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Review

Analysis of utilization technologies for *Eichhornia crassipes* biomass harvested after restoration of wastewater

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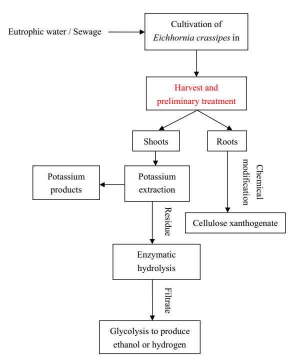
HIGHLIGHTS

- Various utilization technologies of *Eichhornia crassipes* (*EC*) biomass are analyzed.
- Comprehensive utilization of *EC* biomass is proposed based on composition properties.
- High K content in shoots of *EC* indicates the potential of production of K products.
- Low biomass crystallinity leads to *EC*' advantages in material and energy utilization.

GRAPHICAL ABSTRACT



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ABSTRACT

Eichhornia crassipes (*EC*, water hyacinth) has gained attention due to its alarming reproductive capacity, which subsequently leads to serious ecological damage of water in many eutrophic lakes in the world. The traditional mechanical removal methods have disadvantages. They squander this valuable lignocellulosic resource. Meanwhile, there is a bottleneck for the subsequently reasonable and efficient utilization of *EC* biomass on a large scale after phytoremediation of polluted water using *EC*. As a result, the exploration of effective *EC* utilization technologies has become a popular research field. After years of exploration and amelioration, there have been significant breakthroughs in this research area, including the synthesis of excellent *EC* cellulose-derived materials, innovative bioenergy production, etc. This review organizes the research of the utilization of the *EC* biomass among several important fields and then analyses the advantages and disadvantages for each pathway. Finally, comprehensive *EC* utilization technologies are proposed as a reference.

Abbreviation: *EC*, *Eichhornia crassipes*.

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Contents

1. Introduction

EC, which is a free-floating perennial herb with a shoot that is partially filled with air, lives in fresh water ecosystems. It is widely thought that *EC* is native to the Amazonas Basin (Barrett, 1980). *EC* produces beautiful blooms and foliage, so it has been spread by tourists, and plant collectors alike in more than 80 countries in the world over the last 100 years (Jafari, 2010). Its reproduction capacity is particularly strong, and it uses both asexual reproduction via stolons and sexual reproduction via seed. *EC* grows well upon exposure to a wide range of temperatures and nutrients. Under optimal conditions, the biomass yield can double in six days (Dhir, 2013). *EC* has the highest impact index of 4 and a spread index of 3, which represent its enormous environmental impact and strong spreading capacity, respectively (Bai et al., 2013). Thus, *EC* is undoubtedly in the list of one of the world's top ten malignant weeds. *EC* is a well-known plant species in the world that is relevant to many scientific and environmental engineering disciplines because of its strong tolerance to, and efficient absorption of, heavy metals and nutrients such as nitrogen, phosphorus, and potassium.

As an alien species without natural enemies in most of *EC* invading countries, it multiplied quickly via asexual reproduction and has spread widely. It has caused serious hazards to the local aquatic ecosystems, including channel blocking, water quality deterioration, the extinction of aquatic organisms, biodiversity reduction, and other issues. Many efforts have been made to address these challenges, but such efforts have had little effect (Gunnarsson and Petersen, 2007). To make full use of *EC*'s superior decontamination ability while reducing its hazards to aquatic ecosystems, it is urgent that researchers find efficient, sustainable, and feasible ways to remove the bottlenecks in the utilization of *EC* biomass.

The purpose of this paper is to review the application of *EC* in the restoration of wastewater and to offer an in-depth analysis and discussion of the advantages and disadvantages of different utilization technologies (e.g., nutrient supplier for plant and animal, material utilization, energy utilization, etc.) of *EC* biomass. Moreover, a strategy for the comprehensive utilization of *EC* biomass is also proposed.

2. Application of *EC* in the restoration of polluted water

Currently, the resilience of both human society and the natural environment are being tested on a global level by population and economic growth pressures, which have in turn led to increasing greenhouse gas emissions, declining biodiversity, and other threats to vital natural resources, such as fresh water, soil, forests, and wetlands (Fiksel et al., 2009). Meanwhile, as people have paid much more attention to the protection of the environment, the bioremediation of polluted water has become a pertinent issue. The use of plants is considered to be an efficient, low-cost method for remediating contaminated water. Specific plants, such as *EC*, *Myriophyllum verticillatum* (He and Chi, 2015), *Juncus effusus* (White and Cousins, 2013; Schultze-Nobre et al., 2015), and other aquatic macrophytes, have been identified as useful species for this purpose.

EC is widely used to treat eutrophic water, domestic sewage, and industrial wastewater (Lin and Li, 2016; Yi et al., 2016) due to its extensive root system, strong reproductive capacity, and excellent tolerance to polluted growth conditions and environments. *EC* has shown a good purification capacity in the treatment of domestic sewage. The extensive root system of *EC* generates a large contact area with water and thus forms a dense filtering layer. Insoluble colloids, particularly organic debris, can be deposited through the adhesion or adsorption to the root system, leading to a reduction in the concentration of suspended sediment in water. *EC* is able to efficiently remove BOD_5, COD, phenols, chroma, and odors in domestic sewage (Ajayi and Ogunbayio, 2012), and it is known to be especially useful for the purification of organic wastewater containing naphthalene (polycyclic aromatic hydrocarbons) (Nesterenko-Malkovskaya et al., 2012). Therefore, *EC* can also be used to treat wastewater from industrial processes, such as papermaking, drilling sewage, refinery wastewater, etc.

In addition to the wastewater treatment using *Eichhornia crassipes* alone, the integration of *EC* with different plants in wetlands using various types of decontamination methods has been considered to be effective (Farid et al., 2014; Chen et al., 2015). As can be testified in a wetland planted with *EC*, when the initial physicochemical parameters in industrial wastewater include an electrical conductivity of 1245 μs/cm, COD of 837.6 mg/l, Pb of 1.199 mg/l, Ni of 3.34 mg/l, phosphates of 56.22 mg/l, and ammonia of 52.55 mg/l, the respective removal efficient is 74.9%, 83.7%, 83.4%, 95.1%, 90.2%, and 71.6%, respectively, which shows a better performance than wetlands constructed with sludge (Fazal et al., 2015).

A further advantage of using *EC* to restore polluted water is that it not only effectively removes contaminants from water but also creates favorable habitat conditions for the introduction and colonization of other organisms after the initial restoration. However, due to its unique rapid growth and spreading characteristics, robust management strategies must be employed to control the growth of *EC*. For example, enclosure and grid technologies can be employed to provide effective zoning and regulation if necessary. Moreover, phytoremediation integrated with other plants deserves more attention for its stronger depollution ability and more suitable ecosystem formation, which can prevent *EC*'s excessive proliferation via plant competition.

3. *EC* utilization technologies

The utilization of *EC* biomass can avoid the generation of secondary pollution that is caused by biomass decay after ecological restoration. Further, this utilization can generate certain economic benefits. *EC* biomass utilization methods include use as a substrate for plant growth or as animal feed, recovery of useful elements, such as potassium, and use as a biomass feedstock for the production of bioenergy. The features of each utilization technology are detailed below.

