Integrating animal manure-based bioenergy production with invasive species control: A case study at Tongren Pig Farm in China

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ABSTRACT

Integrated approach and bioresource engineering are often required to deal with multiple and interactive environmental problems for sustainable development at local and regional scales. Pig farming has flourished with fast growing economy and increasing human demands for meat in China. Water hyacinth (Eichhornia crassipes), a noxious invasive species, has encroached into most of the local rivers and lakes. Both the wastes from the booming pig farms as well as the massive plant materials of water hyacinth have caused a range of serious ecological and environmental problems. Here we present an integrated sustainable, ecological and experimental study that was designed to deal with these two problems simultaneously. Our experimental results showed that the mixtures of water hyacinth with pig manure consistently had much higher biogas production than pig manure alone, and that the highest biogas production was achieved when 15% of the fermentation substrates were water hyacinth. Our analysis further revealed that the changing C/N ratio and the lignin content in the fermentation feedstock due to the addition of water hyacinth might be two important factors affecting the biogas production. We also found that the solar-powered water-heating unit significantly increased the biogas production (especially in winter time). Overall, the project proved to be successful ecologically and socially. Through such an integrated approach and bioresource engineering, wastes are treated, energy is harvested, and the environment is protected.

1. Introduction

Integrated approach and bioresource engineering are often required at least as part of the solution to sustainable development at local and regional scales. This is especially true for human-dominated landscapes in which multiple environmental problems must be dealt with simultaneously. With the rapid developments of the Chinese economy in recent decades, people’s living standards have also improved rapidly, which in turn have increased the demand for meat consumption steadily. Consequently, the livestock industry in China has been expanding swiftly. Dominant management approaches have also been changing from traditional scattered and unorganized livestock raising practices to large-
scale and centralized livestock farming systems. These centralized systems are able to not only improve the efficiency but also reduce the costs of livestock production. However, they also result in highly concentrated livestock wastes (animal feces, urine, and feed residues). These wastes, if not treated properly, can lead to a variety of environmental problems, including the contamination of soil, water, and air as well as human health threats [1–5]. These problems clearly defy the principles of sustainable development, and thus must be effectively dealt with. Because livestock wastes contain much biomass, utilizing them as raw materials to produce energy can not only help solve environmental problems but also alleviate energy problems for local people. It is reported that the total animal manure has reached 3 G t per year in China, and there are 3800 large-scale centralized systems that utilize the manure for fermentation to produce biogas. While a number of examples of this approach exist in many parts of the world [1–4,7,8], we have taken a step further to explore how to integrate such livestock waste treatment with invasive species control to achieve a win–win outcome.

Water hyacinth (Eichhornia crassipes) has become one of the most notorious invasive plants in the world [9,10]. Because of the absence of natural enemies in new habitats and the eutrophication of water bodies, the exceptionally high reproductive capability of water hyacinth allows it to expand its distribution range rapidly in lakes and rivers to form massive floating mats of interwoven individuals. The invasion of water hyacinth has affected ship navigation, irrigation and hydropower facilities, fisheries, native biodiversity, and, consequently, the local economy in many parts of the world [10–13]. At present, four ways have been developed to control water hyacinth: physical control, chemical control, biological control, and integrated pest management (IPM). While all the methods have their pros and cons, physical removal has been the primary approach taken in China because of its simplicity in operation and the people’s concerns about chemical treatment. The harvested water hyacinth biomass has often been buried or dumped on the riverside. Burying water hyacinth takes up much land, and biogas generated from such landfills presents hidden dangers. On the other hand, completely exposed dumps of water hyacinth cause secondary pollution due to decomposition. Thus, efforts have been made worldwide to combine the treatment and utilization of water hyacinth, specifically producing biogas using water hyacinth as feedstock [14–17]. However, the energy conversion efficiency of utilizing water hyacinth alone is usually quite low because of incomplete fermentation due to the high lignin content in water hyacinth materials [17,18].

In Haining of Zhejiang Province, China, large pig farms produce a large amount of manure, and water hyacinth has invaded most of the rivers and ponds [10]. In a pioneering sustainable project to deal with the problems of pig manure and water hyacinth simultaneously, we have attempted to explore the possibility of improving the biogas production efficiency by mixing pig manure and water hyacinth through a large-scale integrated sustainable and bioresource engineering experiment. The objectives of our study were: (i) to examine if there would be an optimal proportion of water hyacinth for mixing with pig manure to maximize biogas production; (ii) to explore the feasibility of utilizing solar energy to facilitate pig manure fermentation; and (iii) to evaluate the ecological and social benefits of the sustainable project.

