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Potential of *Eichhornia crassipes* for biomass refining

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Abstract Here we explore the utilization of *Eichhornia crassipes*, commonly known as water hyacinth, as a competitive source of biomass for conversion to fuel. Ecologically, *E. crassipes* is the most undesirable of a class of noxious and invasive aquatic vegetation. Water hyacinth grows rapidly on the surface of waterways, forming a dense mat which depletes the surrounding environment of essential nutrients. These properties, rarely encountered in other plant systems, are features of an ideal feedstock for renewable biomass. The high characteristic water content limits the range over which the material can be transported; however it also makes *E. crassipes* a natural substrate for rapid microbial metabolism that can be employed as a potentially effective biological pretreatment technology. We show through a life cycle analysis that water hyacinth is a competitive feedstock with the potential to be produced at a cost of approximately $40 per ton of dry mass.

Keywords Water hyacinth · Biomass · Feedstock · Cellulosic ethanol

Introduction

Biomass-derived ethanol is one of the few renewable alternative liquid fuels for motor fuel applications [38]. In the United States, renewable ethanol is produced primarily from corn or other grain sources. While corn represents an important ethanol feedstock in the United States, converting all of the US corn grain crop to ethanol would fulfill only 15% of our current transportation needs [38]. In locations where it thrives (e.g., Brazil), sugarcane has proven to be an excellent feedstock for bioethanol production [9]. Although grown commercially in several states, the environment in the US is not conducive to large-scale sugarcane production. Moreover many of these plant crops, considered attractive for making ethanol, are primary dietary staples [6]. Their use as energy sources could induce an undesirable competing effect between the food and energy sectors of the economy. Therefore, to meet the Department of Energy's goal of 60 billion gallons of ethanol by 2030 [38], a major shift from food crops to cellulosic biomass will be required.

This paper first offers a comparison of potential biomass feedstocks for renewable ethanol production. An inexpensive procedure for treating the biomass is then examined, along with explanations of steps in the process. The following section contains an economic life cycle analysis for a combined growth, harvesting, and digestive process to produce a water hyacinth-derived biomass feedstock

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suitable for direct conversion to liquid fuel. Lastly, a sensitivity analysis and discussion of several important variables is presented.

Critical evaluation of biomass feedstocks

An ideal biomass feedstock should be widely available, easily cultivated, require little to no maintenance, and have frequent harvest cycles. Candidate feedstocks include corn, sugarcane, beets, wood, grasses, and aquatic plants (such as algae and *Eichhornia crassipes*).

Wood has long been considered an important potential feedstock. However, as can be seen by Table 1, its harvest is too infrequent to meet current and future demands for biomass. Furthermore, wood has an extremely tough cellular structure, and thus requires expensive and energy-intensive pre-treatment to facilitate access of cellulase enzymes or reagents to the carbohydrates enmeshed in the hemicellulose and lignin.

The potential of aquatic plants as a biomass fuel source has been reviewed by Sheehan et al. [31]. Aquatic vegetation, such as algae and *E. crassipes*, is rich in cellulose and hemicellulose, fairly low in lignin, and does not compete with agricultural crops. Also, the harvest frequency tends to be on the order of days, whereas the frequency for trees, grasses, and crops is on the order of years or months. Algae has received considerable attention as a potential feedstock. It grows rapidly; however, culture density is limited by light availability. Outdoor ponds of algae get relatively poor illumination when the sun's angle is acute. However, floating plants such as water hyacinth project above the water surface, have a relatively high surface area, and thus gather sunlight well at all times of the day.

Special ponds required to cultivate algae are a major hurdle for commercialization. Algae farms must compete with agricultural or recreational use of the land, leading to high capital investments. Additionally, harvesting of algae is difficult because concentrations are low. Large quantities of water are handled to concentrate algae with microstrainers, devices that employ a small liquid head to prevent compacting and clogging on the filter medium.

Table 1 Feedstock comparisons

Crop	Harvest time
Trees	Several years
Corn	Yearly
Sugarcane	Two crops per year in some countries
Grasses	Can be cut several times per year
Water hyacinth	4 days
Algae	1 day

In contrast, millions of dollars are spent each year to harvest and dispose of water hyacinth [32]. Waterways infested with water hyacinth will be improved and become more valuable when the biomass is harvested. Credits for its removal and disposal would help a biomass refinery. Harvesting of water hyacinth can also be improved by simply towing swaths of the highly connective mats to shore. The plentiful availability, low cost, and rapid growth of water hyacinth make it an ideal candidate for biofuel production, particularly in developing countries [1, 14, 16, 23, 25, 27]. Once a viable process has been developed, water hyacinth could be cultivated as an energy crop. A removal credit would not be applied in this case; however, low cultivation costs in existing waterways will make this economically feasible. Our economic analysis assumes methods for collection, concentration, pretreatment, and hydrolysis and permits experimentation with the parameters to find those that most influence these costs.