3.1. Harvesting of EC and its preliminary treatment

Prior to the utilization of *EC*, its biomass needs to be harvested. An appropriate harvesting time will yield more biomass and help achieve a better phytoremediation effect. In an engineering experimental report, a maximum sustainable area of 14,059 m^2 was harvested once a week with total harvest area of 154,649, according to the GPS and remote monitoring satellite data (Sun and Zhu, 2014). The harvesting method consists of manual and mechanical collection. Manual collection is more appropriate for a small scale *EC* harvesting, while mechanical collection is more appropriate for a large scale harvesting. In a phytoremediation project of a eutrophic lake, specially designed ships were used for harvesting *EC* (Zhang et al., 2016). After *EC* is harvested, it needs to be dewatered to reduce volume. Direct dewatering of raw *EC* biomass does not produce good results. Thus, *EC* biomass, first, needs to be broken down with a kibbler. The dewatering methods can be divided into three types according to the machine type (i.e., screw type, hydraulic type, and belt filter press type). Screw type machine is more effective than the other two machine types. Dewatered *EC* still contains some water. Thus, it will rot quickly on a hot and wet day. Therefore, further dewatering (e.g., natural insolation or manual heating arefaction) is required.

3.2. Nutrient supplier

EC contains high concentration of plant nutrition elements. High potassium and nitrogen concentrations are found mainly in the stems and leaves of *EC* plants. *EC* is rich in potassium and has concentrations that are much higher than those of other terrestrial plants. It has been reported that when 10 t/ha of *EC* and cocoa waste were applied, the maximum *Amaranthus cruentus* L. yields could be obtained. Compared with the application effects of potassium fertilizer at potassium levels of 10 kg/ha, the increase in yield was found to be significant at the $p < 0.05$ level (Adeoye et al., 2001).

EC biomass can be used as a substrate for plant growth in multiple forms. The forms and characteristics are listed in Table 1. As a substrate for plant growth, the recycling of *EC* can be an eco-friendly aquatic weed management strategy to improve soil health and nutrient redistribution. This strategy has a fast turnover that could promote sustainable agricultural production in tropical soils (Balasubramanian et al., 2013).

In addition to being used as a plant nutrient supplier, *EC* biomass can be used as a feedstock for animal feed (Jafari, 2010; Albano Pérez et al., 2015). In the 1950s, *EC* was extensively planted in China as pig fodder because it contains high amounts of protein, P, and Ca. Furthermore, its quality as animal fodder was considered to be better than that of other materials, such as rice straw. However, *EC* is not palatable due to high content of crude fiber that causes mouth irritation in animals. To improve the quality of *EC* as fodder, the use patterns of *EC* have been improved continually over time. The forms and characteristics of *EC* as fodder are also listed in Table 1. Enhanced palatability for animals is the key requirement for the use of *EC* as fodder. Besides, to improve the nutritional value, molasses, salt, rice bran, urea, and other substances can be added to the fodder.

3.3. Recovery of elements using EC

Currently, the increasing consumer demands to the limited alkaline metals and some important industrial metals, such as platinum and silver, have put significant pressure on related electronic industries (Gutiérrez-Gutiérrez et al., 2015). Moreover, these industries cause pollution on large areas of water, soil, land, and air due to exploration and manufacturing (Akhtar and Amin, 2011). Consequently, the situation impels people to exploit new methods to surmount this hurdle. Various types of metal recovery methods, including physical absorption (Wang et al., 2016a; Xu et al., 2016a; Gonzalez et al., 2016), chemical precipitation (Fujita and Sakairi, 2016; Wang et al., 2016b), membrane filtration

Table 1
Forms and characteristics of *EC* as the nutrient supplier to plants and animals.

Utilizations	Forms	Characteristics
As a substrate for plant growth	1. Mixed with other materials for aerobic or anaerobic composting to produce biogas and organic fertilizer (Gajalakshmi et al., 2002; Khaket et al., 2012) 2. Used as mulch in fields directly 3. Used as an organic fertilizer or soil modifying agent (Gunnarsson and Petersen, 2007) 4. Mixed with other ingredients to prepare plant growth substrates (Chen et al., 2010)	1. Long residual action (nutrients are made available slowly) (Bi et al., 2016) 2. Comprehensive plant nutrition (EC biomass contains comprehensive trace elements) (Chen et al., 2010)
As a feedstock of animal fodder	1. As fodder directly 2. As fodder after cooking treatment 3. As silage	Poor palatability for animals Enhanced palatability (Jafari, 2010) Long storage and enhanced palatability

(Hebbar et al., 2016; Park et al., 2016), and biological treatments (Fontmorin and Sillanpää, 2015; Ramteke and Gogate, 2016), have been studied and applied to different wastewater treatments. However, these traditional methods have common shortcomings such as high investment, high labor cost, and potential to change or destroy original ecosystems. Thus, the development of new low investment, low labor cost, and environmentally friendly methods should be the mainstream direction in the future. Phytoremediation, including *EC* depollution, is a reliable and eco-friendly approach that uses plant and microbe synergetic effects to absorb and assimilate heavy metals, which may effectively alleviate this pressure and water shortage problems (Ali et al., 2013; Li et al., 2014a).

3.3.1. Silver recovery using EC

EC is uniquely rich in Cd, Cu, Pb, Zn, Fe, and other heavy metals that it acquires through its roots (Saraswat and Rai, 2010; Li et al., 2013). The enrichment and recovery of Ag is a typical example of *EC*'s ability to recover metals.

EC can be used as a pollution monitor for the presence of Ag, and Ag in *EC* can be recovered by chemical methods. Ag recovery rates from *EC* as high as 70% have been reported, and the purity of the recovered Ag was 98% (Ahluwalia and Goyal, 2007). *EC* harvested from the treatment of heavy metal-containing wastewater can be used to produce biogas, whereas the biogas residue can be used to recover valuable metals.

3.3.2. Potassium recovery using EC

The weight ratio of different parts of *EC* is approximately 2 (roots): 3 (stems): 9 (leaves). The corresponding potassium content (%) is approximately 1.36 ± 0.61 in the roots, 4.33 ± 1.77 in the stems, and 6.63 ± 0.60 in the leaves (Zhou et al., 2007). Therefore, *EC* has certain resource advantages for the extraction and utilization of potassium in stems and leaves. One study revealed that the total potassium yield of *EC* stems and leaves (i.e., shoots) was 44.5% via the extraction of stems and leaves with 0.8 mol/L hydrochloric acid for 30 min followed by precipitation with tartaric acid ($C_4H_6O_6$) to form potassium hydrogen tartrate ($KC_4H_5O_6$) (Zhou et al., 2007).

3.4. Material utilization

The chemical composition of cellulose, lignin, and various proteins in plant tissues that have functional groups, such as carbonyl, carboxyl, hydroxyl, etc., can provide multiple sites for the adsorption of metal ions (Saraswat and Rai, 2010; Lin et al., 2012; Ibrahim et al., 2012). Consequently, *EC* can be used as an adsorption material for heavy metals. Further, to make full use of its high fiber content, *EC* can be made into nanoparticle material (Mochochoko et al., 2013; Vanathi et al., 2014) and can be used as a filler in natural rubber or as a water absorbing material (Xu et al., 2016b).

3.4.1. Heavy metal adsorbents

Studies have shown that *EC* plants (living) have high capacities for the removal of trace metals, such as As, Cr, Cd, Fe, Mn, and Cu (Ibrahim et al., 2012; Agunbiade et al., 2009; Li et al., 2016). Harvested *EC* biomass also has a strong adsorption capacity for heavy metals and thus provides a novel method for the removal of heavy metals from water. Using a fixation technique, *EC* powder can achieve a circulation of dosing, recovering, and dosing (Elfeky et al., 2013).

The main advantages of using *EC* biomass or chemically modified *EC* products instead of living *EC* plants for heavy metal removal include:

- No toxic effects of the high concentrations of heavy metals to the plants,
- Easier to reach adsorption saturation than with living roots, and
- Repeated use through adsorption-desorption cycles.

