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The Economic Feasibility of the Valorization of Water Hyacinth for Bioethanol Production

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Abstract: One approach to effectively control the rapid expansion of water hyacinth is to use it as a feedstock in producing valuable goods. While it is technically feasible to produce bioethanol using water hyacinth, the economic feasibility of this valorization is yet unknown. This article conducted an ex-ante cost-benefit analysis of the production of bioethanol from water hyacinth. The results show that in comparison with the active control approach of collection and landfill, it is economically feasible to produce bioethanol from the collected biomass. In addition to its contribution to energy diversification, the production of bioethanol using water hyacinth as a feedstock cannot only control the rapid expansion of water hyacinth but can also contribute to carbon emissions reduction and water quality improvement. While the production cost of bioethanol is high, environmental values play an important role in the economic justification of the production. The coupled use of water hyacinth as a phytoremediation plant and bioethanol feedstock is a potential response to green development strategies.

Keywords: water hyacinth; economic feasibility; cost benefit analysis; bioethanol; landfill

1. Introduction

While green development is considered a crucial pathway to sustainable development around the world, some countries or regions, such as the United States, the European Union, Japan, and South Korea, have proposed strategies to promote green development. Similarly, China announced its green development strategy and specified many potential approaches in its "Nineteenth National Congress" in 2017, in which the construction of a low-carbon and highly efficient clean energy system and ecological improvements are highlighted.

Considered as an important pathway for reducing greenhouse gas (GHG) and pollutant emission, bioethanol is a targeted clean energy under some green development strategies. In 2017, China enacted the "Implementation Plan for Expanding Bioethanol Production and Promoting the Use of Bioethanol-gasoline in Vehicles", according to which bioethanol is to be produced on a large scale and a market mechanism is to be set up by 2025. In a business-as-usual scenario, China's annual gasoline consumption will reach 153 million tonnes by 2020, and, assuming a bioethanol-gasoline ratio of 1:9, approximately 15.3 million tonnes of bioethanol is expected to be demanded annually [1]. However, bioethanol output was only 3.16 million tonnes in 2017, and there is a vast shortage in supply. While its bioethanol is mainly produced from food-based feedstock at present, including corn, sugarcane, soybean, rapeseed and cassava, China is promoting the production of cellulosic bioethanol on a large scale by implementing some research and development programmes.

Considering the issue of food security, sustainable biofuel production will be better achieved by shifting from the production of food-derived biofuel to non-food biofuel [2,3]. For this purpose, the Chinese government issued a regulation on feedstock usage, which requires that biofuels must not compete with grain for land, with consumers for food, and with livestock for feeds, and should not harm the environment [4]. It highlighted that food security should be the priority whenever there is a conflict between food and bioethanol supplies.

Unlike first-generation biofuel which is food-based, cellulosic ethanol, or second-generation biofuel, is promoted because it is produced from agricultural waste and non-food crops, such as straw, grass and wood; thus, it will not result in food security issues, and it has great production potential because there is an enormous amount of cellulosic resources available [5], among which water hyacinth (*Eichhornia crassipes*) is one of the promising candidates [6,7].

Despite its high water content, which complicates the process of harvesting and processing, water hyacinth is a promising feedstock for bioenergy production because it is permanent, plentifully available, biodegradable and is a non-crop plant that has high cellulose and hemicellulose content [7]. In particular, unlike other bioethanol feedstock, such as switchgrass, miscanthus and other planted bioenergy crops, water hyacinth will not compete with agricultural crops for land use. It has potential for reducing the production cost of bioethanol when used as a feedstock because it is an abundant resource, but it is critical to use suitable organisms for fermentation to improve the yield of bioethanol [7].

The use of water hyacinth to produce bioethanol is also a potential approach in controlling the rapid expansion of water hyacinth and improving water quality. Water hyacinth is a well-known noxious and problematic weed because of its fast proliferation, wide spread [7,8] and its detrimental effects on the aquatic system. Although mechanical, chemical and biological approaches have been proposed to control its rapid expansion, the effects are usually temporary and costly because water hyacinth is hardy and reproduces rapidly [9]. To avoid ecological damage, collection-and-landfill control is usually financed by local governments. In addition to the avoidance of ecological damage, this control is also justified by its role in improving water quality because water hyacinth is an ideal phytoremediation plant with the capacity to absorb various elements in water, especially nitrogen and phosphorus [7]. However, a more ideal approach would be one which uses water hyacinth as an input in producing valuable goods [10,11]. Despite its other potential uses, water hyacinth is a promising substrate for bioethanol production because it is an abundant resource; moreover, bioethanol is in high demand and can be conveniently used in engines.

Therefore, the use of water hyacinth to produce bioethanol coupled with water purification represents a green development model, considering its potential contribution to clean energy production and environmental improvement. However, the economic feasibility of this model remains unknown, and this paper aims to answer this question by conducting a cost-benefit analysis of this model.

The contribution of this study is two-fold. First, while water hyacinth is considered a potential non-food feedstock for bioethanol production, many studies have been conducted on the production technology. However, because there is currently no information on its economic feasibility, this study fills this gap. Second, the paper provides basic economic information for a novel integrated model of clean energy production and eutrophic water treatment using water hyacinth. Since water hyacinth is widely distributed around the world and its invasive expansion exerts threats to many aquatic systems, the information from this study can also serve as a reference for countries that are facing the issue of the rapid expansion of water hyacinth, and/or are engaging in developing second generation biofuel.

The remainder of this paper is organized as follows. Section 2 provides a literature review on water hyacinth and its uses, and the feasibility studies of bioethanol production. Section 3 introduces the methodology. Section 4 presents the results. The conclusion and discussion are given in Section 5.

2. Literature Review

2.1. Water Hyacinth and Its Uses

Water hyacinth is one of the fastest growing plants on the planet [11]. It has a strong reproductive capacity, especially in eutrophic water with rich nitrogen and phosphorus [12]. Studies show that the doubling time of water hyacinth is between 6 and 28 days in weight, and between 4 and 58 days in number [8,13]. The proliferation of water hyacinth may cause many negative effects, including the depletion of oxygen in water, barriers to navigation, recreation, irrigation and power generation, and finally results in damage to the environment, human health and economic development [13,14]. Thus, the wide spread of water hyacinth needs to be controlled. Owing to its strong vitality and productivity, the cost of control is high and the effect is limited whether a chemical or biological approach is applied. In practice, the widely used approach is the mechanical approach, that is, water hyacinth is harvested and removed away from water bodies using harvesting machinery [15].

The rapid expansion of water hyacinth is a common environmental problem in tropical and subtropical regions. However, as a phytoremediation plant, it can also improve water quality by removing nutrients from the eutrophic water body as it is taken away from the water body. It has been used to remove nitrogen and phosphorus, eliminate organic pollutants, inorganic pollutants and heavy metal substances in water, and absorb some metal ions that are difficult to biodegrade and recycle [7,16,17]. Additionally, the content of nitrogen and phosphorus in dried water hyacinth was reported to be 3.07% and 0.46%, respectively [18]. As its scale is controlled, water hyacinth can thus be used to improve water quality, and its internalized environmental value is expected to improve the economic performance of using water hyacinth to produce valuable goods.