Process description

Early attempts to harvest water hyacinth from lakes and waterways involved the relatively ineffective use of conveyor belts, grapples, and derricks [4]. Cutters and flail-choppers, more recent advances, are more effective at destroying plants, but leave all the pieces in the water to rot and re-inoculate the lake [36]. Crushers, saw boats, and harvesters have also been used. Crushers and harvesters have the disadvantage of being extremely energy intensive and costly [37]. Harvesters, which "scoop" the hyacinth out of the lake, have the additional ecological disadvantage of also removing other flora and fauna from the water that may be present amongst the water hyacinth population. Therefore, this study considers a mechanical removal method more akin to the saw boat for harvesting water hyacinth.

Economical harvesting of a floating aquatic plant is subject to several constraints. The path to the shore should remain unobstructed, cleared areas should be re-inoculated with plants, and harvesting of the entire area should be timed so that a continuous collection process results. A reasonable alternative for cutting within these constraints is illustrated in Fig. 1.

Note that an area for cutting would be selected as connected to roughly the center of a lake sufficiently large enough so that a saw boat could move freely. One or more cutting zones would radiate from this point. The next cutting would be on one side of this cleared area such that the other side can grow fresh plants. In this way, the cuttings would rotate around the center point at a rate that

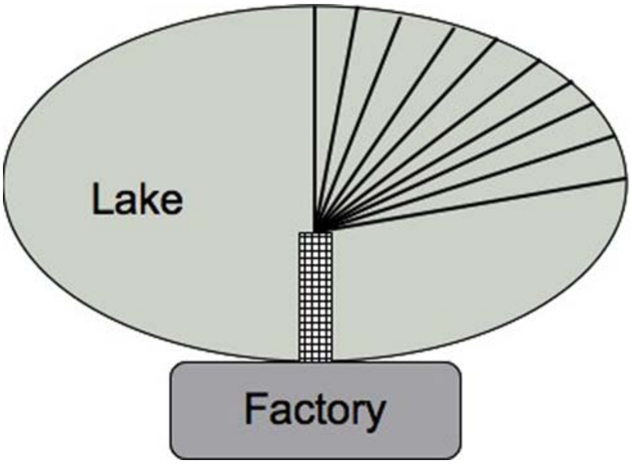

Fig. 1 Sketch of harvesting plan, with *lines* representing cutting zones. Note that void space between cut paths to allow for re-growth

allows for maximum re-growth of biomass and optimizes the productivity of the entire lake. Swaths of cut plants would be towed to the shore. The main channel to the central point should be wide enough that boats can pass each other.

The boat would be steered into the mass of plants to cut a swath determined by the offset of the cutting mechanism and the ability of the operator to edge close to the plants. Operators of other boats would collect swaths by tossing grappling hooks into them and towing them to shore.

Once the swaths of hyacinth mats have been hauled to shore, they will be fed immediately through a series of roll presses to remove excess water. *E. crassipes* is approximately 95 wt% water, which precludes transport to a remote refinery. Dewatering the plants through squeezing acts as both a pretreatment and a method to decrease storage/transportation costs. Presses for the sugar refining industry were researched to determine expected removal percentages. According to a manufacturer of presses (Fulton Iron & Manufacturing, L.L.C.), up to 97 wt% of the water present in fibrous herbaceous materials, such as *E. crassipes*, can be removed. It is estimated that the plant matter will have to be pressed as many as six times to achieve this dewatering goal. Due to the high water content of the plant (95 wt%), the pressed biomass will still contain approximately 36% water by weight, as calculated in Appendix A.

Water removed from the feed during pressing will be treated if necessary, and returned to the lake. The pressed biomass will be then moved on to silage, where it will undergo partial anaerobic digestion.

Much research has been devoted to the decomposition of water hyacinth [3, 5, 8, 11, 12, 13, 15, 17, 18, 25, 26, 41]. Studies have shown that bacterial decay activity occurs most rapidly within the first 14 days of decomposition [8, 11, 13, 25, 41]. A residence time of 14 days (see Table 2) was chosen for the digestor in our process to ensure the cellulose is sufficiently broken down, but not fully lost to carbon dioxide evolution.

