

Review

The Resource Utilization of Water Hyacinth (*Eichhornia crassipes* [Mart.] Solms) and Its Challenges

Weiping Su ¹, Qingping Sun ², Meisheng Xia ³, Zhengshun Wen ⁴ and Zhitong Yao ^{1,*}

¹ College of Materials Science and Environmental Engineering, Hangzhou Dianzi University, Hangzhou 310018, China; swp201309@163.com

² Yangzhou Sinomicro Biotech Ltd., Yangzhou 225107, China; sqp@163.com

³ Ocean College, Zhejiang University, Zhoushan 316021, China; msxia@zju.edu.cn

⁴ School of Food Science and Pharmaceutics, Zhejiang Ocean University, Zhoushan 316022, China; zswenmr@163.com

* Correspondence: sxyzt@126.com

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Abstract: The unchecked growth of *Eichhornia crassipes* can cause significant harm, including covering of the water surface, depletion of oxygen, clogging of river channels, and promotion of the breeding of flies and mosquitoes. These effects can significantly impact farmland irrigation, water transportation, and human health. However, methods for controlling its growth are not ideal, and control using biological and chemical agents can result in secondary pollution. The utilization of *E. crassipes* as a resource, for example, as animal feed or organic substrates, can not only turn waste into valuable resources, but it can also solve the problem of its growth, thus bringing about economic and ecological benefits. In this paper, the growth and ecological characteristics of *E. crassipes*, its nutrient composition, and resource utilization approaches were reviewed. The challenges associated with the large-scale utilization of *E. crassipes* were also analyzed in order to provide references for the control and resource utilization of the species. Regarding challenges such as the difficulty of cultivation and the high cost of harvesting and dehydrating, it is necessary to investigate the proper water surface and coverage characteristics of *E. crassipes* cultivation to assure adequate biomass and protect the ecological landscape. It is also necessary to evaluate the effect of *E. crassipes* cultivation on the health of aquatic ecosystems and the safety of the water environment in order to prevent the significant potential ecological and environmental risks. In addition, developing portable, high-efficiency facilities to promote the effectiveness of harvesting, transportation and dehydration are needed, as well as further improvement in the techniques of utilization and assessment of the economic value.

Keywords: water hyacinth; anaerobic fermentation; compost; biogas; biomass

1. Introduction

Eichhornia crassipes (Mart.) Solms, also known as water hyacinth, is native to the Amazon Basin in South America [1] and it was introduced into China in the 1930s. In the 1950s and 1960s, it was promoted as a livestock feed, especially for pigs. However, due to the popularization of formulated feeds, the utilization rate was reduced, and it has gradually become wild, especially in urban rivers and eutrophic waters in inner lakes. The growth of the plant has been very aggressive. It has not only invaded water bodies, causing anoxia in the water, but it also obstructs rivers and provides a favorable breeding ground for mosquitoes, which seriously endangers farmland irrigation and drainage, water transportation, and human health [2–4]. For the control of water hyacinth, biological and chemical agents, and mechanical control are used in China and abroad. However, biological control takes

effect slowly, and chemical control is costly and mostly used in the case of severe infiltration of water hyacinth. Mechanical control is seen as the best short-term solution to the proliferation of this plant, although it is also costly and requires the use of both land and water vehicles. Therefore, water hyacinth control should be combined with its utilization as a resource. This could not only “turn waste into treasure” and solve the water hyacinth breeding problem, but it could also produce economic and ecological benefits. In this work, the growth and ecological characteristics of *E. crassipes*, its nutrient composition and resource utilization approaches were reviewed. The challenges associated with the large-scale utilization of water hyacinth were also analyzed in order to provide references for the control and resource utilization of the species.

To use water hyacinth as a resource and design the scale of treatment, first, one must understand the ecological characteristics of this plant and estimate the growth of its biomass. Second, one must also address issues such as harvesting, transportation, and post-harvest treatment of water hyacinth.

