still unclear, and many issues need further understanding and analysis. Therefore, a systematical review on these progresses would provide insight into the state-of-art of this research field.

Based on the characteristics and utilization status of invasive plants, this review focuses on the feasibility of invasive plants as feedstock of biochar and its application potential in environmental pollution remediation and agricultural soil amendment, and also proposes the possible future development on the research of IP-DB.

2. The characteristics, distribution and harm of invasive plants

Invasive plants often have strong ecological adaptability, high reproduction ability, and fast-spreading speed (Téllez et al., 2008; Yin et al., 2015). The strong ecological adaptability is mainly manifested in high genetic diversity, strong stress resistance, wide niche, and the ability to produce substances that inhibit the growth of other plants. High reproduction ability is mainly manifested by the ability to reproduce in large numbers through seeds or vegetative bodies and has a strong asexual reproduction ability. The fast transmission speed mainly reflects the multiple transmission channels and the high transmission rate.

The unique properties of invasive plants make them widely distributed in the world. The invasion speed and distribution range of invasive plants are related to climatic conditions and their adaptability. Temperature is a key climatic factor affecting the distribution of exotic plants, and areas with strong human activities are most vulnerable to plants invasion (Zhang et al., 2020c). Furthermore, the cultivated land, towns and areas with many biological species in temperate regions are more susceptible to the invasion of alien plants, while deserts, savanna have less invasive space (Losdale, 1999). Research on the distribution and spread patterns of two alien plants with different invasion histories in North America, and indicated that their invasion range expanded over time (Barney et al., 2008). *Spartina alterniflora* also has a similar invasion pattern in China. A study found that *Spartina alterniflora* had expanded rapidly in the coastal areas of mainland China since 1985, and the invasion area had increased from about 260 hectares to more than 50,000 hectares in just 30 years (Mao et al., 2019).

The number of alien invasive plants in North America, New South Wales (Australia), Chile, Argentina, and the Republic of South Africa accounted for 51.3%, 43.3%, 34.2%, 29.7% and 22.5% of the 120 most widely distributed plants (Stohlgren et al., 2011). China is one of the countries with the richest biodiversity in the world (Feng and Zhu, 2010). With the development of social economy, a large number of exotic plants have been intentionally or unintentionally introduced into China (López-Pujol et al., 2006; Yan et al., 2001). It can be seen from the distribution of invasive plants richness in China (Fig. 1), China has been severely invaded by exotic plants, especially in Yunnan, Guangxi, Guangdong and Hebei Province (Bai et al., 2013). According to literature reports, there are 384 invasive plants in China (including 66 families and 233 genera), which are mainly composed of the families Asteraceae, Poaceae, Fabaceae and Brassicaceae, and genera *Amaranthus* in Amaranthaceae, *Euphorbia* in Euphorbiaceae, and *Solanum* in Solanaceae (Bai et al., 2013).

Invasive alien species seriously threaten the biodiversity, ecological environment, economy and human health of invasive areas (Table 1) (Adhikari et al., 2019; Ewald and Bo, 2008; Mudereri et al., 2020). There are many reports about the effects of invasive plants on ecosystem functions, but more attention is focused on their negative effects. It is believed that plant invasion can lead to the decline of biodiversity in local communities (Simerloff et al., 2003). Invasive plants can directly release allelopathic chemicals and root exudates that have toxic effects on seed germination and plant growth or indirectly affect local plants by affecting soil microbial communities, thereby threatening the growth of plants in the invaded area and causing serious economic losses (Belnap and Phillips, 2001; Fabbro et al., 2014; Inderjit et al., 2011). Studies have shown that the density, richness and diversity of native species are greatly reduced as the area of plant invasion increases (Shackleton et al., 2015). Take the impact of invasive plants on the local economy as an example, *Tamarix ramosissima* invaded the floodplain of the southwestern United States and consumed a huge amount of water. It is estimated that the annual economic losses can reach $127 million to $291 million (Zavaleta, 2000). In addition, the economic losses caused by alien invasive plants in California to agriculture amount to $1 billion to $2.5 billion annually (Chaplin-Kramer et al., 2011). According to statistics, the direct and indirect economic losses resulted from invasive alien species to China in 2000 amounted to RMB 119,661.69 million, which was equivalent to 1.36% of China's GDP (Xu et al., 2006).

In addition to posing a threat to biodiversity and economy, invasive plants contain aromatic, irritating chemicals and unclear toxic substances that can trigger human disease, skin inflammation or fester, and even death by poisonous effect (Abdulahi et al., 2017; Plaza et al., 2018). For example, *Eupatorium adenophorum* contains crested seeds and pollen, which can cause allergic reactions and contact dermatitis (Sun et al., 2004). *Prosopis juliflora* and *Eichhornia crassipes* can greatly

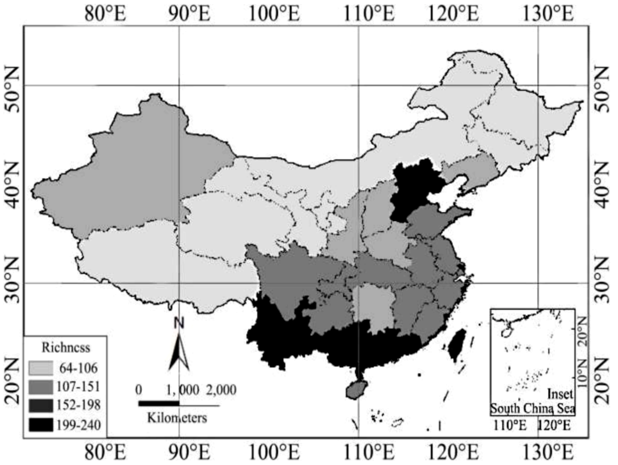

Fig. 1. Invasive plant species richness in China (Bai et al., 2013).

Table 1
The negative impacts of invasive plants on biodiversity, economy and human health.