Table 2 Comparison of pretreatments

Pretreatment	Residence time
Grinding or milling	10 min
Explosion	30 min
Acid soaking	180 min
Digestion or composting	14 days

Biomass requires pretreatment for cellulose hydrolysis so that acid or enzymes can penetrate the tough structure. Furthermore, the cellulose is in a matrix with hemicellulose and lignin that hinders the diffusion of enzymes and reagents. Steam explosion is an excellent pretreatment because it shatters the structure, reduces the crystallinity of the cellulose, and loosens the binding to other constituents. Unfortunately, some of the hemicellulose is degraded during steam explosion. Grinding and milling are popular pretreatment choices; however, digestion is less energy intensive and potentially equally effective.

It would seem from Table 2 that digestion or composting can be dismissed out of hand because the equipment would have to be many-fold the size of that for the other alternatives. However, the process becomes more attractive when storage is considered. A biomass refinery should store its feedstock to compensate for staggered delivery times. For example, trees or grasses cannot be harvested at all times of the year in the United States. A storage facility can furnish feedstock to the initial processing step during those periods without deliveries of fresh biomass. A reasonable time for storage depends on the particular feedstock. One month of storage might be logical for wood that can be harvested during most months of the year. Grasses would require more storage because there are more months when none will be received at the factory. These times match quite well with the residence time for pretreatment by digestion or composting. The structure of water hyacinth can be shattered by either partial anaerobic digestion or composting while causing little harm to the hemicellulose. In other words, combining storage and pretreatment allows digestion or composting to become viable [19].

Plant material naturally decays by autolysis of the cells by their own proteolytic enzymes [13]. Subsequently, other organisms participate in the decomposition. The release of small nutrient molecules attract these organisms that feed and multiply. Larger molecules are digested through pathways that include hydrolysis to monomers. In an aerobic environment, the eventual end products are mostly carbon dioxide and water. Rates are far slower in anaerobic environments, and intermediates accumulate [13]. Some large organic compounds such as lignin are essentially unchanged when conditions are anaerobic. Prolonged anaerobic detention results in the evolution of carbon dioxide and methane and the accumulation of partially digested or undigested residues and the organisms that carried out the transformations.

Anaerobic digestion is a mature technology that is widely used for reducing the amount of sludge in waste treatment plants. To mimic conventional anaerobic digestion, water hyacinth would have to be pulverized and suspended in water at a concentration that would flow to the bioreactor [5]. This would defeat the objective of water removal. If instead the intact water hyacinth is packed into a pile or a container (more akin to composting), there will be opportunities to drain water away.

Manufacturing cost estimation

The comprehensive plant design spreadsheet in Appendix A was created with the goal of estimating the cost of converting water hyacinth into fermentable sugars. The present analysis does not cover a complete biomass refinery. The remaining steps in the refinery are the same as in alternative schemes for making fuel ethanol from biomass.

Values such as yearly plant growth per acre, plant density, and mat connectivity, etc., taken from the literature became starting inputs for cost calculations. Vendors were researched or contacted for data on the energy requirements of commercially available harvesters and roll presses. In an effort to legitimize the estimations, a standardized manufacturing cost summary sheet for the chemical process industry was adapted for the agribusiness plan, and papers outlining bioethanol production economics were consulted [21, 22, 24, 33–35, 39, 40].

A lake covered with 300 acres of water hyacinth was chosen as the basis for the study. The annual growth rate of water hyacinth varies between 8 and 320 tons of dry matter per hectare per year, depending upon location and conditions [14, 30]. An annual growth rate of 100 tons DM/ha per year was used for the purpose of this study. With an average areal growth density of 14 kg/m^2 [29], this allows for approximately 780 wet tons of hyacinth plants to be harvested per day, as calculated by Eqs. 1 and 2.

$$M_T = \frac{\mathrm{AG}(907)(0.404)}{1 - R_{\mathrm{w,in}}} \tag{1}$$

$$M_D = \frac{M_T}{t_{\mathrm{yr}}} \tag{2}$$

where M_T is the total mass of the plants produced on the lake annually in kilograms per year, A is the total lake area covered with plants in acres, G is the annual growth rate in tons of dry matter per hectare per year, $R_{\mathrm{w,in}}$ is the percentage of water in raw water hyacinth, M_D is the amount of water hyacinth that can be harvested in a day in kilograms per day, and t_{yr} is the number of harvesting days per year. This gives the plants a 24-day harvest frequency, which is sufficient for re-growth [28]. The harvest frequency is calculated by Eq. 3:

$$f_H = \frac{A(4046)\rho_A}{M_D} \tag{3}$$

where ρ_A is the areal density in kg/m^2.