Research has expanded beyond simple direct utilization of *EC* biomass for metal ion removal via absorption. It is known that the absorption capacity of *EC* biomass can be enhanced several fold via chemical modification of the feedstock, and the physical properties of the adsorbents can also be significantly modified (Ammar et al., 2014). Taking the preparation of cellulose xanthogenate (heavy metal adsorbent) via the chemical modification of *EC* biomass as an example, the main reactions involved in the process are as follows (Tan et al., 2008):

$$\text{Cell-OH} + \text{NaOH} \rightarrow \text{Cell-ONa} + H_2O, \quad (1)$$

$$\text{Cell-ONa} + CS_2 \rightarrow \text{Cell-OCS}_2\text{Na, and} \quad (2)$$

$$2\text{Cell-OCS}_2\text{Na} + Mg^{2+} \rightarrow (\text{Cell-OCS}_2)_2\text{Mg} + 2Na^+ \quad (3)$$

where Cell-OH represents cellulose—the main component of the biomass that is utilized, CS_2 is a sulfonating agent, and (Cell-$OCS_2)_2$Mg is the effective ingredient of the adsorbent. Compared with rape straw and corn stocks, which are used as raw materials for chemical modification via the same modification process, cellulose xanthogenate that is prepared from *EC* biomass has a higher adsorption capacity for Cu^{2+} under the same adsorption conditions (361.0, 303.1, and 334.5 cmol/kg for *EC*, rape straw, and corn stock-derived cellulose xanthogenate, respectively) (Zhou et al., 2011). Meanwhile, the physical properties of *EC*-based adsorbents (such as mechanical strength) are significantly higher than those of other plant biomass-derived adsorbents. The main reason for this is that the degree of crystallinity of biomass (or its cellulose) in *EC* is lower than in other plants. It has been reported that the crystallinity index of *EC* biomass is 21.6% (Satyanagalakshmi et al., 2011), which indicates that most of the cellulose in *EC* is amorphous cellulose with a higher chemical activity. Therefore, the efficiency for chemical modification and the effective component content of modified *EC* products are both higher than those prepared from other plant materials. This has resulted in higher adsorption capacities and adsorption rates for *EC*-modified products (Zhou et al., 2011). Despite this, every step of the abovementioned cellulose xanthogenate absorbent production consumes significant amount of chemical reagents. Additionally, alkali cellulose (Cell-ONa) production in the first step produces large amount of alkali-wastewater. To decrease the secondary contaminant, two bio-degumming treatments derived cellulose xanthogenate absorbents were synthesized and achieved the same lead absorption effect as the alkali-prepared cellulose xanthogenate absorbent (Deng et al., 2012). This is more environmentally friendly, and such improvement needs to be proposed.

3.4.2. Other materials

The modulus and hardness of natural rubber can be improved by introducing *EC* cellulose as a filler. This process can increase the market value of natural rubber. However, the poor adhesiveness between *EC* cellulose and natural rubber results in a reduction of the tensile strength and abrasion resistance of rubber filled with *EC* cellulose. To avoid these defects, a coupling agent can be added to *EC* cellulose to increase the adhesion between *EC* cellulose and natural rubber (Supri et al., 2013). Easily bio-degradable poly β-hydroxybutyrate is widely used in a range of medical, veterinary, and agricultural practices. The synthesis of this bioplastic material consumes a significant amount of carbon source and leads to a high cost. Therefore, *EC* hydrolysates have been successfully used as a carbon source for the poly β-hydroxybutyrate production via the Cupriavidus necator bacteria (Radhika and Murugesan, 2012).

Due to their excellent properties, metal nanoparticles have been used in many high-tech industries including biosensors, photo catalyst, and pharmaceutical industries (Krishnakumar et al., 2008; Bankar et al., 2010; Abdel-Halim and Al-Deyab, 2011). *EC* or *EC*-extracted cellulose has been also used for the synthesis of metal nanoparticles including silver nanoparticle and zinc oxide nanoparticle (Mochochoko et al., 2013; Vanathi et al., 2014). In these synthetic nanoparticles, *EC* mainly passivates and stabilizes the solution system to prevent the formation of larger particles (Abdel-Halim and Al-Deyab, 2011). The method is more environmentally friendly and less costly compared with traditional physical and chemical methods. Although the method has many good traits, the fine particles that *EC* produces may have negative effects for lacking of enough information currently.

3.5. Energy utilization

Faced with a serious global energy crisis and intractable environmental pollution, many countries have enacted and enforced relevant laws to induce sustainable energy development and reduce greenhouse gas emission. Bioenergy is a promising renewable fuel that can be bio-degraded in a non-toxic manner and that emits less exhaust gas, which will suitably address the abovementioned requirement (Dalai and Bassi, 2010). New effective biorefinery technologies have become significant for future society development (Liang et al., 2008; Lin and Liu, 2014; Asadullah, 2014). Different biomass feedstocks for bioenergy have been developed through many methods, whereas only several methods have been tested and are more cost-effective. Therefore, choosing an appropriate feedstock and proper processes becomes a very important part of bioenergy production (Yan et al., 2010). *EC* grows quickly with more carbohydrates but with less lignin, and it can be easily hydrolyzed (Aswathy et al., 2010; Guragain et al., 2011). These traits make it one of the most intensively studied plants for bio-fuels.

3.5.1. Biogas production

As a useful material, *EC* is often mixed with different materials and has been studied extensively for biogas production in various processes (Gao et al., 2013; Lin et al., 2015; Hernández-Shek et al., 2016). The advantages of using *EC* to produce biogas are its high moisture content, soft organic matter, and good C/N ratio (20:1–30:1). The C/N ratio of *EC* is suitable for microbial decomposition, and the low content of lignin in *EC* is a beneficial characteristic for biogas production. Furthermore, biogas production from *EC* yields target products, which are clean biogas and the high-quality organic fertilizers of biogas residue and biogas slurry (Cheng et al., 2010). Research on biogas production from *EC* has mainly focused on the effects of various ratios of raw materials and the economic feasibility of the process. Different concentrations of methane can be obtained when using various weight ratios of cow dung, *EC*, and mud (Matsumura, 2002). For the economic feasibility, even under optimal process conditions, the cost of biogas production from *EC* is 1.86 times the cost of coal gas production (Matsumura, 2002), which represents a bottleneck for biogas utilization from *EC*. Further study is needed to increase the biogas yield and to reduce the costs involved in biogas production from *EC*.

3.5.2. Ethanol production

In addition to research on biogas production, the utilization of carbohydrates (cellulose and hemi-cellulose) from *EC* for bio-ethanol production has attracted significant attention (Guragain et al., 2011). Although bio-ethanol has not been commercialized on a large scale, it still has an optimistic future (Yan et al., 2010). As an aquatic plant, *EC* has certain advantages over many terrestrial plants as a raw material for sugar production. Previous studies (Guragain et al., 2011) have demonstrated that when wheat straw and *EC* were treated with ionic liquid EMIMDP, glycerin, or dilute sulfuric acid followed by enzymatic hydrolysis under identical conditions, the glucose and total reducing sugar yield from *EC* was 2–3 times higher than that from wheat straw (Guragain et al., 2011). The difference may be related to the composition of cellulose, hemi-cellulose, lignin, crude ash, etc., and the structural features of these components in *EC*, such as the low cellulose crystallinity index that was discussed in Section 3.4.1. These features allow more efficient pretreatment of *EC*, facilitating the subsequent enzymatic hydrolysis steps of bio-ethanol production.

Moreover, cellulose extracted from *EC* biomass has been compared with cellulose extracted from other aquatic and terrestrial plant materials, including water peanut (*Alternanthera philoxeroides*), miscanthus, sugarcane bagasse, and metasequoia chips, and their enzymatic hydrolysis performances under the same conditions have been evaluated. The results showed that cellulose extracted from *EC* and sugarcane bagasse displayed higher reducing sugar yields and faster hydrolysis rates than the other 3 types of cellulose due to their lower crystallinity index (CrI). Therefore, *EC* has a better potential as a feedstock for bio-ethanol production than many crops (Li et al., 2014b).