2. Ecological Characteristics

Water hyacinth reproduces vegetatively through the formation of stolons, and is also sexually propagated through seeds, which can survive in water for six years making water hyacinth difficult to control. Under suitable growth conditions, the number of water hyacinths can double in one week [5]. A water hyacinth plant can produce 140 million ramets within one year, with a fresh weight of 28,000 tons [6]. Water hyacinths are prevalent in eutrophic water bodies and can form dense grass mats covering large areas of water. Akinwande et al. [7] studied the water hyacinth biomass in Nigerian waters, which ranged from 28.8 to 33.2 t dry matter/(ha·year). The water hyacinth has a well-developed root system and can absorb nutrients in the growing environment. Therefore, its material composition is closely related to the growth environment. Poddar et al. [8] reported that water hyacinths growing in swamp areas with a nitrogen content of 2.40 mg/L had a nitrogen content of approximately 1.78%. The nutrient content in stems and roots is generally lower than in the leaf [9]. The general composition of water hyacinth nutrients is shown in Table 1.

Table 1. Nutrient composition of water hyacinth.

Parameters (% Dry Matter Basis)	[7]	[9]	[1]	[10]	[11,12]	[8]	[13]	[12,14]	
								Wet Basis	Dry Basis
Dry matter	9.84	9.5	6.2	9.4	-	-	-	-	-
Organic matter	-	74.3	-	83.65	-	83.61	-	-	-
Crude protein	10.01	20	-	-	11.9	16.25	-	-	-
Crude fat	-	3.47	-	-	-	1.61	-	-	-
Crude fiber	22.75	18.9	-	-	-	16.34	-	-	-
Nitrogen-free extracts	-	31.9	-	-	-	49.41	-	-	-
Ash	14.98	25.7	15	-	20.2	16.39	-	35.6	52.07
C/N ratio	-	-	-	-	-	-	15.8	23.5	25.1
Neutral detergent fiber	44.5	62.3	-	-	-	56.14	-	-	-
Acid washing fiber	28.0	29.0	-	-	-	37.72	-	-	-
Hemicellulose	-	33.4	22	33.97	43.4	18.42	-	-	-
Cellulose	-	19.5	31	18	17.8	25.61	-	-	-
Lignin	-	9.27	7	26.36	7.8	9.93	-	-	-
Water solubles	-	-	-	21.68	-	-	-	-	-
P	0.28	0.53	-	-	-	0.53	0.5	0.26	0.32
C	-	-	-	-	-	-	-	27.6	18.54
N	-	-	-	-	-	2.76	2.9	1.18	0.74
Mg	0.65	0.17	-	-	-	-	-	-	-
Ca	3.08	0.58	-	-	-	2.29	-	-	-
K	4.13	-	-	-	-	2.44	-	4.53	2.27
Ruminant Metabolism Energy (MJ/kg)	-	6.35	-	-	-	-	-	-	-

3. Harvesting

Harvesting of water hyacinth can be conducted manually or mechanically. In the Philippines, water hyacinths in open waters are often salvaged with hand winches. When water hyacinth is near the shore, one person can harvest approximately 200 kg of water hyacinth per hour. A set of harvesting equipment was imported into Shanghai city from the United States in 2001 and can harvest 70–80 t of water hyacinth per hour. The water hyacinth transport method mainly depends on the treatment method and the processing scale. The higher the water content of water hyacinth, the greater amount that needs to be transported. Therefore, the resource processing location is best located near the place where water hyacinth is harvested.

4. Water Hyacinths Used as Feed

Fresh water hyacinth contains approximately 2.38% crude protein, 0.27% crude fat, 0.91% crude fiber, and 3.7% nitrogen-free extract [15]. However, water hyacinth dry matter is rich in nutrients, with crude protein of 10–20% (see Table 1), and thus it can replace part of the protein feed and roughage. Biswas et al. [16] showed that the crude protein content of water hyacinth and leaves was 15.58% and 19.97%, respectively, the crude fat content was 1.33% and 1.85%, the crude fiber content was 13.74% and 11.04%, and the ash content was 16.04% and 14.97% after the water hyacinth was dried, chopped and dried again. Abdelhamid et al. [9] reported that the crude protein content of water hyacinth (dry basis) was 20%, which makes it good animal forage. In terms of output per unit area, the protein produced by water hyacinth is 6–10 times higher than that of soybeans. Cheng et al. [17] mixed 20% wheat bran with water hyacinth slag for silage and added silage fermentation bacteria. The mixed silage had excellent organoleptic qualities.