The energy requirements of the proposed harvester are not yet known and so the 100 kW commercially available Water Witch harvester [20] was used in the estimation. It is expected that the new design will require less energy, and therefore this was used as a maximum value. Assuming an 8-h work day, a cut speed of 45 m/min, and a 3.5-m wide swath of hyacinth mats, one harvester will be required to maintain the daily harvesting goal, as calculated by Eqs. 4–7.

$$A_H = w_{\mathrm{cut}} v_{\mathrm{cut}}(60) \tag{4}$$

$$A_{DH} = A_H t_D \tag{5}$$

$$M_H = A_{DH}\rho_A \tag{6}$$

$$N_H = \frac{M_D}{M_H} \tag{7}$$

where A_H is the area harvested in m^2/h, w_{cut} is the cut width in meters, v_{cut} is the cut speed in m/min, A_{DH} is the daily harvest per harvester in m^2/day, t_D is the hours harvested per day, M_H is the mass of plants harvested per harvester in kg/day, and N_H is the whole number of harvesters required. The total acreage harvested per day is

$$A_D = \frac{A_{DH}N_H}{4046} \tag{8}$$

where A_D is in acres per day. Our study shows that one harvester traveling under our specified conditions can actually cut more water hyacinth than is required per day ($A_D > M_D$), so we will restrict the cutting, and use the lesser of the two numbers to maintain the re-growth rate.

Additionally, Eqs. 9–12 show that three simple boats will be required to tow the mats to shore.

$$l_M = \frac{C_M(600)}{v_m\rho} \tag{9}$$

$$M_M = l_M w_{\mathrm{cut}}\rho_A \tag{10}$$

$$N_M = \frac{M_D}{M_M} \tag{11}$$

$$N_{RB} = \frac{N_M}{t_D(4)} \tag{12}$$

where l_M is the length of the mat in meters, C_M is the connectivity of the mat in Pa, v_M is the speed of the boats pulling the mats in m/s, ρ is the plant density in kg/m^3, M_M is the mass of the hyacinth mats in kg, N_M is the number of mats pulled per day, and N_{RB} is the number of operators required for the boats. Key assumptions in these equations are a time of 10 min to pull a mat to shore, and that one operator is capable of transporting four mats per hour. Scenarios were also investigated using both barges and a winch system to transport the floating hyacinth mats to the shoreline for processing; however, boats with a tow line proved to be the most economical, due to power consumption.

Once on shore, the hyacinth mats will go through a series of roll presses to remove 97% of the water. This is done both as a pretreatment step, and to reduce the volume for silage. The water hyacinth will still contain approximately 36% water by mass after the pressing, as shown by Eqs. 13–21.

$$M_{w,in} = R_{w,in} M_D \tag{13}$$

$$M_{B,in} = \left(1 - R_{w,in}\right) M_D \tag{14}$$

$$M_{P,hr} = \frac{M_D}{24} \tag{15}$$

$$M_{w,rem} = \frac{M_{w,in} R_{w,rem}}{24} \tag{16}$$

$$M_{T,out} = M_{P,hr} - M_{w,rem} \tag{17}$$

$$M_{w,out} = \frac{M_{w,in}}{24} - M_{w,rem} \tag{18}$$

$$M_{B,out} = \frac{M_{B,in}}{24} \tag{19}$$

$$R_{w,out} = \frac{M_{w,out}}{M_{T,out}} \tag{20}$$

$$R_{B,out} = \frac{M_{B,out}}{M_{T,out}} \tag{21}$$

where $M_{w,in}$ is the total mass of water in the entering plants in kg/day, $M_{B,in}$ is the total mass of fiber in the same units, $R_{w,in}$ is the total percentage of water removal desired, $M_{P,hr}$ is the mass of plant material processed per hour, $M_{w,rem}$ is the desired mass of water removed per hour, $M_{T,out}$ is the total mass of biomass leaving the presses per hour, $M_{w,out}$ is the mass of water remaining in the biomass per hour, $M_{B,out}$ is the mass of fiber in the biomass leaving the presses per hour, $R_{w,out}$ is the percent water in the biomass, and $R_{B,out}$ is the percent of fiber in the biomass. Additionally, it is to be noted that Eq. 15 marks the beginning of a continuous process—pressing is estimated to occur 24 h a day.