However, there are some difficulties regarding the use of *EC* as an energy plant in the production of second-generation ethanol. The main problems that must be addressed include the following.

- A suitable pretreatment method needs to be developed to change the structural and compositional properties of *EC* to improve the sugar yield in the subsequent hydrolysis step. The content of hemi-cellulose is approximately 40% in *EC* (Singh and Bishnoi, 2013), which is higher than in both hardwood (18–22%) and softwood (25–35%) (Han et al., 2013), whereas the cellulose content of *EC* (approximately 19%) (Singh and Bishnoi, 2013) is lower than in hardwood (45–50%) and softwood (35–40%). Therefore, to obtain a higher sugar yield from *EC*, hemi-cellulose should be retained during pretreatment. Previous studies have shown that when *EC* biomass was treated with sodium hydroxide, part of its hemi-cellulose was retained, and its lignin content was significantly decreased, which is conducive to enzymatic hydrolysis (Singh and Bishnoi, 2013). Sugar yields from *EC* pretreated with sodium hydroxide are higher than the yields from *EC* pretreated with dilute sulfuric acid.
- The suitable hydrolysis conditions, including cellulase concentrations, the substrate concentration, and reaction times, must be determined for efficient hydrolysis of *EC*'s lignocellulose into fermentable sugars. Ganguly et al. (2013a) investigated the relationship of sugar yield with the dosage of cellulase, the dosage of xylanase, and the substrate concentration of *EC* pretreated with sulfuric acid. The substrate concentration had the most significant effect on the sugar yield. Therefore, to obtain higher sugar yields, it is important to choose suitable substrate concentrations. It must also be noted that the structure of hemi-cellulose is so complicated that synergism of multiple enzymes is required for the effective enzymatic hydrolysis of hemi-cellulose. Consequently, to improve the sugar conversion from *EC*, the hemicellulase activity and its component, the ratio of cellulase to hemicellulase, need to be further investigated.
- The fermentation conditions for ethanol production require further investigation and optimization. One study showed that the reducing sugar produced by the hydrolysis of *EC* was fermented separately by *Pichia stipitis* and *Saccharomyces cerevisiae* to produce ethanol, and the ethanol yield was 4.13 g/L via *Pichia stipitis* fermentation, which is 34.53% higher than the yield

obtained via *Saccharomyces cerevisiae* fermentation (Ganguly et al., 2013b). Another report showed a similar result (Yan et al., 2015). The optimal conditions for the fermentation of *EC* biomass feedstock (yeast type, temperature, and time) should be further investigated.

The mode of enzymatic hydrolysis and fermentation is a critical issue for improving the concentration and yield of ethanol. Four different modes of enzymatic hydrolysis and fermentation have been investigated with *EC* biomass, including pre-fermentation hydrolysis-simultaneous saccharification and fermentation (PH-SSF), separate hydrolysis and fermentation (SHF), simultaneous saccharification and fermentation (SSF), and single batch bioconversion (SBB); the maximum concentration (8.3 g/L) and yield (0.21 g/g) of ethanol was obtained when the PH-SSF mode was used (Mukhopadhyay and Chatterjee, 2010).

3.5.3. Hydrogen production

Hydrogen is widely considered to be one of the most promising fuels primarily because it is clean, it has a high conversion rate for converting hydrogen into available energy, and it has a high mass energy density (Balat and Kirtay, 2010; Cheng and Liu, 2011; Lay et al., 2013).

Cellulose can be hydrolyzed by cellulase and β-glucosidase to produce reducing sugars that can be used for subsequent fermentation to produce hydrogen via hydrogen-producing bacteria. Moreover, proteins and amino acids can be first degraded to pyruvic acid via bacterial metabolism and then fermented into hydrogen. Many studies on different pretreatment methods of *EC* have been conducted, and the fermentation of pretreated *EC* biomass to produce hydrogen has also been investigated. Several methods of hydrogen production are shown in Table 2. The efficiency of hydrogen production via the combination of dark fermentation and photo-fermentation is significantly higher than from the traditional dark fermentation method. The maximum reducing sugar yield was achieved when *EC* was treated with microwave-assisted dilute H_2SO_4 and fermented by activated sludge and photosynthetic bacteria. The hydrogen yield was 5.7 times higher than from dark fermentation.

Except for traditional direct hydrogen production from *EC* via fermentation, Ruen-ngam and Jaruyanon (2014) prepared *EC* with water under the condition of supercritical water in a short time of less than 30 min and formed a considerable amount of hydrogen with few final waste products, which is more suitable for fast and large-scale industrial production. Moreover, ethanol, which is an energy carrier that is produced from *EC*, is also considered to be a precursor for hydrogen production (Trincado et al., 2014). If enough bio-ethanol can be obtained from *EC*, hydrogen storage and transport problems that impede the large scale utility of hydrogen (Yadav and Xu, 2012) can be solved and, consequently, can open up promising prospects for hydrogen utility.

3.5.4. Bio-oil production

EC is a potential plant for bio-oil and/or bio-char production due to its high carbohydrate content (cellulose and hemi-cellulose), lower content of lignin, and lower crystallinity index compared with terrestrial plants. These characteristics contribute to the biomass decomposition and an increase in bio-oil yields (Akhtar and Amin, 2011). Bio-oil and bio-char can be obtained from biomass via pyrolysis processes (Bergier et al., 2012). However, the presence of a high-moisture content in biomass has negative effects on pyrolysis; it requires high heat for vaporization. A solution to the high-moisture content of *EC* is the hydrothermal liquefaction process, a promising biomass to bio-oil conversion method. This method would enable the direct use of *EC* biomass for bio-oil production (Zhang et al., 2013).

Parameters that influence bio-oil production from *EC* biomass via hydrothermal liquefaction include temperature, particle size, solvent properties, solvent density, residence times, etc. Temperature has the most significant effect on the liquid oil yield and biomass conversion (Akhtar and Amin, 2011). One study has shown that the yield of total oil from hydrothermal liquefaction of *EC* increased with an increase of temperatures from 240 °C to 320 °C (Zhang et al., 2013). Furthermore, temperature is a parameter that influences the heating value of bio-oil that is produced from *EC*. Bio-oil obtained from *EC* exhibits higher heating values at 450 °C than at 500 °C (Promdee et al., 2012). To obtain high yields of high-quality bio-oil from *EC*, the optimal conditions, including the major parameters of bio-oil production, such as temperature, solvent properties, and solvent density, must be determined. Besides, alkaline catalyst additive clearly contributed to a higher biogas production (Singh et al., 2015). Thus, this additive also requires further research.

3.6. Recommendation for comprehensive utilization

At the end of the last century, studies on the exploitation and utilization of *EC* biomass were conducted around the world. Due

Table 2
Comparison of several methods of H_2 production from *EC* biomass.

Inoculums	Substrate (dry powder, g/l)	Treatment	Fermentation	H_2 yield (ml/g TVS)	References
Activated sludge	20	Alkali treatment	Dark fermentation	51.7	Cheng et al. (2010)
Pre-cultured activated sludge	20	Steam heating, microwave heating/ alkali treatment	Dark fermentation	76.7	Su et al. (2010)
Pre-cultured activated sludge + Rhodopseudomonas palustris	10	Steam heating, microwave heating/ alkali treatment	Dark fermentation and photofermentation	596.1	Su et al. (2010)
Pig slurry	10	–	Dark fermentation	33.8	Chuang et al. (2011)
Pre-cultured hydrogen producing bacteria	12	Microwave-assisted dilute H_2SO_4 treatment and	Dark fermentation	112.3	Cheng et al. (2012)
Pre-cultured hydrogen producing bacteria + Photofermentation bacteria	12	Microwave-assisted dilute H_2SO_4 treatment and	Dark fermentation and photofermentation	751.5[a]	Cheng et al. (2012)
Domesticated Hydrogen producing bacteria[b]	10	Microwave-assisted dilute H2SO4 treatment and AC detoxification	Dark fermentation	134.9	Cheng et al. (2015)
Pre-cultured hydrogen producing bacteria	10	Microwave-heated alkali pretreatment	Dark fermentation	63.9	Lin et al. (2015)
Hydrogen producing bacteria seed inoculum	–	Dilute H_2SO_4 treatment	Dark fermentation	127.6 mmol H_2/L	Pattra and Sittijunda (2015)

[a] This yield is 75.2% of the theoretical H_2 yield.