Invasive plants	Allelopathic effects	Economy	Human health	References
Eupatorium adenophorum	Reduces germination index of *Pinus yunanensis* by 92.6%	Reduces foodstuff by 3%-11%	Causes allergic reactions and contact dermatitis; Makes asthma patients worse	(Cao et al., 2013; Sun et al., 2004)
Eichhornia crassipes	Reduces germination of wild oat and wheat to zero and 20%, respectively	Reduces fish production and hinders the development of ecotourism	The carried anopheline, culicine mosquito larvae and *Schistosoma mansoni* may infect people with schistosomiasis and malaria	(Gul et al., 2017; Pejchar and Mooney, 2009; Stone et al., 2018)
Centaurea solstitialis	The inhibitory effects of extract on the germination and growth of *Sulla coronaria* (L.) and *Lactuca sativa* seedlings are 84% and 100%, respectively	Causes ranchers spend $7.65 million on livestock feed and $9.45 million eradicating the weeds annually	Causes skin injuries	(Eagle et al., 2007; Hachani et al., 2020; Irimia et al., 2019)
Lantana camara	Threatens 275 native plants in Australia; Reduces the yield of corn and cassava by 26-50%	Causes livestock poisoning; Results in losses to ranchers of up to US$25.7/ha per year in Australia; The annual control cost is US$22.57 million	Provides a favorable shelter for *Glossina* spp. that can cause sleeping sickness	(Mazza et al., 2013; Shackleton et al., 2017)
Prosopis juliflora	Reduces the germination rate of *Sorghum bicolor* from 43% to 17%	Causes declination in crop productivity	Accelerates the spread of *Anopheles* mosquitoes and *Anophlese*; Causes itching	(Abdulahi et al., 2017; Mahdhi et al., 2019; Muller et al., 2017; Stone et al., 2018)
Ailanthus altissima	Reduces the growth of garden cress radicle by 50%	Leads to increased control costs	Causes dermatitis, myocarditis and allergic response	(Pyšek and Richardson, 2010)
Acacia dealbata	The fresh leaves and leaf litters aqueous extracts inhibit the radicle length of *Quillaja saponaria* by 50% and 90%, respectively	Causes economic loss of $US 2.8 million annually in South Africa due to reduced surface runoff and water capacity	Causes allergies	(Aguilera et al., 2015; De Wit et al., 2001; Pyšek and Richardson, 2010)
Spartina anglica	Leads to 75% reduction in root growth of *Solanum nigrum* seedlings	-	Causes skin injuries and wounds	(Pyšek and Richardson, 2010)
Solidago canadensis	Completely inhibits the growth of *Arabidopsis* seedlings when the exudate concentration was 500 μg/mL	Causes declination in crop productivity	Causes itchy skin, sore throat	(Abhilasha et al., 2008; Tyler et al., 2015)
Ambrosia artemisiifolia	Decreases the germination rate of *Zea mays* by 59%	Increases control costs and decreases landscape value	Causes allergy and asthma	(Bonea et al., 2017; Pyšek and Richardson, 2010; Xu et al., 2006)

enhance the spread of malaria (Muller et al., 2017; Pejchar and Mooney, 2009). *Spartina anglica* with sharp edged leaves can result in skin injuries and wounds (Rai and Singh, 2020). In summary, invasive plants have caused varying degrees of impact on ecology, environment, and human health. Therefore, it is urgent to develop efficient technologies to control the growth of invasive plants.

3. The utilization of invasive plants

Resource utilization of invasive plants is a reliable way to reduce their negative effects. As shown in Fig. 2, invasive plants are often used as raw materials to produce different products, such as activated carbon, compost, fuel, feed, and biochar, each of which has its own advantages and disadvantages.

3.1. Preparation of activated carbon

Currently, the potential of invasive plants as raw materials for the production of activated carbon has been reported (Gautam et al., 2015; Shanmugapriya et al., 2019). *Eupatorium adenophorum* activated carbon can not only remove the low concentration of Pb(II) in wastewater, but also has a good affinity for the basic dye Congo red in aqueous solution

Fig. 2.. Utilization methods of invasive plants and their advantages and disadvantages.

(Guo et al., 2009; Li et al., 2016). Moreover, the composite prepared by *Eupatorium adenophorum* and photocatalyst has good degradability to methylene blue (Cheng et al., 2019). Compared with the traditional heating method, microwave-assisted phosphoric acid-activated *Parkinsonea aculeata* wood sawdust activated carbon has a highly developed porous structure and more surface functional group content, and its adsorption capacity for phenol is significantly enhanced (Nunell et al., 2016). Activated carbon prepared from *Prosopis juliflora* has good porosity and specific surface area, and has good adsorption performance for direct red 23 and Cr(VI) (Gopal et al., 2014; Kumar and Tamilarasan, 2017). Activated carbon prepared by *Leucaena leucocephala* not only has a high specific surface area and microporous structure but also has good capacitance characteristics and high electrosorption properties, which is suitable as electrode material for capacitive deionization for seawater desalination (Hou et al., 2015). Therefore, activated carbon prepared by invasive plants is effective in removing pollutants from the environment. However, the large-scale use of activated carbon has been limited due to its shortcomings such as high operating and regeneration costs, and non-biodegradability, which have led researchers to explore alternative, more cost-effective adsorbents.

3.2. Animal feed

Invasive plants are rich in available sugar, with a complete range of amino acids and rich content, so they have certain feeding value. *Spartina alterniflora* can be used as potential coarse forage for dairy cows, but the proportion of green cut grass should not exceed 25% in dairy feed (Qin et al., 2016). *Leucaena* has high nutritional value, its twig protein content is as high as 31%, it is often used as an important feed (Tangendjaja et al., 1986). *Prosopis juliflora* can extract alkaloids, flavonoids, and phenolic, which play important role in animals (Ibrahim et al., 2013). Invasive plants must be detoxified before being used as feed, because non-detoxified invasive plants may cause varying degrees of damage to the animal liver, kidney, and spleen. Therefore, invasive plants that have not been detoxified are not suitable for use as feed.

3.3. Compost

Most of invasive plants contain a large amount of trace elements, organic matter, and macro elements, which can be used as compost after detoxification treatment. Compared with other animal manure, municipal solid waste and sludge compost, the C/N ratio of *Acacia* species compost has increased, EC value and pH value are lower, and the content of total nitrogen, inorganic nitrogen, and other nutrients is low, indicating that *Acacia* species compost can be used as an organic soil improver in agriculture (Brito et al., 2013). *Eupatorium adenophorum* can be used as compost to increase soil N and P content, maintain soil K element, and promote tomato growth (Li et al., 2014). However, *Eupatorium adenophorum* showed strong enrichment characteristics for Pb, Zn, Cd, and Cu in heavy metals contaminated soil. Therefore, the application of invasive plants as compost has the risk of contaminating the soil. In addition, if high-salt invasive plants (such as *Spartina alterniflora*) are returned to the field for long-term, it is likely to cause soil quality degradation. Therefore, it is not feasible to use high-salt invasive plants as composting materials.

3.4. Fuel

Most of the invasive plants have the characteristics of tall plants, fast reproduction, and large biological yield. They are ideal raw materials for biomass energy. The high productivity and heat value of *Spartina alterniflora* provide conditions for its fuel utilization (Feng et al., 2018; Zheng et al., 2018). The gas production of *Spartina alterniflora* alone can reach 251 mL/g (TS), and the biogas production after mixing *Spartina alterniflora* and potatoes at a certain ratio can increase 52.5% (Li et al., 2011). *Eupatorium adenophorum* contains higher cellulose and lower lignin, and the total solid content in 3-4 weeks reaches 519 mL/g, indicating that *Eupatorium adenophorum* is an ideal raw material for biogas production. By using invasive plants as energy source, both the environment is protected and waste is effectively treated. However, the use of invasive plants to produce biogas also has certain shortcomings. For example, when anaerobic fermentation of *Eupatorium adenophorum* stems will produce active substances, which will damage the structure of microbial cells and affect the normal operation of fermentation process. In addition, the anaerobic digestion products could also be produced in the fermentation process, which will adversely affect the environment if not properly treated.