The power consumption of each roll press is calculated according to the manufacturer estimate in Eq. 22:

$$P_P = (18\,\text{hp-hr/ton})\left(\frac{M_{P,hr}}{907}\right)\left(1 - R_{w,in}\right) \tag{22}$$

where P_P is the individual power requirement of each press in horsepower. The number calculated by Eq. 22 is then multiplied by the number of presses to calculate the total press energy consumption (P_{PT}), as shown by Eq. 23:

$$P_{PT} = N_P P_P \tag{23}$$

where N_P is the number of roll presses required.

The plants will then be placed in silage for approximately 14 days to allow for decomposition of the cell walls [29–33]. Any loose liquid will be drawn off, processed, and returned to the lake.

The state of Florida spends approximately $4 million annually[1] to control 33,000 acres of water hyacinth [32]. Therefore, an annual removal credit of $130 per acre was applied to the cost estimation. The process as described will produce approximately 12,000 tons of dry biomass per year, at a cost of $40 per dry ton. All manufacturing cost estimates and calculations are shown in Appendix B. According to previous estimates by Turhollow [34] and the DOE [10], this places water hyacinths within the realm of economically competitive biomass feedstocks. Table 3 with best guesses for the assumptions, summarizes the contribution of each step into the final cost of the biomass. However, should water hyacinths be grown as an energy crop, the estimated removal credit of $3.22 per dry ton could not be applied.

Sensitivity analysis and discussion

A sensitivity analysis was performed using the manufacturing cost estimation generated for this process. While all the input factors for the process were varied to determine their effect on the final feedstock price per ton, only the dominant factors will be presented here.

As explained in the process description section, a method is proposed for slicing the thick mats of water hyacinth and towing them to shore. The width of the hyacinth swath has a pronounced effect on the ultimate price of the biomass, as shown in Fig. 2. This effect is not linear because as the cut width becomes wider, fewer harvesters (and thus operators) are required in a given day to harvest the 780 tons of hyacinth. Increasing the width beyond 9 m has little effect on the economics, because at that point only one harvester and operator are required,

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[1] According to Simberloff et al. [3] an average annual cost of $2.7 million was spent to manage 13,400 ha of water hyacinth mixed with water lettuce. The cost was adjusted for inflation using the CPI inflation calculator.

Table 3 Manufacturing cost estimation, revised values

Operating costs ($/dry ton biomass)	
Manufacturing expenses	
Direct	
Removal credit	$3.22
Operating labor	$13.30
Supervisory and clerical labor	$1.33
Utilities	
Electricity	$12.09
Gasoline	$2.05
Maintenance and repairs	$1.58
Operating supplies	$0.16
Indirect	
Overhead, packaging, storage	$4.05
Local taxes	$0.98
Insurance	$1.97
General expenses	
Administrative costs (25% of overhead)	$1.01
Depreciation	$4.92
Total cost to produce, per dry ton	$40.23

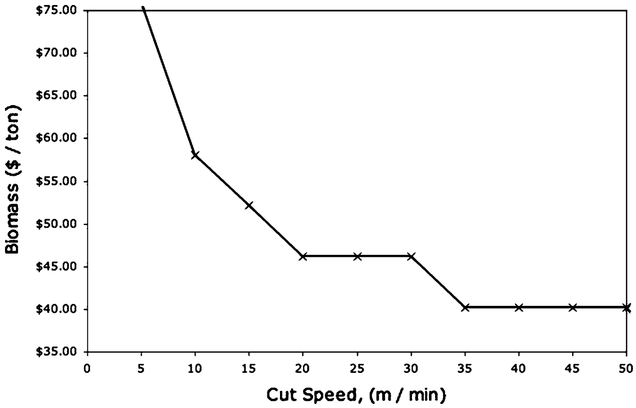

Fig. 3 Biomass price per dry ton as a function of harvester cut speed in meters per minute

making further reduction of costs impossible. This width may be restricted by the design of the apparatus for mechanical squeezing. Options such as folding the mat to make it fit into the squeezer have not been considered here.

The speed at which the harvester cuts the mats of hyacinths is another factor affecting final biomass price. Other commercially available harvesters can travel at top speeds of 6.5–8.5 knots [20], or approximately 200–260 m/min. At speeds above 35 m/min, only one harvester is required, and the price no longer drops in our estimation, as shown in Fig. 3. Depending on the productivity of the day, the harvester operator could then help out with other functions, thus eliminating the need for more operators. A potential drawback of higher harvester boat speeds could be accelerated degradation of the cutting saw. The optimal speed would have to be discussed with the design manufacturer. As expected, the price of biomass per dry ton increases linearly with both the harvester and transport boat energy requirements. However, the effect is slight, especially in the case of the transport boat. Therefore, if the energy requirements used in the estimation are incorrect, they will have little effect on the overall price of the biomass.