Table 3
Analysis of utilization technologies of *EC* biomass.

Utilizations	Main features and benefits	Shortcomings or problems to solve
Fodder and feedstuff	High protein content	High crude fiber content, poor palatability to animals, secondary pollution caused by residual biomass
Compost	High content of mineral nutrient elements (N, P, K, etc.) in dry weight bases and comprehensive trace nutrients	High moisture content (more than 92–94%) and low dry matter content, high labor intensity and cost for its salvage, compost turning allows the material to develop into a muddy state and the products into a rigid bulk state, apparent increase in compost pH, significant loss of nitrogen in the form of ammonia
Preparation of activated carbon	Compared with the activated carbon prepared from rice straw, activated carbon prepared from *EC* has a wider pore size distribution and stronger adsorption capacities for phenol, aniline, and other organic pollutants	Yield of the product is low
Extraction and recovery of potassium	K^+ in *EC* shoot organs can be extracted using hydrochloric acid, and the extraction solution can be adjusted to be alkaline to precipitate Ca^{2+} and Mg^{2+}. K^+ in the supernatant can be converted into potassium hydrogen tartrate precipitate using tartrate, which can be used as a raw material for the food and pharmaceutical industries (Zhou et al., 2007)	The economic benefit of this use is fairly low. A combination of this use with other use patterns to improve the comprehensive utilization benefits is needed
Preparation of adsorbent for heavy metals	The preparation of the adsorbent is simple, and the product has a better adsorption performance compared with adsorbents prepared from other plant materials using the same preparation procedure (Tan et al., 2008; Zhou et al., 2011, 2009)	To improve the usability, the adsorption stability of the adsorbent and the convenience of its use requires further improvement
Biogas production	It is easy to use in the production of biogas containing high purity methane due to the high moisture content, soft organic matter, and the good C/N ratio of *EC* biomass. Biogas residue and biogas slurry are both organic fertilizers of high quality	The economic benefit is not considered adequate due to the high cost of the biogas production process (Matsumura, 2002). To improve the economic benefit, further research on the composition of the raw materials required for hydrogen production should be considered
Enzymatic hydrolysis to produce sugar and fermentation to produce ethanol	Compared with terrestrial plant straws, EC biomass is easier to hydrolyze, and higher sugar conversion rates can be obtained using lower enzyme concentrations (Singh and Bishnoi, 2013)	Appropriate pretreatments need to be selected to remove the ash components in the biomass and to separate the cellulose, lignin, and hemi-cellulose from the biomass to promote enzyme activity and improve the accessibility of enzymes to the cellulose matrix. Further economic evaluation needs to be conducted, particularly considering that it will require much labor to harvest the *EC* biomass

to its high content of crude fiber, its palatability for animals is poor. Therefore, the direct utilization of *EC* as an animal feed is limited. However, although *EC* is a good compost material, its high moisture content, high labor intensity required for harvest, and high cost of salvage are major obstacles. As for *EC*-derived absorbents, several types of highly effective materials have been successfully synthesized and applied, whereas a full configuration that comprises a cycling device requires further improvement. Similar to other feedstock-derived bioenergies, *EC* bioenergy has its challenges in the market, primarily because of its expensive cost. However, the low crystallinity of *EC* cellulose makes *EC* advantageous over other feedstocks for easier bio-refinery. To summarize, the main features/advantages and drawbacks/problems to be solved for various *EC* utilization methods are provided in Table 3.

As more studies have been conducted on *EC*, the number of potential utilization pathways has increased. Nevertheless, the economic benefits of the utilization technologies for *EC* that are detailed in this review are limited. It is critically important to accelerate the development of a comprehensive and feasible utilization of *EC* biomass.

Through comprehensive evaluation of the benefits and drawbacks of the various utilization technologies, and from the point of view of making full use of *EC* biomass based on its physical and chemical properties, the authors recommend that the application of *EC* in water pollution control and the subsequent comprehensive utilization of *EC*'s biomass can be performed as follows. *EC* can be cultured in eutrophic water/wastewater with mesocosm, and the harvested *EC* biomass can be split into shoot and root components. The potassium, which is of a high content in the shoots, can be recovered using chemical methods to produce appropriate potassium products. The potassium recovery process can also be used as a pretreatment of *EC* shoot material for subsequent sugar production (the efficiency of the subsequent sugar production can be increased significantly via this pretreatment). The residue of the *EC* shoots, following the potassium extraction, can be used for the subsequent sugar production with cellulase, followed by fermentation with yeast to produce bio-ethanol or with

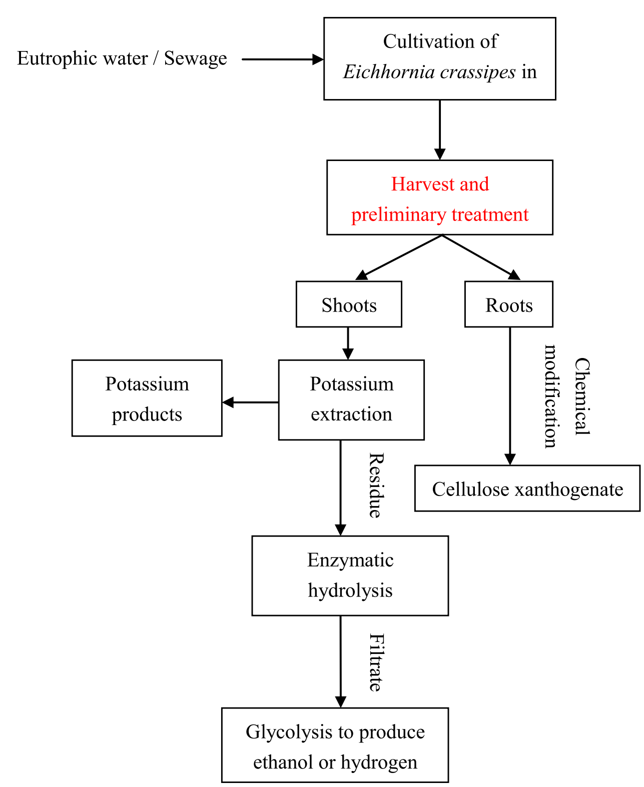

Fig. 1. Recommendation for pollution control and the comprehensive utilization of *Eichhornia crassipes* biomass.

hydrogen-producing bacteria to produce hydrogen. *EC* roots have little value as a raw material for potassium extraction due to their low potassium content, but the cellulose in roots can be directly converted into cellulose xanthogenate, which is a heavy metal adsorbent, via chemical modification. The recommendation for the comprehensive utilization of *EC* is shown in Fig. 1.

4. Conclusion

EC is effective for nutritious element removal due to its fulminant breeding. Its high potassium content in the shoot portion of the plant can be used for potassium extraction, and its naturally low crystalline cellulose content makes it an excellent feedstock for derived material and relatively highly efficient for bioenergy transformation. These characteristics are advantages of *EC*. Nevertheless, its high water content leads to low energy density in bioenergy products or a high cost for dewatering treatment before other utilization technologies can be applied. Therefore, a highly effective and low-cost anhydration technology is the key for *EC*'s large scale utilization.