Water hyacinth cannot just be used to produce paper, fibreboard, animal feed and fertilizer [19], but is also a potential cellulose and hemicellulose resource. As its water content is reduced, water hyacinth biomass can be used to produce energy [20], including bioethanol [21,22], biogas [23] and hydrogen [24].

Considering its technical feasibility and resource abundance, water hyacinth could be used as the feedstock of second-generation bioethanol [25]. Recent studies focus on two main aspects, the effects of different pretreatment processes on ethanol production [21,26], and the effects of different strains, enzymes and accelerators on the ethanol production in the simultaneous saccharification and fermentation (SSF) stage [22,27,28]. For example, some studies show that water hyacinth can be used to produce bioethanol by using different enzymes, such as *Saccharomyces cerevisiae* and *Pichia stipitis*, and/or with different pretreatment techniques including physical, chemical or biological processes [6,7].

2.2. Economic Feasibility of Bioethanol Production

Several works in the literature studied the technical and economic feasibilities of first-generation bioethanol such as sugarcane [29], cassava [30], sweet sorghum stalks [30] and corn stover [31], among others. The results showed that it is financially feasible to produce bioethanol from these food crops at the current technology level. However, the financial feasibility is affected by the prices of feedstock, enzymes, and bioethanol, the revenue from by-products, and the incentive policies such as tax exemption and subsidization.

According to the lifecycle assessment of bioethanol produced from corn [32], cassava [30,33], sweet sorghum [30], sugarcane [34] and corn stover [31,35], the production and consumption of first generation bioethanol, compared to that of gasoline, can significantly contribute to carbon emission reduction, except for cassava bioethanol. The environmental benefits can be further improved by switching to second generation bioethanol. For example, switchgrass is more effective in carbon sequestration and results in lower soil loss [36].

The production of bioethanol is mainly driven by carbon emission reduction, energy security, and environmental improvement [2,37]. The substitution of fossil fuel with bioethanol has external benefits, which are expected to improve the lifecycle economic performance of bioethanol if these externalities are internalized. However, the second generation bioethanol, compared to the first generation technology, has not been commercially competitive due to its high production cost, and its economic feasibility is also affected by the yield and price of bioethanol, production costs and their uncertainties [38]. For example, the internal cost of switchgrass bioethanol is 69%–144% higher if the value of the selected external consequences is not included [39]. Although the positive externalities may enable the production and use of bioethanol to be economically feasible, subsidies need to be provided or positive externalities need to be internalized and incorporated to make bioethanol projects financially feasible because the production cost of bioethanol is high for most cellulosic feedstocks, such as switchgrass and miscanthus [38,40]. For example, biofuels produced from switchgrass cost 17.8% more than corn and are 34.4% more costly than gasoline when measured on an energy equivalent basis in 2005 dollars [32,41]. While there are many studies on the economic feasibilities of bioethanol production from many types of feedstock, including switchgrass and miscanthus [42,43], there is no available literature on the economic feasibility of bioethanol production using water hyacinth to date.

Due to its relatively lower cellulose contents, water hyacinth is not competitive in terms of bioethanol yield rate when it is compared with other feedstock (Table 1). However, as lignin compounds cannot be converted into sugars and may limit the microbiological activity during the fermentation process [7], the low content of lignin in water hyacinth can enable cellulose and hemicellulose to be more easily converted to fermentable sugar and then bioethanol [25]. That is, there is a potential of significantly improving the bioethanol yield rate as long as suitable organisms for fermentation can be found [7]. Furthermore, water hyacinth can also generate external values as other feedstock if its wide expansion is well controlled.

Table 1. Bioethanol yield from different feedstock.

Feedstock	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Bioethanol Yield (kg/kg of Feedstock)	Reference
Water hyacinth	18.07	28.21	7.03	0.1289–0.192	[44–46]
Corn stover	36.2	23.2	18.5	0.13–0.25	[31,47,48]
Cassava	46.7	32.6	16.9	0.418	[49,50]
Corn grain	18.7	28.7	7.5	0.33–0.39	[51–53]
Miscanthus	32.4	48.6	16.5	0.30	[53,54]
Switchgrass	32.0	25.2	18.1	0.30	[47,53]

3. Methodology

3.1. Study Site

The study site is Dianchi Lake, which is located in Kunming, Yunnan Province, China. With an area of 311.34 square kilometres, the lake plays an important role in the economic and social development of Kunming. It is not only the water source for urban, industrial and agricultural uses, and for shipping and fishery, tourism and microclimate mediation but is also a sink of Kunming urban sewage, industrial and agricultural wastewater [55]. In the past 30 years, with the rapid development of urbanization and the regional economy, the water quality of Dianchi Lake has decreased from Class II in the 1970s to the current inferior Class V according to the National Surface Water Environmental Quality Standard (GB3838-2002). Additionally, the lake is now plagued by eutrophication due to its high concentration of nitrogen and phosphorus.

As Dianchi Lake becomes eutrophic, the rapid proliferation of water hyacinth has become a serious ecological problem. The municipal government of Kunming is taking some measures to control its wide expansion, and has invested a total of 337 million Yuan to implement a pilot water quality improvement programme since 2011, in which water hyacinth is considered to be a phytoremediation plant while its expansion is under control. Water hyacinth is regularly collected and the biomass is disposed by landfill. At present, the annual growth of water hyacinth in Dianchi Lake is approximately

250,000 tonnes. Since the harvesting cost of water hyacinth is high, an effective approach requires identifying a usage for the harvested biomass, instead of disposing it by landfill. Considering its technical feasibility and China's green development strategy, the production of bioethanol using water hyacinth is expected to be a more effective alternative to landfill.

3.2. Scenario Description

The economic feasibility analysis was conducted by comparing two scenarios. One is the status quo, or the without-project scenario, representing the current approach used to control the wide spread of water hyacinth and to dispose the harvested biomass by landfill (hereafter referred to as the landfill option). Another is to use water hyacinth to produce bioethanol after it is harvested (hereafter referred to as the bioethanol option). For easy comparison, it is assumed that amounts of water hyacinth disposed in the two options are the same, namely, 241,729.32 tonnes per year, and so are the time horizons of the two options.

3.2.1. Landfill Option

The landfill option is the current active approach used to control the wide expansion of water hyacinth, according to which water hyacinth is harvested from eutrophic water bodies and is then disposed by landfill. In this scenario, water hyacinth is considered to be an exotic weed, and its rapid proliferation is a threat to water body. To avoid its damage to the aquatic system, water hyacinth is controlled in a given water area and is cultivated as a phytoremediation plant, but the biomass is regularly harvested and removed away from the water body. The harvested biomass is considered to be a waste and disposed by landfill. The landfill gas is recovered and is used to generate electricity. The process is shown in Figure 1.