3.5. Biological pesticides

Studies have shown two isochlorogenic acids isolated from the aqueous extract of *Ipomoea cairica* have analgesic effects (Ferreira et al., 2006). *Solidago canadensis* is mainly used for the treatment of diabetes, chronic kidney disease, cystitis, rheumatism, urinary stones, it can also be used as an anti-inflammatory agent in clinical (Cubría et al., 1998). *Disphania ambrosioides* L. is rich in volatile oils, which has antibacterial, insecticidal, inhibition of cancer cell growth and treatment of gastric ulcers, and can be used as a potential plant fungicide for pesticide product development (Jardim et al., 2008; Kumar et al., 2007). When the mass concentration of *Eupatorium adenophorum* extract was 1.5 kg/L, the lethality to *Haemaphysalis longidum* larvae and pupae reached 100% within 6 h (Nong et al., 2013). Invasive plants contain a large number of secondary metabolites. Studying the biological activities of these metabolites, isolating and extracting substances that can treat diseases, and finally developing productive drugs from them have broad application prospects. However, the research and development of the medicinal value of invasive plants also face some challenges on some core technology-related issues (Balunas and Kinghorn, 2005). Besides, some active substances contained in invasive plants may have adverse effects on human health, therefore we should pay attention to their negative effects during the process of development and utilization.

4. Physicochemical properties of IP-DB

Biochar has received extensive attention because of its stable chemical properties, large specific surface area, many pores, and abundant surface functional groups. The preparation of invasive plants into biochar not only saves production costs, but also improves the biological value of invasive plants, making them widely used in the fields of environment, agriculture, and energy (as shown in Fig. 3), which is an efficient resource utilization way.

During the preparation of IP-DB, the differences in raw materials and carbonization conditions will cause great differences in the physicochemical properties of biochar, such as pore volume, specific surface area, surface functional groups, yield, ash, cation exchange capacity, pH, and elemental composition, which can affect the adsorption performance of biochar (Fan et al., 2019) (Table 2). Pyrolysis temperature is the basic factor that determines the physical and chemical properties of biochar (Harvey et al., 2012; Xu et al., 2020). Increasing the pyrolysis temperature will increase the carbon sequestration and porosity of biochar, but the yield will decrease significantly (Manyà and Joan, 2012). For example, the yield of *Solidago canadensis* L. biochar gradually decreased with the increase of pyrolysis temperature and residence time, but the yield of biochar increased with the increase of heating rate (Zhang et al., 2018). When the pyrolysis temperature of *Ambrosia artemisiifolia* L. increased from 300 to 400°C, the yield of biochar declined sharply, mainly due to the loss of cellulose and hemicellulose. Continued heating led to pyrolysis of lignin, and the yield of biochar continued to decrease, but at a slower rate (Yousaf et al., 2018). Liao et al. (2013) prepared biochar from invasive plants (Brazilian Pepper and Air Potato) and found that the yield of the two kinds of invasive plant biochar is higher than water oak and energy cane when the pyrolysis temperature

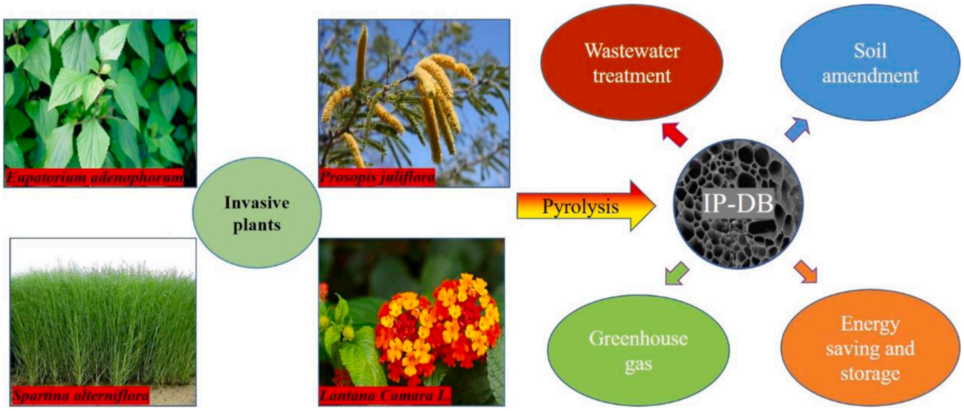

Fig. 3.. Application of IP-DB.

is 450°C. Cui et al. (2016) also pointed out that the yield of biochar derived from *Thalia dealbata* has a clear advantage over traditional raw materials (orange peel, cottonseed hulls and corn stover) when the pyrolysis temperature is 500°C (Chen and Chen, 2009; Mullen et al., 2010; Uchimiya et al., 2011). This result shows that invasive plants can be used as raw materials to produce high value-added biochar. Besides, long residence time will aggravate the degradation and volatilization of organic matter, resulting in low biochar yield. Therefore, the pyrolysis temperature and residence time of biochar have a negative correlation with biochar yield. *Eupatorium adenophorum* biochar prepared at a lower pyrolysis temperature has a larger specific surface area and content of water-soluble calcium, magnesium, nitrogen, and phosphorus, while biochar prepared at a higher pyrolysis temperature has higher alkalinity, aromaticity, and better stability and heavy metal removal activity (Fan et al., 2019).

The carbon content of biochar is an important factor reflecting its adsorption performance (Kolodyńska et al., 2012). Previous studies found that the carbon content of biochar increased with the increase of pyrolysis temperature, but the polarity, the content of hydrogen and oxygen decreased (Godlewska et al., 2017; Xie et al., 2011). By comparing the physicochemical properties of biochar derived from *Eupatorium adenophorum*, wood chips and rice husk, it is found that *Eupatorium adenophorum* derived biochar has significantly higher carbon content than the other two biochar, and the biochar prepared by *Eupatorium adenophorum* has higher adsorption capacity for acetochlor than wood chips (Li et al., 2018). Walter and Rao (2015) also compared the properties of the biochar prepared by *Imperata cylindrica* and rice husk. The results showed that the carbon content of *Imperata cylindrica* biochar was significantly higher than that of rice husk biochar, and the content of N, P, K, Ca, and Mg elements was also higher, indicating that applying *Imperata cylindrica* biochar to soil can be used as an important source of plant nutrients.