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References

Abdel-Halim, E.S., Al-Deyab, S.S., 2011. Utilization of hydroxypropyl cellulose for green and efficient synthesis of silver nanoparticles. Carbohydr. Polym. 86 (4), 1615–1622.
Adeoye, G.O., Sridhar, M.K.C., Ipinmoroti, R.R., 2001. Potassium recovery from farm wastes for crop growth. Commun. Soil Sci. Plan. 32, 2347–2358.
Agunbiade, F.O., Olu-Owolabi, B.I., Adebowale, K.O., 2009. Phytoremediation potential of Eichornia crassipes in metal-contaminated coastal water. Bioresour. Technol. 100, 4521–4526.
Ahluwalia, S.S., Goyal, D., 2007. Microbial and plant derived biomass for removal of heavy metals from wastewater. Bioresour. Technol. 98, 2243–2257.
Ajayi, T.O., Ogunbayio, A.O., 2012. Achieving environmental sustainability in wastewater treatment by phytoremediation with water hyacinth (Eichhornia Crassipes). J. Sustainable Dev. 5 (7), 80–90.
Akhtar, J., Amin, N.A.S., 2011. A review on process conditions for optimum bio-oil yield in hydrothermal liquefaction of biomass. Renewable Sustainable Energy Rev. 15, 1615–1624.
Albano Pérez, E., Ruiz Tellez, T., Ramos Maqueda, S., Casero Linares, P.J., Vazquez Pardo, F.M., Rodriguez Medina, P.L., Labrador Moreno, J., Lopez Gallego, F., Gonzalez Cortes, J., Sanchez Guzman, J.M., 2015. Seed germination and risks of using the invasive plant Eichhornia crassipes (Mart.) Solms-Laub. (water hyacinth) for composting, ovine feeding and biogas production. Acta Bot. Gallica 162, 203–214.
Ali, H., Khan, E., Sajad, M.A., 2013. Phytoremediation of heavy metals—Concepts and applications. Chemosphere 91, 869–881.
Ammar, N.S., Elhaes, H., Ibrahim, H.S., El hotaby, W., Ibrahim, M.A., 2014. A novel structure for removal of pollutants from wastewater. Spectrochim. Acta, Part A 121, 216–223.
Asadullah, M., 2014. Barriers of commercial power generation using biomass gasification gas: A review. Renew. Sust. Energy Rev. 29, 201–215.
Aswathy, U.S., Sukumaran, R.K., Devi, G.L., Rajasree, K.P., Singhania, R.R., Pandey, A., 2010. Bio-ethanol from water hyacinth biomass: An evaluation of enzymatic saccharification strategy. Bioresour. Technol. 101, 925–930.
Bai, F., Chisholm, R., Sang, W., Dong, M., 2013. Spatial risk assessment of alien invasive plants in China. Environ. Sci. Technol. 47, 7624–7632.
Balasubramanian, D., Arunachalam, K., Arunachalam, A., Das, A.K., 2013. Water hyacinth [Eichhornia crassipes (Mart.) Solms.] engineered soil nutrient availability in a low-land rain-fed rice farming system of north-east India. Ecol. Eng. 58, 3–12.
Balat, H., Kırtay, E., 2010. Hydrogen from biomass – Present scenario and future prospects. Int. J. Hydrogen Energy 35, 7416–7426.
Bankar, A., Joshi, B., Kumar, A.R., Zinjarde, S., 2010. Banana peel extract mediated novel route for the synthesis of silver nanoparticles. Colloids Surf. A 368 (1–3), 58–63.
Barrett, S.C.H., 1980. Sexual reproduction in Eichhornia crassipes (water hyacinth). II. Seed production in natural populations. J. Appl. Ecol. 17 (1), 113–124.
Bergier, I., Salis, S.M., Miranda, C.H.B., Ortega, E., Luengo, C.A., 2012. Biofuel production from water hyacinth in the Pantanal wetland. Ecohydrol. Hydrobiol. 12, 77–84.
Bi, S.Z., Peng, L.C., Chen, K.L., Zhu, Z.L., 2016. Enhanced enzymatic saccharification of sugarcane bagasse pretreated by combining O_2 and NaOH. Bioresour. Technol. 214, 692–699.
Chen, X.X., Jiang, Z.H., Chen, X., Lei, J.G., Weng, B.Q., Huang, Q., 2010. Use of biogas fluid-soaked water hyacinth for cultivating Pleurotus geesteranus. Bioresour. Technol. 101, 2397–2400.
Chen, J., Liu, Y.S., Ying, H.C., Feng, L., Liu, S.S., He, L.Y., Chen, Z.F., Yang, Y.Q., Chen, F. R., 2015. Removal of antibiotics and antibiotic resistance genes in rural wastewater by an integrated constructed wetland. Environ. Sci. Pollut. Res. 22, 1794–1803.
Cheng, X.Y., Liu, C.Z., 2011. Hydrogen production via thermophilic fermentation of cornstalk by clostridium. Energy Fuels 25, 1714–1720.
Cheng, J., Xie, B.F., Zhou, J.H., Song, W.L., Cen, K.F., 2010. Cogeneration of H_2 and CH_4 from water hyacinth by two-step anaerobic fermentation. Int. J. Hydrogen Energy 35, 3029–3035.
Cheng, J., Xia, A., Liu, Y.Q., Lin, R., Zhou, J.H., Cen, K.F., 2012. Combination of dark- and photo-fermentation to improve hydrogen production from Arthrospira platensis wet biomass with ammonium removal by zeolite. Int. J. Hydrogen Energy 37, 13330–13337.
Cheng, J., Lin, R., Song, W.L., Xia, A., Zhou, J.H., Cen, K.F., 2015. Enhancement of fermentative hydrogen production from hydrolyzed water hyacinth with activated carbon detoxification and bacteria domestication. Int. J. Hydrogen Energy 40, 2545–2551.
Chuang, Y.S., Lay, C.H., Sen, B., Chen, C.C., Gopalakrishnan, K., Wu, J.H., Lin, C.S., Lin, C.Y., 2011. Biohydrogen and biomethane from water hyacinth (Eichhornia crassipes) fermentation: Effects of substrate concentration and incubation temperature. Int. J. Hydrogen Energy 36, 14195–14203.
Dalai, A.K., Bassi, A., 2010. Bioenergy and green engineering. Energy Fuels 24, 4627.
Deng, L., Geng, M.J., Zhu, D.W., Zhou, W.B., Alan, L., Yun, Y., Zhu, Z.X., Wang, Y.Y., 2012. Effect of chemical and biological degumming on the adsorption of heavy metal by cellulose xanthogenates prepared from Eichhornia crassipes. Bioresour. Technol. 107, 41–45.
Dhir, B., 2013. Aquatic plant species and removal of contaminants. In: Phytoremediation: Role of Aquatic Plants in Environmental Clean-up. Springer India, India, pp. 21–50.
Elfeky, S.A., Imam, H., Alsherbini, A.A., 2013. Bio-absorption of Ni and Cd on Eichhornia crassipes root thin film. Environ. Sci. Pollut. Res. 20, 8220–8226.
Farid, M., Irshad, M., Fawad, M., Awan, Z.A., Eneji, A.E., Aurangzeb, N., 2014. Effect of cyclic phytoremediation with different wetland plants on municipal wastewater. Int. J. Phytorem. 16, 572–581.
Fazal, S., Zhang, B., Mehmood, Q., 2015. Biological treatment of combined industrial wastewater. Ecol. Eng. 84, 551–558.
Fiksel, J., Graedel, T., Hecht, A.D., Rejeski, D., Sayler, G.S., Senge, P.M., Swackhamer, D.L., Theis, T.L., 2009. EPA at 40: Bringing environmental protection into the 21st century. Environ. Sci. Technol. 43, 8716–8720.
Fontmorin, J.M., Sillanpää, M., 2015. Bioleaching and combined bioleaching/Fenton-like processes for the treatment of urban anaerobically digested sludge: Removal of heavy metals and improvement of the sludge dewaterability. Sep. Purif. Technol. 156 (2), 655–664.
Fujita, S., Sakairi, N., 2016. Water soluble EDTA-linked chitosan as a zwitterionic flocculant for pH sensitive removal of Cu(ii) ion. RSC Adv. 6, 10385–10392.
Gajalakshmi, S., Ramasamy, E.V., Abbasi, S.A., 2002. High-rate composting–vermicomposting of water hyacinth (Eichhornia crassipes, Mart. Solms). Bioresour. Technol. 83, 235–239.
Ganguly, A., Das, S., Bhattacharya, A., Dey, A., Chatterjee, P.K., 2013a. Enzymatic hydrolysis of water hyacinth biomass for the production of ethanol: optimization of driving parameters. Indian. J. Exp. Biol. 51, 556–566.
Ganguly, A., Halder, S., Laha, A., Saha, N., Chatterjee, P.K., Dey, A., 2013b. Effect of alkali preteatment on water hyacinth biomass for production of ethanol. Adv. Chem. Eng. Res. 2, 40–44.
Gao, J., Chen, L., Yan, Z.C., Wang, L., 2013. Effect of ionic liquid pretreatment on the composition, structure and biogas production of water hyacinth (Eichhornia crassipes). Bioresour. Technol. 132, 361–364.
Gonzalez, M.A., Trocoli, R., Pavlovic, I., Barriga, C., La Mantia, F., 2016. Capturing Cd (ii) and Pb(ii) from contaminated water sources by electro-deposition on hydrotalcite-like compounds. Phys. Chem. Chem. Phys. 18, 1838–1845.