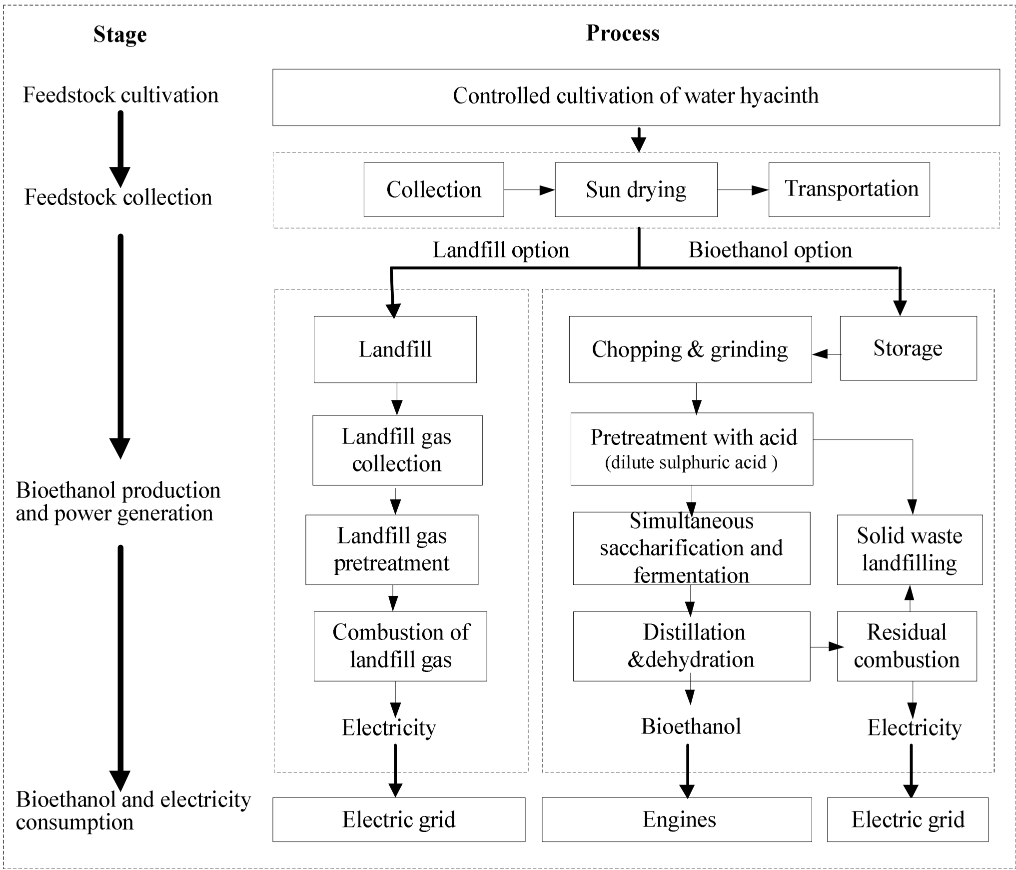

Figure 1. Processes for the disposal of water hyacinth.

The landfill gas from water hyacinth contains 65% methane [56]. Although it can be used as an alternative to natural gas, landfill gas is better suited for power generation considering the enormous infrastructural cost of gas pipes and the instability of gas supply.

3.2.2. Bioethanol Option

The bioethanol option represents an alternative approach to control the wide spread of water hyacinth by processing the collected biomass into bioethanol. In this scenario, water hyacinth is considered to be a feedstock for bioethanol production other than a waste. For the purposes of ecological damage avoidance and water purification, water hyacinth is controlled in a given water area as in the landfill option.

While there is no existing production plant that converts water hyacinth to bioethanol, this ex-ante study refers to an existing corn stover-based bioethanol plant, whose annual production capacity is 5000 tonnes. To minimize the difference in capital sizing, we assumed in the bioethanol option that the annual production capacity was the same as the existing corn stover-based bioethanol plant. This reference is appropriate because the organic contents and the bioethanol yield rates of sundried water hyacinth and corn stover are similar. The product is bioethanol, which is considered an alternative of gasoline, and the by-product is electricity, which is generated from the combustion of biomass residuals.

As shown in Figure 1, the production process is composed of 4 stages, including feedstock cultivation, feedstock collection, bioethanol production and power generation, and bioethanol and electricity consumption.

This study refers to the biochemical technology in Zhang et al. (2016) [44] and Wang (2015) [45], which is composed of the major steps of key technologies including dilute acid treatment, SSF, distillation and dehydration. The technological processes in the two references are similar with those of the referred corn stover-based bioethanol plant. According to the two references, which are based on the same work by the same research team at Eastern China Normal University, the optimal condition for fermentation by the SSF process is 38.87 °C for 81.87 hours with *Saccharomyces cerevisiae*, and the bioethanol yield rate of dry matter water hyacinth is 0.1289 g/g or 1.289g/L, as measured in different units. Thus, this study uses 0.1289 g/g as the baseline value to estimate the bioethanol output.

The production of 1 tonne of bioethanol consumes 5–6 tonnes of corn stover, and an annual output of 5000 tonnes of bioethanol will consume 25,000 tonnes of corn stover. To produce bioethanol using different cellulosic feedstock, the basic production process is similar except for different inputs such as the types and quantities of enzymes. According to the optimal biochemical process in Zhang et al. (2016) [44], 25,000 tonnes of sundried water hyacinth with a water content of 35.70% [57] can be used to produce approximately 2072.07 tonnes of bioethanol. Since the water content of fresh water hyacinth is 93.35% [18], an annual production of 2072.07 tonnes of bioethanol will consume 241,729.32 tonnes of fresh water hyacinth.

The plant would be built in the first year, the production would be started from the second year and the project time horizon is 16 years according to the lifespan of the major production equipment.

3.3. Data Sources

Both primary and secondary data are used in the study. Primary data are associated with the collection and the disposal of water hyacinth in the landfill scenario and the bioethanol scenario, as shown in Figure 1.

Secondary data were collected from the literature and related reports, including the growth rate of water hyacinth, the capacity of water hyacinth in reducing nutrients, the methane emissions rate from a water hyacinth landfill, as well as the related parameters used in the production of bioethanol.

Market prices are used to estimate the shadow prices of some inputs and outputs. The values of sulfuric acid, $CaCl_2$, enzyme, yeast and other chemicals are valued based on their domestic market prices which are adjusted by deducting the taxes. Diesel and gasoline are valued at their shadow prices, which are the international market prices adjusted using a conversion factor of 1.08 according to the National Development and Reform Commission and the Ministry of Construction, China (NDRC-MS, 2006) [58]. The shadow price of bioethanol is estimated according to that of gasoline in terms of equivalent thermal value per volumetric unit.

3.4. Methods

To inform whether or not to use water hyacinth to produce bioethanol depends on the social surpluses of the new use and the current use. If it can bring higher welfare to society than that attained by the current use, then the new use is recommended. That is, a policy decision can be made based on the difference in social welfare (ΔW).

$$\Delta W = NPV_1 - NPV_0 \quad (1)$$

where NPV_1 and NPV_0 are the net present values, or the sum of the expected net cash flows after discounting, which represents the social surplus from the new use and the current use (status quo), respectively. It is calculated as follows:

$$NPV_i = \sum_{t=0}^{n} \frac{P_{it}Q_{it} - V_{it}X_{it}}{(1+r)^t} - C_{i0}\ (i = 0, 1) \quad (2)$$

where r is the discount rate; n is the end year of the time horizon, which is 15 in the study; P_{it} and Q_{it} are the vectors of the output prices and quantities for the ith use at time t; V_{it} and X_{it} are the vectors of the input prices and quantities of the ith use at time t; and C_{i0} is the initial investment cost of the ith use at time 0.