The types and contents of surface functional groups of biochar play important role in its application. The surface of biochar is rich in functional groups such as -OH, -COOH, C-O, C-C, C-H, and low pyrolysis temperature is beneficial to the formation of surface functional groups (Fan et al., 2019). The surface functional groups of biochar can interact with pollutants by surface complexation, ion exchange, electrostatic attraction, etc., thereby promoting the adsorption of pollutants (Hu et al., 2020; Sumaraj and Padhye, 2017). Previous studies shown that the adsorption of Cu(II) by water hyacinth biochar is mainly due to the rich functional groups on the surface of biochar participating in the chelation of Cu(II) (Li et al., 2015). The efficient adsorption capacity of buffalo weed biochar for TNT and RDX is also because of the electrostatic interaction between the surface functional groups of biochar and pollutants (Roh et al., 2015).

IP-DB has a porous structure, rich surface functional groups, relatively high specific surface area, and stability (Inyang et al., 2016). These characteristics provide favorable conditions for IP-DB to improve the retention capacity for water and fertilizer as well as its adsorption capabilities for pollutants (Masto et al., 2013). For example, the biochar produced by pyrolysis of *Alternanthera philoxeroides* has a rough surface, loose structure and rich surface functional groups such as C-H, C-O, and C=C, which has a good adsorption performance for rhodamine B (Du et al., 2018). As can be seen from Fig. 4, compared with the original material, the fine pore structure is evenly and densely distributed on the surface of the *Eupatorium adenophorum* biochar. These special structures can provide rich adsorption sites for pollutants and enhance the ability to remove pollutants from the environment. Besides, applying IP-DB with certain pore structure to the soil can not only improve soil porosity and water holding capacity, reduce soil bulk density, but also provide a good living environment for microorganisms, thereby increasing the number and activity of microorganisms.

The chemical properties of IP-DB are relatively stable, so it has less negative impact on the environment (Yousaf et al., 2018). Yousaf et al. (2018) produced biochar from *Ambrosia artemisiifolia* L. enriched with heavy metals and found that most of the heavy metals have been converted into a more stable form. Therefore, the potential risk of heavy metals in invasive plants to the environment can be reduced by pyrolysis. In summary, as a cheap and readily available raw material for biochar, pyrolyzed invasive plants can be used in the fields of environmental remediation and soil amendment.

5. Application of IP-DB in environmental remediation

In recent years, with the rapid development of industries such as mining, chemical industry, coatings, electroplating, and tanning, a large number of high-concentration heavy metals and organic wastewater have been generated, causing serious pollution of water and soil environments. Heavy metal pollution has become one of the most concerning issues in various environmental pollutions (Qin et al., 2006). The adsorption method has a good effect in removing pollutants and has been applied to remove heavy metals, organic dyes, and other pollutants in the environment (Li et al., 2019; Luo et al., 2018). Biochar has a rich pore structure and a large specific surface area (Peng et al., 2017). It is a good adsorbent for removing pollutants (Hu et al., 2019; Lyu et al., 2016). The carbonization treatment of invasive plants into an adsorbent for the absorption of pollutants in wastewater can not only reduce the production cost of the adsorbent, but also prevent the destruction of pollutants on the ecological environment, and achieve the purpose of controlling and removing harmful substances in the environment.

Due to the diversity of invasive plants, the adsorption capacity of biochar for heavy metals is greatly affected by the pyrolysis temperature and feedstocks (Table 3). The adsorption capacity of Cu(II) by *Spartina alterniflora* biochar increased first and then decreased with the pyrolysis temperature, reaching the maximum adsorption amount at 600°C, and

Table 2.
Physicochemical properties of biochar from different invasive plants.

Invasive plants	Pyrolysis temperature (°C)	Yield (%)	Ash (%)	pH	C (%)	H (%)	O (%)	N (%)	Specific surface area ($m^2 \bullet g^{-1}$)	Pore volume ($cm^3 \bullet g^{-1}$)	Pore diameter (nm)	References
Ambrosia artemisiifolia L	300	74.40	10.20	8.6	44.7	-	-	-	6.0	-	-	(Yousaf et al., 2018)
Ambrosia artemisiifolia L	400	42.40	15.20	10	61.1	-	-	-	12.7	-	-	(Yousaf et al., 2018)
Ambrosia artemisiifolia L	500	41.40	16.70	10.2	69.8	-	-	-	24.2	-	-	(Yousaf et al., 2018)
Ambrosia artemisiifolia L	600	38.30	20.20	11.4	70.9	-	-	-	32.0	-	-	(Yousaf et al., 2018)
Ambrosia artemisiifolia L	700	35.80	21.40	11.6	72.0	-	-	-	38.2	-	-	(Yousaf et al., 2018)
Eupatorium adenophorum	300	44.43	9.73	7.25	58.81	2.79	27.27	1.39	-	-	-	(Fan et al., 2019)
Eupatorium adenophorum	600	29.10	14.77	10.34	66.75	0.64	16.71	1.12	-	-	-	(Fan et al., 2019)
Eupatorium adenophorum	550	-	-	10.4	-	2.16	-	0.66	-	-	-	(Cornelissen et al., 2016)
Ambrosia trifida L	300	50.00	20.36	-	78.09	4.26	7.44	78.09	3.98	0.01	4.56	(Ahmad et al., 2014)
Ambrosia trifida L	700	29.00	32.34	-	84.96	1.09	6.56	84.96	9.25	0.02	5.63	(Ahmad et al., 2014)
Water hyacinth	250	75.70	22.65	7.24	-	-	-	-	-	-	-	(Zhang et al., 2015)
Water hyacinth	350	50.60	34.76	9.43	-	-	-	-	-	-	-	(Zhang et al., 2015)
Water hyacinth	450	42.00	39.07	10.49	-	-	-	-	-	-	-	(Zhang et al., 2015)
Water hyacinth	550	40.00	43.04	10.46	-	-	-	-	-	-	-	(Zhang et al., 2015)
Spartina alterniflora	300	45.94	7.07	7.8	39.32	3.08	49.76	0.77	-	-	-	(Luo et al., 2017)
Spartina alterniflora	600	24.99	11.58	9.88	65.55	2.19	19.22	1.46	-	-	-	(Luo et al., 2017)
Prosopis juliflora	500	-	-	-	11.86	-	51.44	-	-	-	-	(GuhaRay et al., 2019)
Sicyos angulatus L.	700	-	-	12.56	78.07	2.48	14.66	4.78	2.31	0.0084	-	(Vithanage et al., 2014b)
Sicyos angulatus L.[a]	700	-	-	5.04	65.65	2.73	22.56	4.40	571	0.1338	-	(Vithanage et al., 2014b)
Sicyos angulatus L.[b]	700	-	-	5.65	60.76	3.65	32.09	3.49	411	0.1180	-	(Vithanage et al., 2014b)
Sicyos angulatus L.	300	51.83	25.40	10.86	65.98	5.55	23.09	5.08	0.85	0.004	0.008	(Rajapaksha et al., 2015)
Sicyos angulatus L.	700	27.52	43.72	12.32	69.41	1.31	24.45	4.61	2.31	0.008	6.78	(Rajapaksha et al., 2015)
Elodea nuttallii	200	-	39.40		-	3.26	20.1	1.82	-	-	-	(Poerschmann et al., 2015)
Elodea nuttallii	240	-	41.90		-	3.03	15.7	1.69	-	-	-	(Poerschmann et al., 2015)
Parkinsonia aculeata	500	-	-	-	79.6	2	22.6	0.5	1.6	0.01	1.4	(Messina et al., 2016)
Parkinsonia aculeata [c]	500	-	-	-	82.3	2.8	14.2	0.9	73.8	0.04	0.2	(Messina et al., 2016)
Imperata cylindrica	550	-	20.70	8.61	54.2	-	-	0.82	-	-	-	(Walter and Rao, 2015)
Solidago canadensis	300	-	-	-	66.09	-	28.15	-	-	-	-	(Zhang et al., 2018)
Solidago canadensis	500	-	-	-	68.6	-	29.27	-	-	-	-	(Zhang et al., 2018)