4.1. Post-Harvest Treatment

Bolenz et al. [1] conducted microscopic examination of water hyacinth and found that it contained needle-shaped crystals of calcium oxalate, which may cause damage to the digestive tract. Therefore, water hyacinth should be crushed before feeding. During the silaging of water hyacinth, sorbic acid can be added to prevent mildew. At the same time, sugars are added to adjust pH to less than 4. The moisture content of water hyacinth is as high as 90%, so it is difficult to directly transport without drying and to store water hyacinth. In the process of actual utilization, a drying process is needed. It can be dried naturally by the sun, such as drying on the ground, and no mold contamination was found after natural drying of water hyacinth [5]. Polprasert et al. [13] reported that water hyacinth can be halved after being naturally dried for several days. Ye et al. [18] produced dried powders from fresh aquatic plants such as water hyacinths by chopping, blanching, killing green, using permeating dehydration, and pulping. The powders maintained the original flavor, color and nutritional quality.

4.2. Feeding Effect

Tag El-Din [5] studied the effect of feeding water hyacinth instead of legume straw to sheep. When water hyacinth was used as a single roughage, the sheep's daily weight gain was reduced. Sheep growth rate did not decrease when water hyacinth dry powder replaced 30% legume straw. Brij et al. [19] examined the performance of goats feeding on 0%, 15% and 30% water hyacinth with dry feed. The dry matter and crude fiber digestibility of the 15% water hyacinth group was the highest. The addition of water hyacinth had no significant effect on the digestibility of crude protein, crude fat, and nitrogen-free extract. The dry matter intake, digestible crude protein, and daily weight gain of the treated group were not significantly different from those of the control group. Biswas et al. [16] showed that the weight gain of broilers fed the basal diet, straw + *Brachiaria mutica*, and water hyacinth + treat molting for 56 days was 18.25, 21.75, and 21.87 kg, respectively, and dry matter consumption was 183.30, 163.27, and 173.42 kg. Eleraky et al. [20] investigated the growth performance, carcass characteristics after slaughter, and some related physiological changes in rabbits fed with gum arabic

and water hyacinth. The results showed that the addition of gum arabic and water hyacinth in the basal diet did not affect the slaughter rate. The addition of 15% and 30% Arabia gum and 15% water hyacinth reduced the cost of feed. Xing et al. [21] investigated the appropriate proportion of water hyacinth in pig feed and analyzed the economic benefits. The growing pig reached a standard weight of 90 kg, and the optimal ratio of concentrate to water hyacinth was 1:0.5 in the previous period and 1:1 in the later period. Compared with the control group, each pig saved 8184 kg of refined material, resulting in cost savings of 9.95 Chinese yuan. Bai et al. [22] used water hyacinth extrusion dehydration with other substrates (straw, vinegar grains, wheat bran) and additives (molasses, corn flour) in complex silage fermentation as feed for goats, which achieved above-average production levels. Yang et al. [23] reported that the ratio of water hyacinth in mixed feed affects popularization and application in duck production. The optimum proportion of water hyacinth was approximately 20%. Huang et al. [24,25] investigated the effect of water hyacinth slag and wheat bran mixed silage on the growth performance of goats. The results showed that adding 30% of water hyacinth slag mixed silage to feed does not affect the growth performance of goats.

5. Water Hyacinths Used to Produce Biogas and Compost

5.1. Biogas Production

Biogas is an ideal clean energy source, and the development of biogas can improve ecological and environmental conditions, such as reducing the deforestation of forests. Biogas can be used for cooking and generating electricity. Biogas residue contains regular nutrients, organic matter, trace elements, amino acids and vitamins, etc., which makes both quick and slow organic compound fertilizers [26]. The water hyacinth C/N ratio is approximately 20:1. Under anaerobic conditions, micro-organisms can use their nutrients for anaerobic fermentation of methane [27]. Gunnarsson et al. [28] found that water hyacinth and other aquatic plants are able to be easily degraded. The anaerobic fermentation produces large amounts of gas, which not only solves the problem of water hyacinth breeding but can also generate energy, turning waste into a valuable resource.

5.1.1. Post-Harvest Treatment

Shredding the water hyacinth can increase the contact area between the micro-organism and the fermentation substrate [29]. Moorhead et al. [30] investigated the effect of comminution particle size, nitrogen content and inoculum size on the anaerobic fermentation of water hyacinth. Compared with the crushed particle sizes of 1.6 and 12.7 mm, the amounts of biogas and methane produced by water hyacinth were larger when the crushed particle size was 6.04 mm. Water hyacinth has a high content of cellulose and hemicellulose and is not easily utilized by micro-organisms. Patel et al. [31] used thermochemical methods to treat water hyacinths to increase gas production. Patel et al. [11] found that the addition of Fe^{3+} , Zn^{2+} and other metal ions can increase the amount of gas produced by water hyacinth fermentation and increase the methane content in the gas. Geeta et al. [32] reported that the addition of nickel or cow dung to water hyacinth can also increase gas production. Kivaisi et al. [33] compared the fermentation effect of a single water hyacinth with a 7:3 mixture of water hyacinth and cow dung, and the degradation rates were 38% and 43%, respectively.