From the perspective of economics, a policy will be recommended to produce bioethanol using water hyacinth as long as ΔW is greater than zero.

Since economic feasibility is analysed from a social perspective by comparing the change in social welfares between the landfill option and the bioethanol option, costs and benefits are estimated at shadow prices, and the external values of GHG emission reduction and water quality improvement are also included.

In estimating the net present values, the costs and benefits were adjusted to reflect the shadow prices of inputs and outputs according to their market prices, and the external costs and benefits were valued using specific methods. The economic value of GHG emission change is estimated according to the opportunity cost of GHG emission reduction in the national economy and that of water quality improvement is estimated according to the opportunity cost of nutrient removal from wastewater. Corresponding to the real-value discount rate, the cost and benefit are calculated at constant shadow prices. The prices and quantities for specific inputs and outputs are shown in Table 2.

Sensitivity analysis is conducted to identify the critical variables affecting the net social welfare (ΔW). The analysed variables include discount rate, bioethanol yield rate and price, price of GHG emission reduction, variable cost of bioethanol production, equipment cost of bioethanol production (the 2^{nd} stage), and exchange rate. Since the benefit or cost is equal to the product of the price and the quantity, the same proportion changes in the quantity and the price of a given product have the same effect on the social welfare, and thus only one of them is analysed.

Table 2. Prices and quantities of inputs and outputs.

Stage/Option	Item	Shadow Price	Quantity	Amount (MYY)
Cost				
Biomass collection and transportation	WH control	20.63 Yuan/tonne	241,729.32 tonnes	4.99
	Workers' wage	49,643 Yuan/person	30 people	1.49
	Harvesting machines	24,000 Yuan/set	10 sets	0.24
	Diesel	7.42 Yuan/L	227,480 litres	1.69
	Drivers' salary	60 Yuan/trip	5000 trips	0.30
Bioethanol Production	Sulfuric acid	2586.21 Yuan/ tone	276.39 tonnes	0.71
	Yeast	25,862.07 Yuan/ tonne	25.32 tonnes	0.65
	$CaCl_2$	1281.45 Yuan/ tonne	803.75 tonnes	1.03
	Enzyme	25,862.07 Yuan/ tonne	60.28 tonnes	1.56
	Molecular sieve	16,037.74 Yuan/ tonne	69.07 tonnes	1.11
	Utility	Water: 3.06 Yuan/ tonne	14,289.60 tonnes	0.04
		Electricity: 0.31 Yuan/kWh	6,367,794.96 kWh	1.97
	R & M			1.50
	Employees' Wages	123,926 Yuan/person for managerial staff and 49,643 Yuan/person for workers	5 managerial staff and 30 workers	2.11
	Overhead cost			1.09
Landfill and power generation	Chemicals	275.86 Yuan/kg	387.50 kg	0.11
	GHG emissions	124.51 Yuan/tonne	1747.18 tonnes	0.22
	Utility	Water: 3.06 Yuan/ tonne	22,916.66 tonnes	0.07
		Electricity: 0.31 Yuan/kWh	1,200,562.33 kWh	0.37
		Diesel: 7.42 Yuan/L	14,705.88 litres	0.11
	R & M			2.02
	Salary/Wages	123,926 Yuan/person for managerial staff and 49,643 Yuan/person for workers	2 managerial staff and 13 workers	0.89
	Overhead cost			0.12
Benefits				
Bioethanol option	GHG emission reduction	124.51 Yuan/tonne	1375.98 tonnes	0.17
	Sale of electricity	0.31 Yuan/kWh	82,833 kWh	0.03
	Sale of ethanol	7556.32 Yuan/tonne	2072.07 tonnes	15.66
landfill option	Sale of electricity	0.31 Yuan/kWh	14,820,000 kWh	4.61

Note: WH: water hyacinth; MYY: million Yuan per year; R & M: Repair and maintenance costs.

3.4.1. Cost Estimation

(1) Costs of controlling, harvesting and transporting water hyacinth

These costs are the same in both the bioethanol option and the landfill option. To better understand the production performance of the two options, they are presented in the study.

Water hyacinth is controlled in a given area so as to avoid its damage to the aquatic system and use it as a phytoremediation plant to purify water. Since the density of water hyacinth cluster in water surface is 750 tonnes per hectare, a supply of 241,729.32 tonnes of fresh water hyacinth requires approximately 322.31 hectares of controlled water areas. The annual cost of water hyacinth control is 4.99 million Yuan, as estimated according to Kang and Liu (2015) [16].

Water hyacinths can be collected by artificial and mechanical methods. The latter are more cost effective and thus are selected because its unit cost is 15.61 Yuan/tonne, which is lower than that of the former, 21.32 Yuan/tonne. The harvesting machine was made by the Shanghai Electric Group in Shanghai with a capacity of harvesting 100 tonnes of water hyacinth per day (8 working hours). Thus, the harvest of 241,729.32 tonnes of water hyacinth requires 10 machines, whose total cost is 8 million Yuan. With a lifespan of 15 years, these machines are assumed to have a residual value equal to 5% of the total machinery cost, and the repair cost is 3% of the total machinery cost. The annual cost of harvest is estimated to be 3.77 million Yuan.

According to Zhang (2004) [59], a harvesting machine with an engine efficiency of 36.8 kW generally consumes 200–250 g of diesel for generating one kWh of electricity. On average, it consumes

79.8 litres of diesel per day (8 working hours). For the harvesting of 241,729.32 tonnes of fresh water hyacinth, a total of 207,480 L of diesel is needed to run the 10 machines in a year (260 working days).

The average annual wages of the agriculture, forestry, animal husbandry and fishery sector in 2016 was 36,939 Yuan per worker according to the China Labour Statistics Yearbook of 2017. The shadow price of labour was estimated by adjusting the market wages with an accounting ratio of 0.75 for unskilled labour according to NDRC-MS (2006) [58]. The harvesting of 241,729.32 tonnes of freshwater hyacinth requires 186 workers to work 260 days per year.

The collected water hyacinth is either transported to the bioethanol plant or the landfill field. Due to its high water content, water hyacinth will be sundried on the bank of the lake for 6 days before it is disposed. Finally, a total of 241,729.32 tonnes of fresh water hyacinth with a water content of 93.35% is to be sundried into 25,000 tonnes of biomass, whose water content is 35.70%. It is assumed that a truck with a carrying capacity of 5 tonnes per trip will consume 4 litres of diesel, and thus the transportation of 25,000 tonnes of water hyacinth requires 5000 trips, consuming 20,000 litres of diesel. The driver's salary is 60 Yuan per trip and the price of diesel is 7.42 Yuan per litre.

(2) Cost of landfill process

In the landfill scenario, the landfill-specific costs are mainly associated with the landfill practices and the power generation equipment and its installation.

Approximately 3.02 ha of land is required for the disposal of 25,000 tonnes of sundried water hyacinth by landfill, and the land rent is 0.60 million Yuan as estimated at the shadow price of marginal land in Kunming, 12,508 Yuan/ha/year. In addition, the annual cost of the operation and management of the landfill field is 3.58 million Yuan, including 0.55 million Yuan of utility cost, 2.02 million Yuan of maintenance cost, 0.89 million Yuan of wages, and 0.12 million Yuan of overhead cost exclusive of land cost. In addition, some chemical applications for pest control and lining in the landfill field are implemented, and their total cost is 0.81 million Yuan for a period of 15 years.