2. Experimental design and methods

2.1. Overall experimental design

Our experimental site is located next to the Tongren Pig Farm in the Haining municipality, Zhejing Province, China. Tongren Pig Farm, which is located at 30° 27′ 34.78″ N and 120° 38′ 55.48″ E, is an industrial and cooperative farm in the Haining municipality. The experimental facility was composed of eight 50 m³ underground digesters (fermentation tanks) and two 300 m³ ground-level digesters (Fig. 1). In order to accurately gauge the biogas production of each digester, a biogas flow meter was installed on each fermentation tank. One advantage of underground digesters is that temperature changes much less rapidly than aboveground, so it is easier to maintain a relatively constant temperature for the fermentation process. Also, the construction cost of an underground digester was lower than that of a ground-level digester. The 8 underground digesters were divided into two groups, and digesters in each group were connected serially. Such serial connections for underground digesters allowed for a more complete fermentation compared to parallel connections. The two ground-level fermentation tanks were connected in parallel to the rest of the digester systems (Fig. 1). Pig manure and water hyacinth materials went into the underground digesters first, then the fermentation process continued in the ground-level digesters, and finally the fermentation residues were kept into the deposition pool.

It is well known that temperature is a critically important factor affecting the biogas production through fermentation [19,20]. While low temperature reduces biogas productivity, increasing the temperature of the fermentation tanks requires energy input. In Haining, heating up the digesters with the common energy source (primarily electricity) was not feasible because this would compete for the limited energy against other uses by the local residents and industries. To solve this dilemma, we introduced a solar-powered water-heating system to the fermentation system (Fig. 1; see more details on the solar system below). This solar system was able to provide enough warm water constantly to the digesters, so that the fermentation process was sped up in the cold season.

In order to expand the range of utilities of the bioenergy, we wanted to transform biogas into electricity. The biogas produced from the fermentation tanks was transported into biogas storage tanks connected to an electrical generator through an airtight pipeline. The electricity generator had a power of 50 kW and was driven by biogas and diesel together. The solid residues of biogas production were used as organic manure, while the fermentation liquid was used for irrigating a mulberry field near the facility. Thus, the design of
the Tongren integrative biogas production project followed
the principle of multiple uses in system approach and bio-
resource engineering. The upper limit of the biogas system
can deal with the manure from 10,000 commercial pigs every
year.

2.2. Materials and methods

The solar-powered water-heating system was attached
to a tank of 1.96 m in diameter and 2.1 ms in height, which could
contain 6 t of water when filled up. Driven by the temperature
gradient, water circulated in the tank and allowed incoming
cold water to be warmed up constantly. To reduce the heat
loss from the water-heating system, an insulating cover was
constructed using rubbery and plastic materials reinforced
with glass fiber and aluminum foils. The system consisted of
18 groups of solar energy collectors, each of which included 56
individual collector tubes. The total system occupied an area
of 100.8 m². The outer diameter of each solar energy collecting
tube was about 48 mm, the inner diameter about 38 mm, the
wall thickness about 1.5 mm, and the length about 1.5 m. The
mean daily efficiency of these solar energy collecting tubes
was 51%.

Water hyacinth was collected from a river near the Tong-
ren pig farm. The plant materials were then mechanically
crushed into pieces of about 6 mm (diameter) in dimension. Previous studies have shown that this size was optimal for
water hyacinth-based biogas production in terms of fer-
mentation efficiency and feedstock handling [17]. The pig manure
was collected from the Tongren pig farm, which was fed into
the acidification pools (at the entrance to the underground
digesters to pre-fermentation) by local farmers with push-
carts. The farmers collected 10 pushcarts of pig manure
everyday, each of which was 200 kg. This amounted to 2 t of
pig manure per day, or 400 kg of dry pig manure (the water
content of fresh pig manure was 80%).

To determine an optimal mixture of water hyacinth and
pig manure, we explored four different combinations
(Table 1). The mixtures were put into one (underground
fermentation tank team 1 seen from Fig. 1) of the two groups
of underground digesters whereas the other group (under-
ground fermentation tank team 2 seen from Fig. 1) was used as
the experimental control (CK), filled with 100% pig manure.
The duration of the fermentation experiment was 30 days,
and biogas production of the two groups of digesters was
recorded every day.

Fermentation liquid strength was about 8%, hydraulic
retention time (HRT) was about 10 days, solid retention time
(SRT) was about 60 days, COD for input was about
4000–6000 mg L⁻¹, COD for fermentation was about
3500 mg L⁻¹, COD for output was about 800 mg L⁻¹, and the
yield of biogas with dry pig manure was about 0.6 L g⁻¹.