5.1.2. Anaerobic Fermentation

The gases produced by anaerobic fermentation mainly include methane, carbon dioxide and ammonia, and they may also contain a small amount of hydrogen sulfide. The proportion of methane is generally 60%, which is mainly determined by the properties of the fermentation substrates. Temperature, pH, and pressure may also have an effect on the gas composition. Water hyacinth has a high content of fermentable substances and a great gas production potential. However, water hyacinth has a high lignin content, which results in a decrease in actual gas production. EI-Shinnawi et al. [34] conducted anaerobic fermentation studies on various agricultural crop wastes. Rice straw, corn stover,

cotton straw, and water hyacinth were separately mixed with cow dung in different containers for fermentation. Calculated by the addition of volatile solids per unit, the amount of gas produced from water hyacinth blended cow dung was higher than that from corn straw and cotton straw. Kivaisi et al. [34] explored the production of water hyacinth in a two-phase ruminal anaerobic reactor. According to Zhou et al. [35,36], the average gas production capacity of anaerobic digestion of water hyacinth is 100 L/kg of fresh water hyacinth. The yield of water hyacinth increased to 134 L/kg of fresh water hyacinth after pretreatment with acid addition. After two-phase anaerobic biological treatment of animal excrement, the amount of gas produced was as high as 134 L/kg of fresh water hyacinth. Gunnarsson et al. [28] reported that the biogas residue produced by anaerobic fermentation is rich in nutrients and organic matter. Nitrogen is mostly present in organic form, with ammonia nitrogen accounting for 20–50% and a small part of nitrate nitrogen [37]. Biogas residues are easily dehydrated. Therefore, what is commercially available as fertilizer is dry residue. Compared with the farmyard fertilizers, biogas residues are used as fertilizers to increase the crop yield by 30% [29]. If the biogas residue is directly covered on the soil, or the storage of the biogas residue is not closed enough, the loss of ammonia nitrogen through volatilization will result. The specific volatilization amount depends on the characteristics of the biogas residue, the usage mode of the biogas residue, and the soil properties [37]. With the increase in ammonia nitrogen concentration and pH, the volatilization of ammonia nitrogen increased. In high-temperature areas, the use of biogas residue as fertilizer must be buried deep in the soil; otherwise, the nitrogen loss can be as high as 70–80% [38]. Parker et al. [39] reported that if the C/N ratio of biogas residue is higher than 20, the possibility of nitrogen volatilization is high.

5.2. Aerobic Compost

Composting is a controlled biological process that converts solid organic materials into humic substances, which can be used beneficially as a soil amendment and fertilizer [40]. Decomposed water hyacinth can promote the mineralization of nutrients, and the organic matter in the compost can increase the content of soil organic carbon, nitrogen, phosphorus and potassium, as well as increase crop yield [39]. Pulverization of water hyacinth can increase the contact area between micro-organisms and raw materials. Polprasert et al. [13] reported that grinding the hyacinth to a 5 cm long segment before fermentation could improve the fermentation efficiency. Haug [29] reported that a suitable C/N ratio for micro-organisms is 15 to 30. A low C/N ratio will not affect the composting process, but it will lead to excessive nitrogen loss in the form of ammonia. Polprasert et al. [13] reported that the best C/N ratio for microbial decomposition is 20–40. Composting of single water hyacinth is less efficient than composting of manure and leaves. This may be because leaves are mainly composed of hemicellulose and cellulose, which is easier to biodegrade than lignin, which is the main substance of water hyacinth. The C/N ratio of water hyacinth is approximately 16 [31], and Dalzell et al. [41] reported a C/N ratio of 20. Therefore, when composting water hyacinth, cellulose-rich substances such as leaves (C/N 60.8) must be added in order to reduce ammonia loss. According to Elserafy et al. [42], the optimum moisture content for compost is 60%, and the optimal range given by Dalzell et al. [41] is 50–60%. Selection of composting sites is also critical, and the composting can be carried out in deep pits or stacks. Deep pits are suitable for composting in the dry season, and stacking to avoid rainwater accumulation is suitable in the rainy season. When composting, windblown water loss and direct sunlight should be avoided. To prevent evaporation of water and loss of ammonia nitrogen, the compost can be covered with straw or plastic sheeting. When covered with straw, microbes can use rice straw as an energy source to make up for lost nitrogen [43] and reduce the nutritional losses caused by rain.