Gunnarsson, C.C., Petersen, C.M., 2007. Water hyacinths as a resource in agriculture and energy production: A literature review. Waste Manage. 27, 117–129.
Guragain, Y.N., De Coninck, J., Husson, F., Durand, A., Rakshit, S.K., 2011. Comparison of some new pretreatment methods for second generation bioethanol production from wheat straw and water hyacinth. Bioresour. Technol. 102, 4416–4424.
Gutiérrez-Gutiérrez, S.C., Coulon, F., Jiang, Y., 2015. Wagland, S. Rare earth elements and critical metal content of extracted landfilled material and potential recovery opportunities. Waste Manage. 42, 128–136.
Han, J., Elgowainy, A., Cai, H., Wang, M.Q., 2013. Life-cycle analysis of bio-based aviation fuels. Bioresour. Technol. 150, 447–456.
He, Y., Chi, J., 2015. Phytoremediation of sediments polluted with phenanthrene and pyrene by four submerged aquatic plants. J. Soils Sediments 16, 309–317.
Hebbar, R.S., Isloor, A.M., Ananda, K., Ismail, A.F., 2016. Fabrication of polydopamine functionalized halloysite nanotube/polyetherimide membranes for heavy metal removal. J. Mater. Chem. 4, 764–774.
Hernández-Shek, M.A., Cadavid-Rodríguez, L.S., Bolaños, I.V., Agudelo-Henao, A.C., 2016. Recovering biomethane and nutrients from anaerobic digestion of water hyacinth (Eichhornia crassipes) and its co-digestion with fruit and vegetable waste. Water Sci. Technol. 73, 355–361.
Ibrahim, H.S., Ammar, N.S., Soylak, M., Ibrahim, M., 2012. Removal of Cd(II) and Pb (II) from aqueous solution using dried water hyacinth as a biosorbent. Spectrochim. Acta Part A 96, 413–420.
Jafari, N., 2010. Ecological and socio-economic utilization of water hyacinth (Eichhornia crassipes Mart Solms). J. Appl. Sci. Environ. Manage. 14, 43–49.
Khaket, T.P., Singh, M., Dhanda, S., Singh, T., Singh, J., 2012. Biochemical characterization of consortium compost of toxic weeds Parthenium hysterophorus, and Eichhornia crassipe. Bioresour. Technol. 123, 360–365.
Krishnakumar, T., Pinna, N., Kumari, K.P., Perumal, K., Jayaprakash, R., 2008. Microwave-assisted synthesis and characterization of tin oxide nanoparticles. Mater. Lett. 62 (19), 3437–3440.
Lay, C.H., Sen, B., Chen, C.C., Wu, J.H., Lee, S.C., Lin, C.Y., 2013. Co-fermentation of water hyacinth and beverage wastewater in powder and pellet form for hydrogen production. Bioresour. Technol. 135, 610–615.
Li, X.S., Liu, S.L., Na, Z.Y., Lu, D.N., Liu, Z., 2013. Adsorption, concentration, and recovery of aqueous heavy metal ions with the root powder of Eichhornia crassipes. Ecol. Eng. 60, 160–166.
Li, K., Pidatala, V.R., Shaik, R., Datta, R., Ramakrishna, W., 2014a. Integrated metabolomic and proteomic approaches dissect the effect of metal-resistant bacteria on maize biomass and copper uptake. Environ. Sci. Technol. 48, 1184–1193.
Li, L., Zhou, W.B., Wu, H.W., Yu, Y., Liu, F., Zhu, D.W., 2014b. Relationship between crystallinity index and enzymatic hydrolysis performance of celluloses separated from aquatic and terrestrial plant materials. BioResources 9, 3993–4005.
Li, Q., Zhan, J., Chen, B., Meng, X.Q., Pan, X.J., 2016. Removal of Pb, Zn, Cu, and Cd by Two Types of Eichhornia crassipes. Environ. Eng. Sci. 33, 88–97.
Liang, D.T., Yan, R., Lee, D.H., 2008. Introduction to the special section of energy & fuels, bioenergy outlook 2007, Singapore. Energy Fuels 22. 1-1.
Lin, Y., Li, B., 2016. Removal of pharmaceuticals and personal care products by Eichhornia crassipe, and Pistia stratiotes. J. Taiwan Inst. Chem. Eng. 58, 318–323.
Lin, L., Liu, S.J., 2014. Special section for the 4th International conference on biorefinery–toward bioenergy. Energy Fuels 28. 4241-4241.
Lin, S., Wang, G.X., Na, Z.Y., Lu, D.N., Liu, Z., 2012. Long-root Eichhornia crassipes as a biodegradable adsorbent for aqueous As(III) and As(V). Chem. Eng. J. 183, 365–371.
Lin, R., Cheng, J., Song, W.L., Ding, L.K., Xie, B.F., Zhou, J.H., Cen, K.F., 2015. Characterisation of water hyacinth with microwave-heated alkali pretreatment for enhanced enzymatic digestibility and hydrogen/methane fermentation. Bioresour. Technol. 182, 1–7.
Matsumura, Y., 2002. Evaluation of supercritical water gasification and biomethanation for wet biomass utilization in Japan. Energ. Convers. Manage. 43, 1301–1310.
Mochochoko, T., Oluwafemi, O.S., Jumbam, D.N., Songca, S.P., 2013. Green synthesis of silver nanoparticles using cellulose extracted from an aquatic weed: water hyacinth. Carbohydr. Polym. 98 (1), 290–294.
Mukhopadhyay, S., Chatterjee, N.C., 2010. Bioconversion of water hyacinth hydrolysate into ethanol. BioResources 5, 1301–1310.
Nesterenko-Malkovskaya, A., Kirzhner, F., Zimmels, Y., Armon, R., 2012. Eichhornia crassipes capability to remove naphthalene from wastewater in the absence of bacteria. Chemosphere 87, 1186–1191.
Park, J., Bazylewski, P., Fanchini, G., 2016. Porous graphene-based membranes for water purification from metal ions at low differential pressures. Nanoscale 8, 9563–9571.
Pattra, S., Sittijunda, S., 2015. Optimization of factors affecting acid hydrolysis of water hyacinth stem (Eichhornia Crassipes) for bio-hydrogen production. Energy Proc. 79, 833–837.
Promdee, K., Vitidsant, T., Vanpetch, S., 2012. Comparative study of some physical and chemical properties of bio-oil from Manila grass and water hyacinth transformed by pyrolysis process. Int. J. Chem. Eng. Appl. 3, 72–75.
Radhika, D., Murugesan, A.G., 2012. Bioproduction, statistical optimization and characterization of microbial plastic (poly 3-hydroxy butyrate) employing various hydrolysates of water hyacinth (Eichhornia crassipes) as sole carbon source. Bioresour. Technol. 121, 83–92.