Electricity, used primarily to run the dewatering presses, is one final parameter that can be improved. Approximately 131 kW of electricity will be required per hour to run the presses. A standard value of $0.15 per kilowatt-hour was used in the estimation. Electricity could potentially be generated onsite through the burning of lignin or residual biomass, further reducing the price of the biomass.

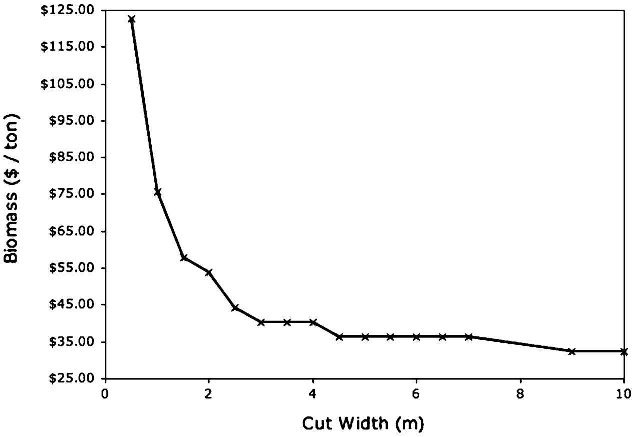

Fig. 2 Biomass price per dry ton as a function of harvester cut width in meters

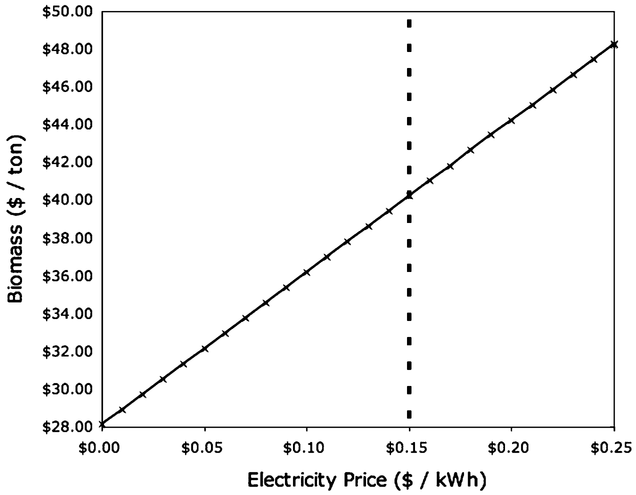

Fig. 4 Biomass price per dry ton as a function of electricity kilowatt-hour price

Figure 4 shows the sensitivity of the overall process cost to the price of electricity. Additionally, electricity could be obtained for less depending on the location of the plant and proximity to a power source.

Conclusions

Our preliminary analysis has shown that using water hyacinth as a feedstock could economically produce biomass at approximately $40 per ton dry mass, without the benefit of subsidies. This is in line with other estimates of less than $50 per ton of dry biomass [10]. While water hyacinth can be grown in temperate climates with the winter season preventing its undesirable spread, it is already growing in vast amounts in warmer climates. Millions of dollars are spent annually to remove water hyacinth from infested lakes and waterways worldwide [32]. While uses ranging from animal feed to paper-making have been implemented for this wastewater hyacinth [14, 23], using it as a biomass feedstock can benefit the community at large. We estimate that the collection costs for a biomass refinery will not be much greater that the various methods now needed for its control. These current control costs can be considered as credits for collection for the biorefinery, which would in turn lower production costs. As shown by this proposed process and life-cycle analysis, water hyacinth is as of yet a largely underutilized and cost-competitive resource for bioethanol production.