5.3. Other Utilizations

Zhou et al. [44] used heat-pretreated anaerobic activated sludge as an inoculant to ferment hydrogen production from water hyacinth. When stems and leaves were added after sodium

hydroxide pretreatment and enzymatic hydrolysis, the amount of hydrogen production was 49.7 mL/g. Water hyacinth is rich in cellulose, protein, and fat. As the cultivation matrix of edible fungi, the suitable C/N ratio was 24:3 (rice straw 53:5) compared with rice straw, and the lower lignin content was 9% (rice straw is 17%). Water hyacinth was used as a raw material for cultivating straw mushrooms, and the dosage was preferably 20–60% [45]. Singh et al. [46] conducted hydrothermal liquefaction of water hyacinth under various conditions. Biswas et al. [47] conducted pyrolysis of azolla, verbena, and hyacinth under a nitrogen atmosphere at a temperature of 300–450 °C. The maximum liquid product yield of water hyacinth was 24.6 wt% at 400 °C.

6. Engineering Application Challenges

Attention must be paid to ecological security issues during water hyacinth resource utilization. In the absence of scientific and sensible management, water hyacinth can escape to downstream waters, causing ecosystem problems such as blocking water traffic and irrigation, and interference with hydroelectricity and water supply systems. In addition, if the water hyacinth cannot be harvested in time, the plants will decompose and reduce the dissolved oxygen concentration in the water after death, which will increase the eutrophication of the water body. Therefore, in the process of engineering, the issues of water control, water conservation, and subsequent harvesting should be considered first.

Currently, manual salvage and mechanical harvesting are common methods for water hyacinth harvesting. Manual salvage is labor-intensive work, with high energy and low efficiency, and it is suitable for small-scale waters. In contrast, mechanical harvesting is the best method for clearing large areas of water hyacinth in the short term. In addition, to facilitate transportation, it is necessary to have a high efficiency and low cost drying and dehydration technology to reduce the moisture content and volume of the plants during harvesting. At present, there are few reports on the drying and dehydration of water hyacinth in China and abroad. When water hyacinth is used on a small scale, natural drying can be used. However, mechanical dehydration should be considered when it is utilized in a large-scale and its water content was reduced to a lower level.

7. Conclusions

It is undeniable that the early introduction of water hyacinth in China greatly promoted the development of the livestock and poultry industries. However, with the development of the feed industry, water hyacinth is no longer used as feed, but has been allowed to breed. The reason for this is that water hyacinth has a high moisture content and low nutrient content. However, water hyacinth dry matter is rich in nutrition and can replace part of the protein feed and roughage. However, there are few research reports on large-scale applications. The main reason is that the actual application process is faced with problems such as difficulties in control, harvesting and dehydration. Future research should focus on and address the following issues: (1) Explore suitable controlled water areas and water coverage, while ensuring that the water hyacinth biomass does not affect the ecological landscape. Regularly monitor and evaluate the impact of water hyacinth breeding on the health of aquatic ecosystems and the safety of the water environment so as to prevent the potential ecological risks and environmental impacts of large-scale planting. (2) The problems of low efficiency and high cost of water hyacinth harvesting and dehydration, require the further development of mobile, fast and efficient special equipment for improving the efficiency of harvesting, transportation and drying. (3) Innovative water hyacinth resource utilization technology, such as preparation of water hyacinth dry powder, water hyacinth silage, and high temperature compost, should be used to fully develop the economic value of water hyacinth. (4) Using water hyacinth as a raw material to produce biogas could be an alternative way. However, it is necessary to mix it with other organic substrates, such as sewage sludge, animal manure and municipal waste due to its lower cellulose content. In addition, the lignin physically protects cellulose and hemicelluloses from degradation. More pretreatments such as ionic liquids and crude glycerol pretreatment, need be developed to remove the lignin and enhance the hydrolysis of cellulose.

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