The cost of landfilling and power generation is 33.94 million Yuan, of which the construction of the landfill field costs 2.6 million, and the landfill gas power generation facility and its installation account for 27.84 million and 1 million, respectively. Additionally, accessories of the generating facility account for 2.5 million.

The energy consumption for the construction of landfill field was estimated according to Kegel (1978) [60] and Wu and Yang (2001) [61]. The consumption of diesel and electricity in landfill practices was estimated according to Dahua engineering management Co. Ltd.

(3) Cost of GHG emission from the landfill process

GHG emission is quantified in terms of the carbon dioxide equivalent (CO_2eq). The value of GHG emission reduction is the product of the net GHG emission reduction and the carbon dioxide price. The GHG balance is the difference between GHG emission reductions and GHG release. Since the amounts of water hyacinth disposed by the two options are the same, the carbon fixed by the photosynthesis of water hyacinth is the same; the carbon change in photosynthesis is thus not considered. The GHG in the study included CO_2, CH_4 and N_2O. Within a time span of 100 years, the global warming effects of CH_4 and N_2O were 23 times and 296 times that of CO_2, respectively [62]. The GHG emission reduction is valued at the shadow price of the GHG emission reduction in China's economic system, 124.51 Yuan per tonne [63]. The detailed GHG accounting is shown in Table 3.

The external cost of GHG emission from the landfill is mainly a result of energy consumption, anaerobic digestion and the combustion of landfill gas. For the construction of the landfill field, a total of 1289.84 GJ of energy is to be consumed, including 31,037.84 L of diesel and 127,211.8 kWh of electricity, resulting in an emission of 127.27 tonnes of CO_2eq. The GHG emission from the harvesting and transportation of water hyacinth is estimated according to the consumption of diesel. Since the CO_2 emission rate of diesel is 2.63 kg/L (National standard GB/T 2589-2008), an annual consumption of 207,480 L of diesel emits 545.67 tonnes of CO_2. A truck with a carrying capacity of 5 tonnes consumes 4 litres of diesel each trip, resulting in an emission of 10.52 kilograms of carbon dioxide. An annual transportation of 241,729.32 tonnes of water hyacinth requires 5000 truck-trip events and will emit 52.6 tonnes of carbon dioxide.

Table 3. Accounting of annual GHG emissions (tonne of CO_2eq).

	Item	Bioethanol Production	Landfill
Feedstock preparation	Collection	545.67	545.67
	Transportation	52.60	52.6
Bioethanol production	Biomass chopping, grinding and storage	7.31	
	Pre-treatment with acid	46.19	
	Hydrolysis and fermentation	39.19	
	Solid waste treatment	2.08	
	Simultaneous saccharification and fermentation	643.55	
	Electricity generation	1810.79	
	Wastewater treatment	3.09	
	Chemicals transportation	0.95	
	Production of chemicals	1046.21	
	Sub-total	3599.36	
Landfill	Landfill process		1235.64
	Landfill gas collection and pretreatment		5154.64
	Power generation from landfill gas		9534.17
	Sub-total		15,924.45
Bioethanol consumption	Substitution of gasoline with bioethanol	−5490.98	
Substitution of coal-fired electricity		−82.63	−14,775.54
Balance without buildings and utility facility		−1375.98	1747.18

The landfill gas from the anaerobic digestion of water hyacinth is mainly composed of methane and carbon dioxide, which account for 65% and 35%, respectively [56]. In this study, the landfill gas is recovered to generate electricity, which translates to a lower emission of CO_2eq since methane is oxidized into carbon dioxide. A landfill gas model based on IPCC (2006) [64] was used to estimate the methane emissions from the landfilling of water hyacinth. The model is specified as:

$$Q_{CH_4} = 16/12 * S * WH_f * MCF * DOC * DOC_f * F\left(1 - e^{-kt}\right) \quad (3)$$

where Q_{CH_4} is the methane emission in the tth year; S is the weight of sundried water hyacinth in the tth year. WH_f is the ratio of the landfilled water hyacinth to the total harvest. The value is 1, meaning that the collected water hyacinth is completely landfilled. MCF is a methane correction factor. When the anaerobic digestion process is well controlled, the value is 1. DOC is the proportion of organic carbon that can be degraded in water hyacinth, while DOC_f is the proportion of decomposition (conversion to methane or carbon dioxide); the value is 0.77. F is the proportion of methane in the landfill gas, with a value of 0.65 [56], and the decay rate k is a constant, which is the ratio of ln(2) to the half-life $t_{1/2}$, expressed as $k = \ln(2)/t_{1/2}$ [64].

The sundried water hyacinth has a biomass content of 64.30%, the dry biomass has a nitrogen content of 1.2% to 3.2%, and the C/N ratio is approximately 15, so the DOC value of the water hyacinth is estimated to be 20.89%. Because water hyacinth degrades quickly, the half-life of water hyacinth is assumed to be 2 years.

It is assumed that the landfill field was built 10 years earlier than the bioethanol plant. According to Equation (3), the annual output of methane from the landfill of water hyacinth is 3466.97 tonnes on average and that of CO_2 is 5154.64 tonnes. As it is combusted to generate electricity, one mole of methane will be converted into one mole of carbon dioxide. The combustion of 3466.97 tonnes of methane is expected to release 9534.17 tonnes of CO_2. The electricity and diesel used in the landfill practice is 1,200,562.33 kWh and 14,705.88 litres for 25,000 tonnes of water hyacinth, respectively. The annual GHG emissions from the landfill option are 15,924.45 tonnes of CO_2eq (Table 3).

According to Wang et al. (2006) [65], an internal combustion engine generator with an output rate of 1250 kW of electricity requires an input of 3783 kW of landfill gas. Considering the lower heating value of methane at 50.0 MJ/kg, the landfill gas generated from 241,729.32 tonnes of fresh water hyacinth can be continuously supplied to two such generators for 260 entire days. As a result, the net output of electricity is 14.82 million kWh, which can reduce GHG emission by an amount of 14,775.54 tonnes of CO_2eq annually.

In summary, a total of 1747.18 tonnes of CO_2eq is expected to be emitted from the landfill option (Table 3).

(4) Costs of bioethanol production

The cost of bioethanol production is composed of 8 million for the plant building and 20 million for equipment, and 2 million for other expenses.

Since there is currently no bioethanol production using water hyacinth, this ex-ante study refers to the process of corn stover-based bioethanol production of the Fengyuan Corporation, including the plant design, basic production facilities and equipment, etc. The specific biochemical production of bioethanol using water hyacinth is based on the technology in Zhang et al. (2016) [44]. Although there is a potential to increase the bioethanol yield from water hyacinth by using other microbes like *Zymomonas mobilis*, this study consider *Saccharomyces cerevisiae* only according to Zhang (2016) [44]. There are two reasons: first, *Saccharomyces cerevisiae* is widely used in industry and is easily available; second, although other microbe, such as *Zymomonas mobilis*, can be used to decompose 5-C sugars, but it is not available in massive volume, and thus is not incorporated into the estimation.