[a] *Sicyos angulatus* L.biochar produced at 700°C activated with sulfuric acid.
[b] *Sicyos angulatus* L.biochar produced at 700°C activated with oxalic acid.
[c] Wood sawdust was demineralized by a mild acid treatment.

the removal rate of Cu(II) was 83.0% (Li et al., 2015). There was no significant change in functional groups of Cu(II)-Cr(VI) binary mixture before and after adsorption of *Eupatorium adenophorum* biochar, indicating that the adsorption process was dominated by physical adsorption, and the adsorption capacities for Cu(II) and Cr(VI) were 27.62 and 9.68 mg/g, respectively (Chen et al., 2016). The adsorption capacity of biochar prepared by mixing *Eupatorium adenophorum* and buckwheat straw for Cu(II) was significantly enhanced, and the adsorption capacity of this biochar to Cu(II) has reached 56.62 mg/g (Chen and Ping, 2015). *Ambrosia trifida* L. biochar can effectively remove Cd(II) in aqueous

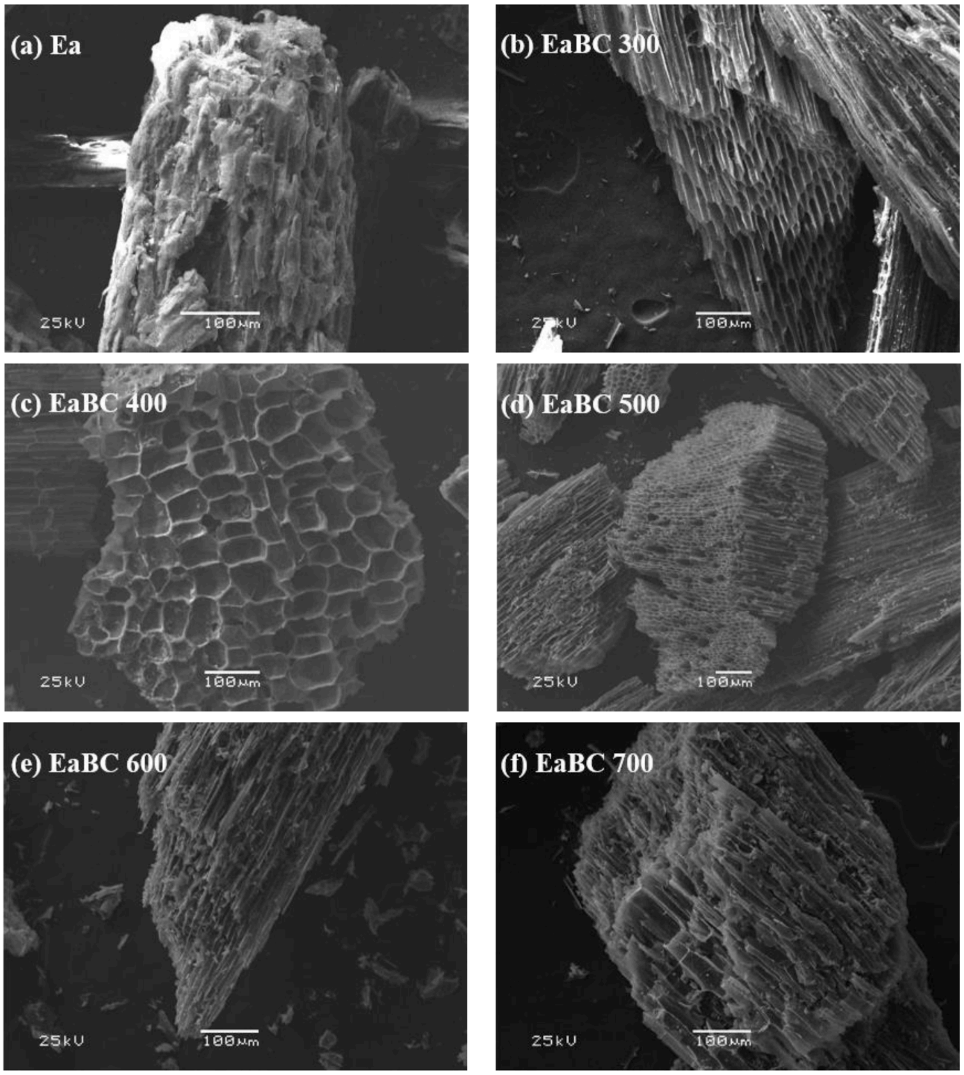

Fig. 4.. Scanning electron microscopic images of *Eupatorium adenophorum* (Ea), and the derived biochar produced at 300-700°C. EaBC represents *Eupatorium adenophorum* biochar, and the digital represents pyrolysis temperature.

solution. The adsorption capacities of Cd(II) on biochar prepared by pyrolysis at 700°C can reach 11.63 mg/g (Yakkala et al., 2013). Under different initial Cd(II) concentrations, the removal effect of water hyacinth biochar for Cd(II) at 450°C was better than other temperatures. Moreover, when the initial Cd(II) concentration was $\leq$50 mg/L, the removal rate was nearly 100% within 1 h (Zhang et al., 2015). The studies found that the biochar prepared from invasive plants-*Prosopis juliflora, Alternanthera philoxeroides, Ambrosia trifida* L. showed a good adsorption effect on Pb(II), and the maximum adsorption capacity was 43.00, 257.12, 333.33 mg/g, respectively (Saravanakumar et al., 2019; Yakkala et al., 2013; Yang et al., 2014). Compared with the typical raw materials of biochar, the adsorption capacity of IP-DB for Pb(II) has more advantages (Fig. 5). Most biochar has relatively abundant inorganic ash and carboxyl functional groups, higher alkalinity, and lower anion exchange capacity. Therefore, the adsorption capacity of biochar for anions is generally low (Beesley et al., 2014). The removal rate of As (V) by unmodified water hyacinth biochar is only 8.9%, and the removal rate after modification with Fe^{2+}/Fe^{3+} can reach 100% (Zhang et al., 2016). In addition, magnetically modified water hyacinth biochar with low-temperature pyrolysis has a higher adsorption efficiency for As(V) than biochar with high-temperature pyrolysis. This is mainly because the low temperature pyrolysis biochar has a larger specific surface area and more fixed iron, which are beneficial to the complex reaction between As(V) and Fe sites on the surface (Deliyanni et al., 2013). Therefore, the lower pyrolysis temperature required for biochar production has obvious advantages in industrial applications.