Ramteke, L.P., Gogate, P.R., 2016. Treatment of water containing heavy metals using a novel approach of immobilized modified sludge biomass based adsorbents. Sep. Purif. Technol. 163, 215–227.
Ruen-Ngam, D., Jaruyanon, P., 2014. Hydrogen production from water hyacinth under hydrothermal treatment: experimental section. In: The International Conference on Science, Technology and Innovation for Sustainable Well-Being.
Saraswat, S., Rai, J.P.N., 2010. Heavy metal adsorption from aqueous solution using Eichhornia crassipes dead biomass. Int. J. Mineral Process 94, 203–206.
Satyanagalakshmi, K., Sindhu, R., Binod, P., Kanakambaran, U., Janu, R.K., Sukumaran, A.P., 2011. Bioethanol production from acid pretreated water hyacinth by separate hydrolysis and fermentation. J. Sci. Ind. Rev. 70, 156–161.
Schultze-Nobre, L., Wiessner, A., Wang, D.D., Bartsch, C., Kappelmeyer, U., Paschke, H., Mattusch, J., Kuschk, P., 2015. Removal of dimethylphenols from an artificial wastewater in a laboratory-scale wetland system planted with Juncus effusus. Ecol. Eng. 80, 151–155.
Singh, A., Bishnoi, N.R., 2013. Comparative study of various pretreatment techniques for ethanol production from water hyacinth. Ind. Crop. Prod. 44, 283–289.
Singh, R., Balagurumurthy, B., Prakash, A., Bhaskar, T., 2015. Catalytic hydrothermal liquefaction of water hyacinth. Bioresour. Technol. 178, 157–165.
Su, H.B., Cheng, J., Zhou, J.H., Song, W.L., Cen, K.F., 2010. Hydrogen production from water hyacinth through dark- and photo- fermentation. Int. J. Hydrogen Energy 35, 8929–8937.
Sun, L., Zhu, Z.S., 2014. A decision model for harvesting Eichhornia crassipes once a week. Adv. Mater. Res. 889–890, 1660–1663.
Supri, A.G., Tan, S.J., Ismail, H., Teh, P.L., 2013. Enhancing interfacial adhesion performance by using poly(vinyl alcohol) in (low-density polyethylene)/(natural rubber)/(water hyacinth fiber) composites. J. Vinyl Add. Technol. 19 (1), 47–54.
Tan, L.F., Zhu, D.W., Zhou, W.B., Mi, W.J., Ma, L.X., He, W.T., 2008. Preferring cellulose of Eichhornia crassipes to prepare xanthogenate to other plant materials and its adsorption properties on copper. Bioresour. Technol. 99, 4460–4466.
Trincado, M., Banerjee, D., Grutzmacher, H., 2014. Molecular catalysts for hydrogen production from alcohols. Energy. Environ. Sci. 7, 2464–2503.
Vanathi, P., Rajiv, P., Narendhran, S., Rajeshwari, S., Rahman, P.K.S.M., Venckatesh, R., 2014. Biosynthesis and characterization of phyto mediated zinc oxide nanoparticles: a green chemistry approach. Mater. Lett. 134, 13–15.
Wang, F., Lu, X., Li, X.Y., 2016a. Selective removals of heavy metals (Pb^{2+}, Cu^{2+}, and Cd^{2+}) from wastewater by gelation with alginate for effective metal recovery. J. Hazard. Mater. 308, 75–83.
Wang, J., Zhang, W.T., Yue, X.Y., Yang, Q.F., Liu, F.B., Wang, Y.R., Zhang, D.H., Wang, J. L., 2016b. One-pot synthesis of multifunctional magnetic ferrite-MoS_2-carbon dot nanohybrid adsorbent for efficient Pb(ii) removal. J. Mater. Chem. 4, 3893–3900.
White, S.A., Cousins, M.M., 2013. Floating treatment wetland aided remediation of nitrogen and phosphorus from simulated stormwater runoff. Ecol. Eng. 61, 207–215.
Xu, G., Xie, Y.J., Cao, J., Tao, M.L., Zhang, W.Q., 2016a. Highly selective and efficient chelating fiber functionalized by bis(2-pyridylmethyl)amino group for heavy metal ions. Polymer Chem. 7, 3874–3883.
Xu, X., Su, X., Bai, B., Wang, B., Wang, H.L., Suo, Y.R., 2016b. Controlled pesticide release of a novel superabsorbent by grafting citric acid onto water hyacinth powders with the assistance of dopamine. RSC Adv. 6 (36), 29880–29888.
Yadav, M., Xu, Q., 2012. Liquid-phase chemical hydrogen storage materials. Energy Environ. Sci. 5, 9698–9725.
Yan, X., Inderwildi, O.R., King, D.A., 2010. Biofuels and synthetic fuels in the US and China: A review of Well-to-Wheel energy use and greenhouse gas emissions with the impact of land-use change. Energy Environ. Sci. 3, 190–197.
Yan, J.P., Wei, Z.L., Wang, Q.P., He, M.M., Li, S.M., Irbis, C., 2015. Bioethanol production from sodium hydroxide/hydrogen peroxide-pretreated water hyacinth via simultaneous saccharification and fermentation with a newly isolated thermotolerant Kluyveromyces marxianu strain. Bioresour. Technol. 193, 103–109.
Yi, Z.J., Yao, J., Chen, H.L., Wang, F., Yuan, Z.M., Liu, X., 2016. Uranium biosorption from aqueous solution onto Eichhornia crassipes. J. Environ. Radioact. 154, 43–51.
Zhang, L., Li, C.J., Zhou, D., Zhang, S.C., Chen, J.M., 2013. Hydrothermal liquefaction of water hyacinth: product distribution and identification. Energy Sources A Recovery Utilization Environ. Effects 35, 1349–1357.
Zhang, Z.Y., Wang, Z., Zhang, Z.H., Zhang, J.Q., Guo, J.Y., Li, E.H., Wang, X.L., Liu, H.Q., Yan, S.H., 2016. Effects of engineered application of Eichhornia crassipes on the benthic macroinvertebrate diversity in Lake Dianchi, an ultra-eutrophic lake in China. Environ. Sci. Pollut. Res. 619, 387–388.
Zhou, W.B., Zhu, D.W., Tan, L.F., Liao, S.J., Hu, Z.H., Hamilton, D., 2007. Extraction and retrieval of potassium from water hyacinth (Eichhornia crassipes). Bioresour. Technol. 98, 226–231.
Zhou, W.B., Zhu, D.W., Langdon, A., Li, L., Liao, S.J., Tan, L.F., 2009. The structure characterization of cellulose xanthogenate derived from the straw of Eichhornia crassipes. Bioresour. Technol. 100, 5366–5369.
Zhou, W.B., Ge, X., Zhu, D.W., Langdon, A., Deng, L., Hua, Y.M., Zhao, J.W., 2011. Metal adsorption by quasi cellulose xanthogenates derived from aquatic and terrestrial plant materials. Bioresour. Technol. 102, 3629–3631.