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Appendix A

Crop				
A	Lake area covered	300 (acres)	Parameter	
G	Annual plant growth	100 (tons DM/ha per year)	Parameter	[14, 30]
M_{T}	Plants grown on lake annually	2.20E+08 (kg/year)	$M_{\mathrm{T}} = \frac{\mathrm{AG}(907)(0.404)}{1-R_{\mathrm{w,in}}}$	Eq. 1
r_{A}	Plant areal density	14 (kg/m^2)	Parameter	[29]
t_{yr}	Days/year working	310 (days/year)	Parameter	
M_{D}	Mass that can be harvested/day	7.09E+05 (kg/day)	$M_{\mathrm{D}} = \frac{M_{\mathrm{T}}}{T_{\mathrm{yr}}}$	Eq. 2
Harvest				
w_{cut}	Cut width	3.5 (m)	Parameter	
v_{cut}	Cut speed	45 (m/min)	Parameter	[20]
A_{H}	Area harvested hourly	9,450 (m^2/h)	$A_{\mathrm{H}} = w_{\mathrm{cut}} v_{\mathrm{cut}}(60)$	Eq. 4
T_{D}	Hours harvested/day	8 (h)	Parameter	
A_{DH}	Daily harvest per harvester	75,600 (m^2/day)	$A_{\mathrm{DH}} = A_{\mathrm{H}} t_{\mathrm{D}}$	Eq. 5
M_{H}	Mass plants harvested per harvester	1.06E+06 (kg/day)	$M_{\mathrm{H}} = A_{\mathrm{DH}} \rho_{\mathrm{A}}$	Eq. 6
N_{H}	Whole number harvesters required	1	$N_{\mathrm{H}} = \frac{M_{\mathrm{D}}}{M_{\mathrm{H}}}$	Eq. 7[a]
A_{D}	Total acres per day harvested	18.7 (acres)	$A_{\mathrm{D}} = \frac{A_{\mathrm{DH}} N_{\mathrm{H}}}{4046}$	Eq. 8
f_{H}	Re-growth rate required to maintain	24 (days)	$f_{\mathrm{H}} = \frac{A(4046)\rho_{\mathrm{A}}}{M_{\mathrm{D}}}$	Eq. 3
P_{H}	Harvester energy requirements (each)	100 (kW)	Parameter	[20]
Transportation from lake to storage				
C_{M}	Connectivity of hyacinth mats	100 (Pa)	Parameter	[29]
v_{M}	Speed of pulling mat in	2 (m/s)	Parameter	
r	Plant density	167 (kg/m^3)	Parameter	[2]
l_{M}	Estimated length of hyacinth mats	180 (m)	$l_{\mathrm{M}} = \frac{C_{\mathrm{M}}(600)}{v_{\mathrm{m}} \rho}$	Eq. 9
M_{M}	Estimated weight of hyacinth mats	8.80E+03 (kg)	$M_{\mathrm{M}} = l_{\mathrm{M}} w_{\mathrm{cut}} \rho_{\mathrm{A}}$	Eq. 10
N_{M}	Number of mats pulled daily	81 (mats/day)	$N_{\mathrm{M}} = \frac{M_{\mathrm{D}}}{M_{\mathrm{M}}}$	Eq. 11
P_{RB}	Row boat energy requirements	5 (hp)	Parameter	
N_{RB}	Number of operators required	3	$N_{\mathrm{RB}} = \frac{N_{\mathrm{M}}}{t_{\mathrm{D}}(4)}$	Eq. 12[a]

Appendix A continued

Storage/decomposition				
M_D	Mass of plant material entering	7.09E+05 (kg/day)		
$R_{W,in}$	% Water in material	0.95 (mass %)	Parameter	[14]
$M_{W,in}$	Total mass water in entering material	6.74E+05 (kg/day)	$M_{w,in} = R_{w,in} M_D$	Eq. 13
$M_{B,in}$	Total mass fiber in enetering material	3.55E+04 (kg/day)	$M_{B,in} = \left(1 - R_{w,in}\right) M_D$	Eq. 14[b]
$R_{W,rem}$	Total water removal desired	0.97 (mass %)	Parameter	–[c]
$M_{P,HR}$	Mass of plant material processed per hour	2.96E+04 (kg/h)	$M_{P,hr} = \frac{M_D}{24}$	Eq. 15[d]
$M_{W,rem}$	Mass of desired water removed	2.72E+04 (kg/h)	$M_{w,rem} = \frac{M_{w,in} R_{w,rem}}{24}$	Eq. 16
$M_{T,out}$	Total mass leaving presses	2.32E+03 (kg/h)	$M_{T,out} = M_{P,hr} - M_{w,rem}$	Eq. 17
$M_{W,out}$	Mass water remaining in biomass	8.42E+02 (kg/h)	$M_{w,out} = \frac{M_{w,in}}{24} - M_{w,rem}$	Eq. 18
$M_{B,out}$	Mass biomass leaving presses	1.48E+03 (kg/h)	$M_{B,out} = \frac{M_{B,in}}{24}$	Eq. 19
$R_{W,out}$	Percent water leaving presses	36.31% (mass %)	$R_{w,out} = \frac{M_{w,out}}{M_{T,out}}$	Eq. 20
$R_{B,out}$	Percent biomass leaving presses	63.69% (mass %)	$R_{B,out} = \frac{M_{B,out}}{M_{T,out}}$	Eq. 21
N_P	# of presses required to achieve %	6	Parameter	–[c]
P_P	Energy used by each press	29.3 (hp)	$P_P = (18\,\text{hp-hr/ton})\left(\frac{M_{P,hr}}{907}\right)\left(1 - R_{w,in}\right)$	Eq. 22[e]
P_{PT}	Total energy used	175. 9 (hp)	$P_{PT} = N_P P_P$	Eq. 23