IP-DB not only has a good removal effect on heavy metals in water but also can adsorb hard-to-degrade organic pollutants in the environment. High-temperature pyrolyzed *Ambrosia trifida* L. biochar has a better removal effect on trichloroethylene in water due to its low polarity, high aromaticity and high specific surface area and can be used as an effective adsorbent for trichloroethylene (Ahmad et al., 2014). The study also found that *Ambrosia trifida* L. biochar-alginate composite microspheres can not only remove Cd(II) in wastewater, but also have good removal ability for TNT and RDX, and ion exchange and electrostatic attraction mainly occur between the adsorbent and the adsorbate (Roh et al., 2015). Biochar also has a strong adsorption capacity for phenols (Nunell et al., 2016). The removal of 2,4,6-trichlorophenol in water by the nano-iron/nickel bimetal supported by *Eupatorium adenophorum* was more significant than that of pure biochar, and the degradation rate can be increased by 39.7-71.6% under different conditions. Especially under acidic conditions, it had a good removal effect for low concentrations of 2,4,6-trichlorophenol, which was the result of the synergistic action of adsorption and reduction (Liu et al., 2019). In summary, the effect of IP-DB on remediation of pollutants in the environment is significant, but the adsorption mechanism is affected by the

Table 3.
Adsorption characteristics of IP-DB for different pollutants.

IP-DB	Contaminants	Pyrolysis temperature (°C)	pH	Initial pollutant concentration (mg/L)	Reaction temperature (K)	Adsorption time (h)	Dosage of adsorbent (g)	Absorptive capacity (mg/g)	References
Eupatorium adenophorum	Cr(VI)	400	5.0	50	298	0.5	0.1	9.68	(Chen et al., 2016)
Eupatorium adenophorum	Cu(II)	400	5.0	50	298	0.5	0.1	27.62	(Chen et al., 2016)
Spartina alterniflora	Cu(II)	600	6.0	50	298	24	0.05	29.4	(Li et al., 2015)
Water hyacinth	Cu(II)	700	6.0	50	298	24	0.05	28.2	(Li et al., 2015)
Eupatorium adenophorum/ buckwheat straw mixture	Cu(II)	550	3.0	-	298	2	0.25	56.62	(Chen and Ping, 2015)
Water hyacinth	Cd(II)	450	-	500	298	24	0.2	70.31	(Zhang et al., 2015)
Water hyacinth biochar/FeO_x	As(V)	250	6.6	0.118	298	24	0.2	7.4	(Zhang et al., 2016)
Prosopis juliflora biochar/NiO	Pb(II)	400	6.0	10	300	3	0.5	43.00	(Saravanakumar et al., 2019)
Ambrosia trifida L.	Trichloroethylene	300	7.0	13	298	48	-	71.57	(Ahmad et al., 2014)
Ambrosia trifida L.	Trichloroethylene	700	7.0	13	298	48	-	91.15	(Ahmad et al., 2014)
Ambrosia trifida L. biochar-alginate beads	Cd(II)	700	6.0	10	303	4	0.03	9.73	(Roh et al., 2015)
Ambrosia trifida L. biochar-alginate beads	TNT	700	6.0	10	303	4	0.03	90.09	(Roh et al., 2015)
Ambrosia trifida L. biochar-alginate beads	RDX	700	6.0	10	303	4	0.03	28.09	(Roh et al., 2015)

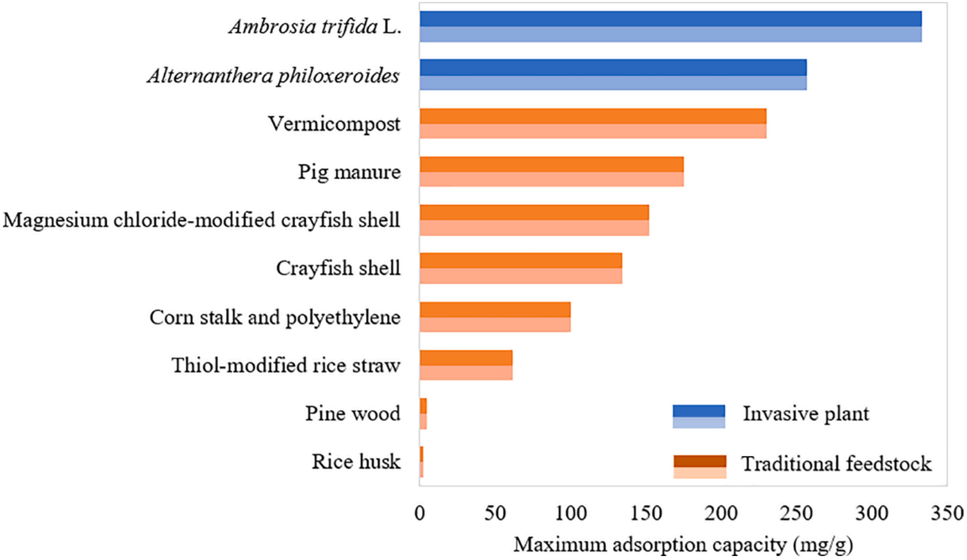

Fig. 5.. Comparison of adsorption properties of IP-DB and biochar from traditional feedstocks for Pb(II) (Fan et al., 2020a; Fan et al., 2020b; Kołodyńska et al., 2012; Liu and Zhang, 2009; Yakkala et al., 2013; Yang et al., 2014; Zhang et al., 2020a; Zhang et al., 2020b).

properties of biochar and the type of pollutants. The possible removal mechanism is shown in Fig. 6. The interactions of electrostatic attraction, ion exchange, physical adsorption, surface complexation and/or precipitation often occur between biochar and heavy metals (Shakoor et al., 2019). For organic pollutants, the possible adsorption mechanism is the result of a combination of electrostatic interaction, hydrophobic effect, hydrogen bonding, and pore filling (Palansooriya et al., 2019). To sum up, these results indicate that using low-cost, high-efficiency IP-DB for environmental pollution remediation may have huge ecological and environmental benefits.