The bioethanol plant is assumed to be built on marginal land. To minimize the difference in capital sizing, it is assumed that the water hyacinth-based bioethanol plant has the same processing capacity, which is 25,000 tonnes of feedstock. Based on this capacity, approximately 2072.07 tonnes of bioethanol and 82,883 kWh of electricity would be produced annually. Because the same amount of feedstock is processed, the sizes of equipment for storage, chopping and grinding, and dilute acid pretreatment are the same in the two plants (Figure 1). However, the sizes of equipment for SSF and the following processes in the two plants might be different as a result of different water contents in sundried water hyacinth and corn stover. While there is no actual bioethanol production from water hyacinth, the equipment for SSF and the following processes of the referred bioethanol plant was used as a proxy.

Since there is no information on the further dehydration of water-ethanol azeotrope in the referred bioethanol plant, this study assumed that molecular sieve separation technology is to be applied to increase the bioethanol purity from 95% to 99.5%. According to Li (2001) [66], the azeotropic ethanol is to be further purified using a zeolite molecular sieve fixed bed, and the associated cost is estimated to be 652.39 Yuan/tonne of bioethanol according to the input of zeolite molecular sieve and its current price.

The required land area is 0.7 ha for the plant, and the cost is 0.14 million Yuan as estimated at the shadow price of marginal land in Kunming in 2018, 12,508 Yuan per ha. The unit capital cost of bioethanol production is 11,049.78 Yuan per tonne, and its composition is shown in Table 4.

Table 4. Unit cost of bioethanol production from water hyacinth.

Item	Price (Yuan/Tonne)	Percentage
Feedstock (water hyacinth)	4444.42	40.22%
Chemicals	1692.67	15.32%
Enzyme and yeast	752.39	6.81%
Energy and water	977.03	8.84%
Capital costs	1640.87	14.85%
Equipment repair	434.35	3.93%
Equipment depreciation	916.96	8.30%
Others	289.57	2.62%
Wages	1017.79	9.21%
Overhead cost	524.62	4.75%
Total Cost	11,049.78	100.00%

In Table 4, the cost of feedstock is mainly associated with the cultivation, harvesting and transportation of water hyacinth, which is 4444.42 Yuan per tonne, accounting for 40.22% of the unit cost of bioethanol. According to Zhang et al. (2016), the optimal enzyme (15,000 u/g of substrate) input was 0.05 g/g of dry water hyacinth [44]. In this study, the enzyme is a commercial enzyme (200,000 u/g of substrate) from Tai'an Xindeli Biological Engineering Co., Ltd. The production of 1 tonne of bioethanol consumes 29 kilograms of enzyme, and its cost is 752.39 Yuan/tonne. The optimal input rate of yeast is 0.0122 g/g of bioethanol and that of $CaCl_2$ is 0.05 g/g of dry water hyacinth. The production of one tonne of bioethanol consumes approximately 0.13 tonnes of sulfuric acid [31], 0.0122 tonnes of yeast and 0.388 tonnes of $CaCl_2$ [44].

The production of one tonne of bioethanol consumes 6.90 tonnes of water, 3.61 tonnes of steam [67] and 546.16 kWh of electricity [31,66]. In this study, gas boilers are used to generate steam, with a power input of 700 kW. That is, the production of a tonne of steam requires 700 kWh of electricity. The shadow prices of water and electricity were 3.06 Yuan/tonne, and 0.31 Yuan/kWh in Kunming City, respectively. Their costs are 977.03 Yuan for the production of one tonne of bioethanol, accounting for 8.84% of the unit cost of bioethanol.

Capital costs include the depreciation of fixed assets, equipment repair and other related costs. Assuming that the residual value is 5% of fixed assets, the depreciation of fixed assets is calculated using the straight-line depreciation method for a period of 15 years. Repair cost is assumed to be 3% of the fixed assets, and other associated capital costs account for 2% of the fixed assets.

The bioethanol plant is to be staffed with 5 managerial persons and 30 skilled workers, and the total salary is 2.1 million Yuan per year. According to the China Labour Statistics Yearbook of 2017, the average annual salary of managerial staff in 2016 was 123,926 Yuan, and the average annual wage of manufacturing workers was 49,643 Yuan. These wages from the labour market are adjusted to obtain the shadow prices of labour using an accounting ratio of 1 for skilled labour according to NDRC-MS (2006) [58].

The shared overhead cost, including land rent, office supplies, management cost, etc., is 524.62 Yuan for the production of one tonne of bioethanol, accounting for 4.75% of the unit cost of bioethanol.

3.4.2. Benefit Estimation

(1) Electricity benefit of the landfill option

In the landfill scenario, approximately 15.6 million kWh of electricity can be generated from the combustion of 3466.97 tonnes of landfill gas per year. Deducting 5% of the generated electricity for the operation of the landfill field, the net output of electricity is 14.82 million kWh per year, whose value is 4.61 million, as estimated at the shadow price of electricity in Yunnan Province, 0.31 Yuan/kWh.

(2) Bioethanol and electricity benefits of the bioethanol option

In the bioethanol option, the revenues come from the sales of bioethanol and electricity. The former is the major product of the project, while the latter is a by-product from the combustion of the residual biomass. According to the national standard GB2589-81, the caloric value of one kilogram of gasoline is 43,070 KJ and that of one kilogram of ethanol is 29,700 KJ. That is, one unit of bioethanol is equivalent to 0.69 units of gasoline in terms of equal caloric value. In August and September 2018, the average price of gasoline and diesel in the international market were 1.13 and 1.04 U.S. Dollars per litre, respectively, according to which the bioethanol price is estimated to be 7556.32 Yuan per tonne. From a bioethanol plant with an annual capacity of processing 25,000 tonnes of sundried water hyacinth, approximately 82,883 kWh of electricity can be generated, resulting in a revenue of 0.03 million Yuan, as estimated at the shadow price of electricity in Kunming.

(3) Benefit of GHG emission reduction of the bioethanol option

In the lifecycle of bioethanol, GHG emission originates from the combustion of diesel in harvesting machines and trucks, and in the bioethanol plant, while GHG emission that is avoided is the result of substituting gasoline with bioethanol in engines, and substituting coal-fired electricity with biomass-combusted electricity. Due to the lack of data, only the direct energy consumption and energy generation are considered.

The GHG emission from the harvesting and transportation of water hyacinth is the same as in the landfill scenario, while that from the construction of the bioethanol plant was estimated based on the energy consumption according to Kegel (1978) [60] and Wu and Yang (2001) [61]. To build a 0.7 ha bioethanol plant, a total of 2078.02 GJ of energy is required, including 56,265.76 L of diesel and 10,597.22 kWh of electricity. As a result, a total of 158.54 tonnes of CO_2eq will be emitted.

The GHG emission from the manufacturing process of bioethanol is estimated according to Tian et al. (2011) [31], Aden et al. (2002) [68] and Kaltschmitt and Reinhardt (1997) [69]. The GHG emission rates of enzyme, $CaCl_2$ and sulfuric acid are 4.85 kg CO_2eq/kg [70], 0.89 kg CO_2eq/kg and 0.14 kg CO_2eq/kg [71], respectively. The GHG emission from bioethanol production is estimated to be 3599.36 tonnes. Assuming that bioethanol is distributed near the plant, the GHG emission from the transportation of bioethanol can be ignored. The detailed GHG emission from each production stage is shown in Table 3.