[a] Rounded up

[b] 1 Day is equivalent to 8 h

[c] Manufacturer specification

[d] Process becomes continuous

[e] Manufacturer general rule of thumb: 18 hp/ton fiber per h

Appendix B

Capital				
C_S	Site	\$1,000,000	Parameter	
C_E	Equipment	\$192,000	Parameter	
C_{fix}	Fixed capital costs	\$1,192,000	$C_S + C_E$	
C_W	Working capital	\$119,200	$0.1 C_{fix}$	[35]
C_T	Total capital costs	\$1,311,200	$C_W + C_{fix}$	
Manpower				
MH_H	Harvesting	8 (Manhours/day)	$T_D M_H$	
MH_T	Transporting	24 (Manhours/day)	$T_D N_{RB}$	
MH_P	Pressing/digestion	8 (Manhours/day)	Parameter	
C_{wage}	Wage + benefits	\$13.00 (\$/Manhour)	Parameter	
$C_{wage,T}$	Total, per year	\$161,200.00 (\$/year)	$(MH_H + MH_T + MH_P) C_{wage} t_{yr}$	
$C_{wage,S}$	Supervisory labor, per year	\$16,120.00 (\$/year)	$0.1 C_{wage,T}$	[35]
Maintenance and operation				
$C_{fuel,H}$	Fuel for harvester	\$22,320 (\$/year)	$t_{yr} t_D$ [3 (\$/gal)] ([$N_H P_H$ 1,000 (W/kW) 3600 (s/hr)]/[43E6 (J/kg)]) [264.172 (gal/m^3)/737.22 (kg/m^3)]	
$C_{fuel,RB}$	Transport power required	\$2,498 (\$/year)	$t_{yr} t_D$ [3 (\$/gal)] ([$N_{RB} P_{RB}$ 1000 (W/kW) 3,600 (s/hr)]/[43E6 (J/kg)]) [264.172 (gal/m^3)/737.22 (kg/m^3)]	
C_P	Mill press power	\$146,473 (\$/year)	[$N_P P_P$0.746 (kW/hp)] 0.15 (\$/kWh) 24 (hr/day)t_{yr}	
C_{MR}	Maintenance and repairs	\$19,200 (\$/year)	$0.1 C_E$	[35]

Appendix B continued

C_{OS}	Operating supplies	\$1,920 (\$/year)	$0.1C_{MR}$	[35]
C_O	Overhead	\$49,130 (\$/year)	$0.25(C_{wage,T} + C_{wage,S} + C_{MR})$	[35]
C_{LT}	Local taxes	\$11,920 (\$/year)	$0.01C_{fix}$	[35]
C_I	Insurance	\$23,840 (\$/year)	$0.02C_{fix}$	[35]
C_{Admin}	Administrative costs	\$12,283 (\$/year)	$0.25C_O$	[35]
C_{MO}	Total maintenance and operation costs	\$466,903 (\$/year)	$C_{wage,T} + C_{wage,S} + C_{fuel,H} + C_{fuel,RB} + C_P + C_{MR} + C_{OS} + C_O + C_{LT} + C_I + C_{Admin}$	
Depreciation				
C_D	Straight-line depreciation	\$59,600 (\$/year)	$0.05C_{fix}$	
Credit				
C_{cred}	Water hyacinth removal credit	\$130 (\$/acre)	Parameter	[7, 32]
$C_{total,yr}$	Total annual cost	\$487,503 (\$/year)	$C_{MO} + C_D - (C_{credA})$	
Biomass production				
$M_{biomass}$	Bioimass produced annual	1.21E+04 (ton/year)	$[M_{B,out}/907.18\ (\text{kg/ton})]\ [24(\text{hr/day})]t_{yr}$	
C_{Final}	Price per ton to produce	*\$40.22 (\$/ton)*	$C_{total,yr}/M_{biomass}$	

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