6. Application of IP-DB in agricultural soil amendment

Biochar is a kind of soil amendment with large specific surface area, porous structure, negatively charged, and strong adsorption capacity. The effect of biochar on soil amendment is mainly to improve the soil environment by affecting its physical, chemical properties, and microbial activity (Chen et al., 2020; Cornelissen et al., 2013; Xu et al., 2019). For example, it can increase the retention capacity of soil water and nutrients, reduce the emission of N_2O, CO_2 and CH_4 in the soil, release soluble C and micronutrient elements, and increase the pH value of

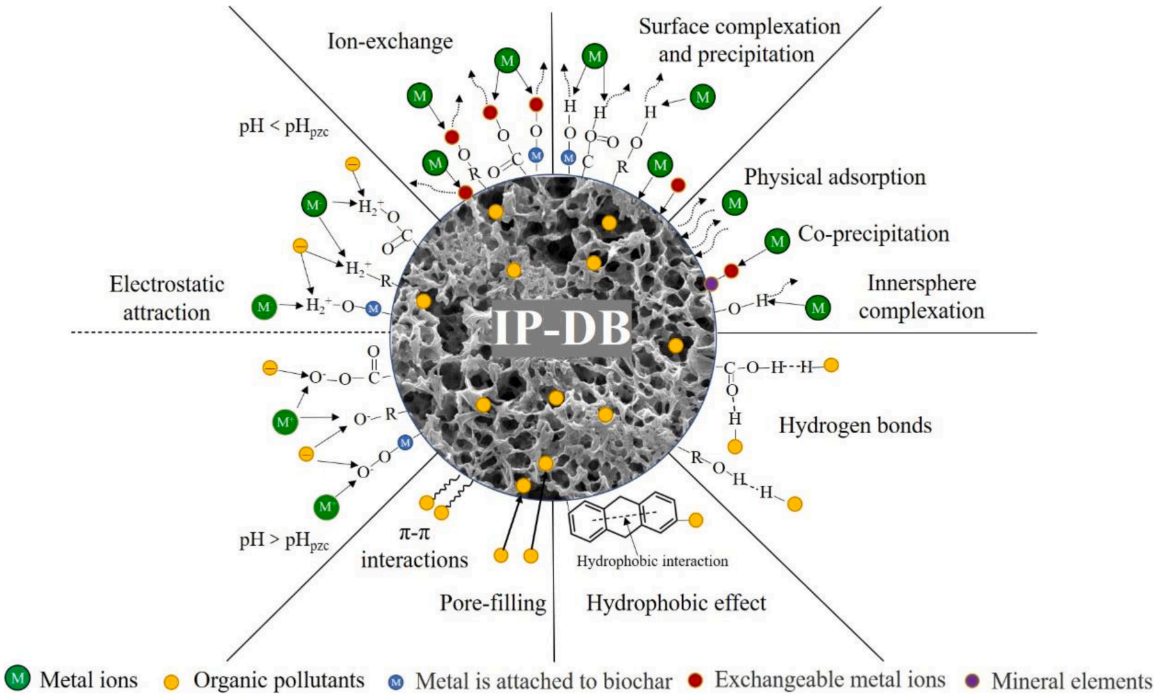

Fig. 6.. Adsorption mechanisms of heavy metals and organic contaminants by IP-DB.

acidic soil (Chen et al., 2019; El-Naggar et al., 2019). The use of IP-DB can be used as an effective material for soil carbon fixation and soil fertility improvement.

Studies have shown that adding a certain amount of water hyacinth biochar in red soil can significantly increase soil enzyme activity, soil respiration, and metabolic coefficient, and promote corn seed germination and growth (Masto et al., 2013). Biochar can promote crop growth mainly due to lime effect, the improvement of soil water holding capacity and nutrient availability (Jeffery et al., 2011). The pH value of the red soil selected in this study is neutral, and water hyacinth is rich in plant nutrients. Therefore, the growth of corn may be mainly due to the nutrients in water hyacinth biochar (Mazumder et al., 2020). The effects of combined application of different concentrations of *Eupatorium adenophorum* and four different dosages of N, P, K fertilizers, water, and lime on corn yield were studied. The results showed that the addition of biochar increased soil moisture, potassium, plant-available phosphorus, and soil pH value, and the yield of corn supplemented with biochar was significantly higher than that under sufficient nutrition (Pandit et al., 2018). The effect of the addition of *Eupatorium adenophorum* biochar on crops in a smaller range has no significant difference. Compared with unimproved soil, 1% and 4% biochar can significantly increase CEC, OC content, reducing the aluminum/calcium ratio. In addition, the yield of corn treated with nutrient-enriched biochar significantly increased compared with non-enriched biochar , indicating that the addition of biochar enhanced the effectiveness of fertilizer (Pandit et al., 2017). *Prosopis Juliflora* biochar and expanded black cotton soil mixed uniformly under the same compaction state can increase the shear strength and California bearing ratio, and reduce the free expansion index of the expansive soil. Therefore, biochar can be used as a stable material for expansive soils (GuhaRay et al., 2019). Studies showed that the adsorption of Cu(II) by *Spartina alterniflora* and water hyacinth biochar promotes the release of Ca. Ca played an important role in improving soil structure by bridging with cations of clay particles and soil organic carbon (Bronick and Lal, 2005; Li et al., 2015). Biochar not only remediate the environment contaminated by heavy metals but also release nutrients and promote soil particle agglomeration, thereby improving the soil. Therefore, IP-DB can be used as an effective material for environmental restoration and soil improvement at the same time.

Biochar can also reduce the bioavailability of harmful chemical pollutants in contaminated soil and promote plant growth (Bogusz et al., 2019; Konczak and Oleszczuk, 2018; Liu et al., 2018; Stefaniuk and Oleszczuk, 2016). Acid soil is not suitable for crop growth. The low pH of the soil is usually related to dissolved aluminum ion concentration (Gruba and Mulder, 2008). Adding biochar to the soil as a calcifying agent can greatly reduce the concentration of aluminum and improve the soil environment (Martinsen et al., 2015). In the presence of biochar, the concentrations of PCBs in Chinese yew and carrot roots decreased by 61.5-93.7% and 12.7-62.4%, respectively (Wang et al., 2013). Li et al. (2018) used corn seedlings as recipient plants and explored the accumulation of acetochlor in corn seedlings treated with biochar at different ages (10 d and 20 d). The results showed that the addition of 10 days *Eupatorium adenophorum* biochar in the soil can reduce the bioaccumulation of acetochlor in corn seedlings. However, the concentration of acetochlor in corn plants with 20 days of *Eupatorium adenophorum* biochar was significantly higher than the concentration of without added biochar and added 10 days of biochar. Therefore, adding the appropriate concentration of *Eupatorium adenophorum* biochar in the soil can reduce the accumulation of herbicides in agricultural products, thereby reducing the risk of human ingesting harmful substances. Poor drainage capacity of heavy clay and poor soil permeability have limited its application in agriculture (Coulombe et al., 1996). In field trials, compared with the control group, the modified heavy clay soils with *Eupatorium adenophorum* biochar have enhanced permeability, increased effective water capacity, and corn yield (Obia et al., 2018). The *Eupatorium adenophorum* biochar was mixed with cow urine and applied to the roots of pumpkin, and the pumpkin yield was significantly improved compared with no cow dung and no biochar (Hans et al., 2015).