For the production of one kilogram of bioethanol, the residual biomass can be used to generate 0.04 kWh of electricity [31], and the annual electricity output is 82,833 kWh. Since the generation of 1 kWh of coal-fired electricity emits 0.997 kilograms of CO_2 [72], the substitution of coal-fired electricity with biomass-derived electricity can avoid an emission of 82.63 tonnes of carbon dioxide every year (Table 3).

In summary, the production of bioethanol from water hyacinth can reduce GHG emissions by 1375.98 tonnes of CO_2eq. The GHG emissions that result from the transportation of water hyacinth and the biochemical process release 52.6 tonnes and 3599.36 tonnes of CO_2eq to the atmosphere, respectively. The GHG emission reduction is a result of the energy substitution. The substitution of gasoline with bioethanol reduces 5490.98 tonnes of CO_2eq, and the other 82.63 tonnes of CO_2eq emission are reduced because the electricity generated from the combustion of the residual biomass is used as substitute for the coal-fired electricity.

(4) Value of water quality improvement

Water hyacinth has a value in improving water quality because it can remove nutrients as it is collected and transferred away from water bodies. This value is the same for both the landfill and the bioethanol scenarios, because the same amount of water hyacinth is collected and disposed in both scenarios. Thus, the economic feasibility analysis of bioethanol production can be performed without estimating the value of water quality improvement. However, the value is estimated in order to better understand the economic performance of the valorization of water hyacinth to produce bioethanol.

Despite many other methods for the economic valuation of water quality improvement, this study adopts the opportunity cost method to estimate the contribution of water hyacinth to water quality improvement. As shown in Table 5, the unit costs of reducing the total nitrogen and total phosphorous are 143,000–754,000 Yuan/tonne and 64.7–377.1 Yuan/tonne, respectively, by using different technologies. In particular, based on the accounted inputs and the amount of removed nutrients, Kang and Liu (2015) [16] found the unit cost is 24.0 and 159.0 Yuan/tonne for the removal of total nitrogen and total phosphorous by using water hyacinth as a phytoremediation plant in Taihu Lake, China. However, they did not include the cost of disposing the collected biomass, and thus the cost is only partially representative of the total cost.

Water hyacinth can simultaneously absorb nitrogen, phosphorous and many other elements, but the absorption rate is the highest for nitrogen [73]. According to Zheng et al. (2008) [18], the contents of nitrogen and phosphorus in dried water hyacinth are 3.07% and 0.46%, respectively. Thus, the unit cost of total nitrogen is used to estimate the value of water quality improvement. In Dianchi Lake, one tonne of water hyacinth can absorb 0.031 tonnes of nitrogen [72]. Since the bioethanol plant annually consumes 241,729.32 tonnes of water hyacinth, 7500 tonnes of nitrogen will be removed from the lake, and the associated value in water quality improvement is 167.25–565.77 million Yuan. Accordingly, the value of water quality improvement for the two scenarios is 1272.12 million Yuan for the whole project horizon, as estimated according to the minimum unit cost or the unit opportunity cost of the removal of total nitrogen from wastewater.

Table 5. Unit costs of reducing nitrogen and phosphorous.

Technology	Unit Cost (10^3/tonne)		Reference
	TN [1]	TP [2]	
A2O [3]	75.4	377.1	
CASS [4]	71.7	358.5	[74]
BICT [5]	54.2	271.1	
CASS	22.3	191.4	[75]
Water hyacinth	24.0	159.0	[16]

Note: [1] TN: total nitrogen; [2] TP: Total phosphorous; [3] A2O: Anaerobic Anoxic Oxic; [4] CASS: Cyclic Activated Sludge System; [5] BICT: Bi-Cyclic Two-phase biological process.

4. Results and Discussion

4.1. Economic Feasibility

The economic feasibility is assessed in terms of the net present value by comparing the disposals of water hyacinth between the bioethanol scenario and the landfill scenario. The comparison was based on the assumption that the same amount (i.e., 241,729.32 tonnes) of water hyacinth is to be disposed in the two scenarios. The project span is 16 years, with one year for plant construction and the following 15 years for operation. The annual working days are 260 days. The costs and benefits were valued at their shadow prices as previously introduced, and a base discount rate of 10% is applied in calculating the net social surplus.

As shown in Table 6, the net social surplus of the bioethanol project is 30.83 million Yuan, revealing that it is economically feasible to produce bioethanol from water hyacinth, compared with the landfill of water hyacinth.

Table 6. Cost-benefit analysis results.

Item		Bioethanol Option (Million Yuan)	Landfill Option (Million Yuan)
Costs			
Biomass collection and transportation	WH control	37.93	37.93
	Harvesting machines	8.00	8.00
	Workers' wage	13.61	13.61
	Repair and maintenance cost	1.83	1.83
	Diesel	12.83	12.83
Bioethanol production or power generation from landfill gas	Buildings, equipment and land rent	30.14	34.54
	Enzyme and yeast	16.84	
	Chemicals	21.69	0.81
	Utility	15.40	4.94
	Repair and maintenance cost	11.41	15.36
	Wages	16.04	6.85
	Overhead cost	8.20	0.91
Total cost		193.92	137.61
Benefits			
GHG emission reduction		1.28	−1.67
Sale of electricity		0.20	35.06
Sale of bioethanol		119.09	
Water quality improvement		1272.12	1272.12
Residual value of equipment		0.53	0.58
Total revenue		1393.21	1306.08
NPV		1199.30	1168.47
ΔW		30.83	

In the landfill scenario, the major benefits are from water quality improvement and the sale of electricity, while the main cost is associated with the collection of water hyacinth, the equipment depreciation and the maintenance of the landfill field. Without considering the economic loss resulting from the massive expansion of water hyacinth, we can infer that the landfill option is a better option than "doing nothing" because it has an NPV of 1168.47 million Yuan.

In the bioethanol scenario, the main benefits include the value of bioethanol, the value of GHG emission reduction and water quality improvement. The main costs are associated with the harvesting of water hyacinth, the construction of the plant, the purchases of enzymes and sulfuric acid, and the employees' wages. However, since the production cost is high, the benefits of bioethanol and its by-product are not sufficient to make the production economically feasible, even if the external benefit of GHG emission reduction is included. That is, the inclusion of the external benefit of water quality improvement is crucial in economically justifying the production.

As shown in Table 6, the external value of water quality improvement is 1272.12 million Yuan, which is much greater than the benefit of bioethanol. The NPVs of both options will become negative if the benefit of water quality improvement is not included. Furthermore, this benefit justifies efforts by the local government to finance the disposal of water hyacinth by landfill. The production of bioethanol from water hyacinth, similar to other cellulosic feedstock, such as switchgrass and miscanthus [38,40], is also expected to be subsidized by the local government, and the benefit of water quality improvement provides an economic justification for such subsidization.

4.2. Sensitivity Analysis

To identify the critical variables affecting the ΔW, sensitivity analyses were conducted by changing the previously given percentages of the values of the bioethanol yield rate, discount rate, bioethanol price, carbon dioxide price, variable production cost of bioethanol, equipment cost of bioethanol production and exchange rate. The results are shown in Table 7.

Table 7. Sensitivity analysis results.