In recent years, the large-scale use of antibiotics has caused a series of environmental problems. Once antibiotics are released to the environment, they will contaminate water and soil, and be absorbed by plants or crops, posing a potential risk to human health (Kim et al., 2010). Among them, sulfonamides antibiotics are the most commonly used drugs in the veterinary medicine industry, and sulfamethazine (SMT) is the most commonly used drug in this class of antibiotics (Bitas et al., 2018; Haller et al., 2002; Stahl et al., 2016). Because of high polarity and water solubility, low octane water partition coefficient and chelating ability of SMT, it has low affinity for soil and shows high mobility in soil (Haller et al., 2002; Kim et al., 2011). The characteristics of biochar with large specific surface area, high porosity, and rich surface functional groups have potential application value in controlling the migration of pollutants in soil (Ahmad et al., 2012). Studies have shown that biochar prepared by pyrolysis of *Sicyos angulatus* L. at 700°C has a high adsorption rate of SMT in the soil after being activated by 30% sulfuric acid and oxalic acid (Vithanage et al., 2014b). The retention rate of SMT in sandy loam and loam soil after treated with *Sicyos angulatus* L. biochar increased by 89% and 82%, respectively, effectively reducing the SMT migration rate in the soil (Vithanage et al., 2014a). Research on the absorption of antibiotics by crops has also found that lettuce in soil with *Sicyos angulatus* L. biochar can significantly reduce absorption of SMT. This is because biochar has high aromaticity and hydrophobicity, and it can enhance the adsorption of SMT on the surface and reduce the bioavailability of SMT after being applied to soil (Rajapaksha et al., 2014). Compared with the conventional non-activated slow pyrolysis, the adsorption capacity of *Sicyos angulatus* L. biochar produced by steam activation increased by 55%, and the adsorption showed obvious pH dependence. There was a good chemistry adsorption and electrostatic interactions between SMT and biochar (Rajapaksha et al., 2015). Therefore, the *Sicyos angulatus* L. biochar can be widely used in the removal of sulfonamides antibiotics in soil.

Therefore, the preparation of invasive plants into biochar for soil amendment is a promising development direction. Not only can it improve soil fertility, increase the quality and yield of agricultural products, but also reduce the migration of pollutants in the soil, reduce the absorption of pollutants by plants, and turn it into a valuable resource. Besides, the mixed-use of IP-DB with other wastes or fertilizers can improve the utilization rate of fertilizers and have a positive impact on crop yields (Hans et al., 2015). This research may also become a hot spot for future research. Finally, IP-DB can be used to improve invasive soil and reduce the inhibitory effect of allelochemicals. Studies have shown that *Solidago canadensis* L. biochar has a large adsorption capacity on its typical allelochemical, dimethyl phthalate, thereby reducing the inhibitory effect of allelochemicals on tomato seeds (Zhang et al., 2018). Therefore, biochar can be used as an adsorbent for allelochemicals, reducing the persecution of invasive plants on native species.

7. Conclusions and future perspectives

The resource utilization of invasive plants has become an effective strategy for controlling and managing invasive plants, which can not only reduce the cost of prevention and control but also turn waste into treasure. The preparation of invasive plants into biochar is a research direction with great development potential in the field of future environmental science. This paper discusses the application research value of invasive plants to prepare biochar, and summarizes its application in environmental remediation and agricultural soil amendment, providing a possible way for the utilization of invasive plants. IP-DB, as a sustainable biological adsorbent, is effective in removing heavy metals and organic pollutants. In particular, biochar prepared from *Ambrosia trifida* L., *Alternanthera philoxeroides,* water hyacinth has a good adsorption effect on heavy metals, and could be used as a low-cost adsorbent to remove heavy metals in water. Moreover, IP-DB could also be used as an effective material for improving soil fertility, increasing soil water and nutrient retention capacity. At the same time, it can also reduce the bioavailability of harmful chemical pollutants such as pesticides and antibiotics in contaminated soils, reduce the absorption of pollutants by plants, and promote the germination and growth of crop seeds. Current researches have found that biochar derived from invasive plants (such as *Eupatorium adenophorum*, water hyacinth, *Sicyos angulatus* L.) have a good effect on soil amendment. Therefore, invasive plants can be used as raw materials of biochar for soil improvement to realize the efficient utilization of invasive plants.

However, as emerging harmful material, invasive plants still face some challenges and barriers in preparing biochar for environmental remediation and agricultural soil amendment.

IP-DB may have relatively limited adsorption capacity for pollutants. Therefore, different modification methods could be considered to improve their adsorption capacity (Wang et al., 2018a). Meanwhile, the removal and immobilization mechanisms of different pollutants by biochar prepared under different invasive plants and pyrolysis conditions are quite different. Therefore, future research should pay more attention to the adsorption mechanism of pollutants by biochar prepared by different invasive plants. Targeted screening of IP-DB with the best adsorption effect will be the key directions for future research.

Although IP-DB has a good adsorption effect on pollutants, how to deal with the IP-DB after adsorbing pollutants is the focus of current researchers. Regeneration treatment can recycle pollutants to reduce the risk of secondary pollution (Tang et al., 2018). The currently reported regeneration methods include hot regeneration (Foo and Hameed, 2012), elution (Dai et al., 2020; Wang et al., 2018b), ultrasonication (Fan et al., 2017), photodegradation (Wang et al., 2016b), etc. These methods have good effect, but there is still a lack of research on the regeneration performance of biochar treated by different regeneration methods. Therefore, it is necessary to conduct systematic studies on the regeneration performance of biochar that adsorbs specific pollutants.

At present, the application of IP-DB is still in the stage of theoretical research. Corresponding international standard and standardized management model are needed to evaluate the pros and cons of IP-DB and promote its large-scale application. Moreover, due to the higher fuel production capacity of invasive plants, there is a possibility that IP-DB may possess higher concentrations of hazardous substances, such as polyaromatic hydrocarbons (Tomczyk et al., 2020; Zhao et al., 2020). Therefore, systematically evaluating the potential risks and adverse effects of IP-DB on humans and environment and finding suitable preparation methods that can reduce harmful substances in IP-DB are the issues that need to be addressed in the future.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

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