Variable	Baseline Value	Change Rate		Switching Value
		Variable	ΔW	
Bioethanol yield rate (g/g)	0.1289	−10%/+50%	−29.11%/+145.53%	−34.36%
Discount rate (%)	10%	−20%/+20%	+10.72%/−8.94%	-
Price of CO_2eq emissions (Yuan/tonne)	124.51	−25%/+25%	−2.40%/+2.40%	-
Price of bioethanol (Yuan/tonne)	7556.32	−5%/+5%	−19.22%/+19.22%	−26.02%
Variable cost of Bioethanol (Yuan/tonne)	8922.07	−5%/+5%	+22.81%/−22.81%	21.93%
Equipment cost of Bioethanol production (Yuan/tonne)	1640.87	−5%/+5%	+4.19%/−4.19%	119.20%
Exchange rate (Yuan/$)	6.5879	−5%/+10%	−19.70%/+39.40%	−25.39%

The use of water hyacinth to produce bioethanol is still at the experimental stage. The previously described economic feasibility study was estimated assuming that the bioethanol yield is 0.1289 g/g of dry water hyacinth. However, in commercial production, the yield can be lower, by an assumed rate of 10%. Nevertheless, the use of more suitable organisms or more efficient treatment for fermentation can improve the yield of bioethanol. According to Ma et al. (2010), the yield can be increased to 0.192 g per gram of dry water hyacinth if a combination of biological pretreatment with mild acid pretreatment is applied to enzymatic hydrolysis [46]. Moreover, the bioethanol yield can also be increased by decomposing 5-Carbon sugars if a microbe such as *Zymomonas mobilis* becomes available in great volume. That is, the potential for increasing the bioethanol yield by 50% exists.

To date, there is no consensus on the shadow price of CO_2eq emission in China. This study refers to the work of Dai et al. (2017), which projected that the shadow price of CO_2eq emission reduction in China is 124.51 Yuan/tonne in 2018 [63]. Here, for the sensitivity analysis, we assume that the price varies in a range of (−25%, +25%).

Bioethanol is priced based on the market price of gasoline in terms of equivalent caloric value. Thus, the bioethanol price may vary by following the volatility of gasoline prices. Based on the equivalent caloric value, the shadow price of bioethanol varies in a range of (7178.50 Yuan/tonne, 7934.13 Yuan/tonne).

The variable cost of bioethanol production represents a combination of many inputs. To obtain an approximate estimation, it is assumed that the production cost varies in a range of (−5%, +5%).

Because of different water contents in sundried water hyacinth and corn stover, the sizes of equipment for SSF and the following processes might be different in producing bioethanol using the two feedstocks. While there is no actual bioethanol production using water hyacinth, we do not know how much the difference is. To overcome this shortage to a certain degree, a sensitivity analysis was conducted by changing the equipment cost of bioethanol production, which includes the depreciation of fixed assets, repair cost and other related costs at the bioethanol production stage only. It is assumed that the equipment cost varies in a range of (−5%, +5%).

In the study, the average exchange rate is 6.5879 Yuan/$, and its volatility range of the exchange rate is set according to the highest and the lowest rates of the exchange rates between January and October, 2018. Thus, by considering the maxima and the minima of the exchange rate in 2018, the volatility range was set to be (−5%, 10%).

According to EDRC (1997) [76], the discount rate for most productive projects is 10−12%. However, the recommended real-term social discount rate is 8% for short and medium term projects in China (NDRC-MS 2006) [58]. For environmental projects, the discount rate is usually lower. For example, Tang et al. (2009) [77] applied a discount rate of 5% to analyses the economic viability of a reforestation project under the clean development mechanism. Obviously, this bioethanol project is an integrated one with both bioethanol production and environmental improvement. Therefore, this study assumes a discount rate varying in a range of 8−12%. In other words, the discount rate may increase or decrease by 20%.

Critical variables are identified as those whose values change by 1% (increase or decrease), resulting in a change of more than 1% (positive or negative) in ΔW. As shown in Table 7, the critical variables are the bioethanol yield rate, price of bioethanol, variable cost of bioethanol and the exchange rate. The net social surplus is not sensitive to the discount rate, equipment cost of bioethanol production and the price of CO_2eq emission reduction. As revealed by changing the values, the economic feasibility is most sensitive to variable cost of bioethanol, the bioethanol price and exchange rate. As far as switching values are concerned, the net social surplus ΔW will tend to become zero as the variable cost increases by around 22%, or as the price of bioethanol or the exchange rate decreases by approximately 26%. However, it is rare for the latter two variables to fluctuate by a rate of 26% or higher, especially when a low bioethanol yield rate was used in the analysis.

As previously mentioned, the equipment for SSF and the following processes for the referred bioethanol plant was used as proxies for bioethanol production using water hyacinth. This treatment may involve difference in capital cost. According to Table 7, the economic feasibility is not sensitive to the change of the equipment cost of bioethanol production, and thus this treatment is acceptable.

Although the economic feasibility is most sensitive to the variable cost of bioethanol production, there is a potential to reduce this cost. Some studies showed that hydrous ethanol gasoline could be considered as a promising alternative for engines [78,79], and thus, it is potential to reduce the dehydration cost of water-ethanol azeotrope.

In summary, the results of sensitivity analysis reveal that the economic feasibility is robust.

5. Conclusions

The implementation of a green development strategy calls for green energy production and environmental improvement. Although it is usually considered an invasive weed that is disposed of as a waste, water hyacinth exhibits potential as feedstock for bioethanol production and as a phytoremediation plant for water quality improvement, and thus can contribute to a green development strategy. Despite many studies on the technologies of such applications, there is still lack of studies on its economic feasibility. The present study fills this gap by conducting a cost-benefit analysis, in which the bioethanol scenario is compared to the status quo, i.e., the landfill scenario.

The findings of this study indicate that it is economically feasible to produce bioethanol using water hyacinth. Compared with the landfill of water hyacinth, bioethanol production is a better choice from the perspective of economics because it can increase social welfare. It can also contribute to GHG emission reduction compared to the disposal of water hyacinth by landfill. The critical variables affecting the economic feasibility include the bioethanol price, exchange rate, bioethanol yield rate and the variable cost of bioethanol production.

The results of this paper have the following policy implications. First, the production of bioethanol from water hyacinth is a better choice than landfill disposal and thus deserves promotion. It is a potential positive response to a green development strategy, in terms of its contributions to clean energy production, GHG emission reduction and water quality improvement. Second, although it does not affect the economic feasibility because it is the same in both scenarios, the value of water hyacinth in improving water quality should not be ignored. Since the values of final products are not sufficient to enable the net present value of bioethanol production to become positive, this external value provides an economic justification for subsidizing the production of bioethanol using water hyacinth. Third, while the volatilities of the bioethanol price and the exchange rate may undermine the economic feasibility but they are beyond producers' control, efforts should be devoted to improving the bioethanol yield rate and to reducing the production cost. The former can be improved by promoting studies on the pretreatment, simultaneous saccharification and fermentation technologies, in particular the commercial production of microbes for hemicellulose decomposition, while the latter can be reduced by optimizing the production process.

To select feedstocks for meeting a bioethanol output target, future study is suggested to compare the economic and environmental performance of cellulosic bioethanol production using water hyacinth and other feedstocks.

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