To determine the effects of water temperature on
fermentation efficiency, the experiment was run with warm
and cold water, respectively. In this case, all other factors,
such as pig manure quantity, solution density, pH, and
fermentation time, were kept the same in the two digester
groups (treatment and CK). Water temperatures in the tanks
and ambient environment were monitored throughout the
experiment. The experiment ran from the middle of
February through March for 5 weeks, with the warm water
temperature at about 40 °C and the cold water temperature
at about 6 °C.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water hyacinth</td>
<td>10%</td>
<td>15%</td>
<td>20%</td>
<td>25%</td>
<td>0</td>
</tr>
<tr>
<td>Pig manure</td>
<td>90%</td>
<td>85%</td>
<td>80%</td>
<td>75%</td>
<td>100%</td>
</tr>
</tbody>
</table>
3. Results

3.1. Effect of adding water hyacinth to pig manure on biogas production

With all other factors kept constant, the mixtures of water hyacinth and pig manure had consistently higher biogas production than pig manure alone (Fig. 2). Specifically, biogas production increased by 31.2%, 46.1%, 34.2%, and 32.2% with 10%, 15%, 20%, and 25% of the mixtures being water hyacinth, respectively (Fig. 2A–D). These results clearly indicated that the combination of 15% water hyacinth with 85% pig manure was an optimal mixture for biogas production (Fig. 3). The fluctuations of the curves reflected the variations in environmental conditions in the experimental site (primarily ambient temperature). For example, the generally increasing trend in biogas production from fermentation both with and without water hyacinth shown in Fig. 2A corresponded to a gradual increase in temperature during the same period of time.

To explain the effects of adding water hyacinth on biogas production, we also measured the carbon:nitrogen (C:N) ratio of the fermentation substrates for different water hyacinth treatments. Our results showed that the C:N ratio increased linearly as the proportion of water hyacinth in the fermentation substrates increased progressively from 10%, 15%, 20%, to 25% (Fig. 4).

Our findings were accord with previous reports on biogas production with water hyacinth, Madamwar et al. [21] also observed a marked increase in degradation and biogas production when water hyacinth plants were mixed with cowdung at a ratio of 7:3, Kivaisi and Mtila [22] also reported that the overall extent of degradation obtained for the mixture of the water hyacinth shoots with cowdung (7:3) was about 10% higher than that of the water hyacinth shoots alone.

3.2. Effect of solar-powered water heating on pig manure fermentation

The hot water constantly generated by the solar-powered heating system was able to maintain a relatively constant and high temperature in the fermentation tanks. As a result, the energy conversion rate of pig manure was up to 9.63% with hot water from merely 7.06% without the addition of hot water. This means that the use of the solar-powered water-heating unit led to a 36.4% increase in biomass energy conversion efficiency with pig manure fermentation (Table 2).
3.3. Electricity generation with biogas

As described earlier, the biogas produced through the fermentation were transported from the digesters to a 50 kW electric generator to output electricity. This process required mixing biogas with diesel. On average, 116.86 MJ of electricity were generated per hour by pig manure without water hyacinth, consuming 20.58 m³ of biogas and 1.5 kg of diesel. The experimental facility produced 500 m³ of biogas per day, or an annual output of 160,000 m³ (operating for 320 days). Because generating 3.6 MJ of electricity required 0.24 kg of diesel, 1.5 kg of diesel alone would generate 22.5 MJ of electricity. Thus, of the total amount of electricity generated by the mixture of diesel and biogas, the contribution of diesel was 19.9% whereas biogas accounted for 80.1%. This means that 1 m³ of biogas generated 5.69 MJ of electricity, which was higher than the reported values of 4.32–5.4 MJ by Li et al. [23]. Based on these numbers, the annual electricity output was 910.8 GJ. When 10%, 15%, 20%, and 25% of the fermentation substrates were water hyacinth, the electricity output was increased by 24.2%, 36.9%, 27.4%, and 25.8%, respectively.

3.4. Organic manure from fermentation residues

The remaining solid residues of fermentation were output as organic manure with a yield of about 480 t per year. This organic manure contained more than 35% of organic matter, about 6% of nitrogen, phosphorus, and potassium, and approximately 18% of moisture [24]. The liquid form of fermentation wastes, also as organic manure, was used to irrigate a mulberry orchard and a rice paddy field through pipelines.

4. Discussion

4.1. Mechanisms for increased biogas production with water hyacinth and pig manure mixtures

Why did the mixtures of water hyacinth and pig manure have higher biogas productivity than pig manure alone? There may be several possible mechanisms responsible for the increase in biogas production with water hyacinth addition. First, water hyacinth itself contains biomass energy which contributes to biogas production through fermentation. Second, mixing water hyacinth with pig manure makes the C:N ratio of the feedstock more suitable for fermentation. Previous studies have indicated that the optimal C:N ratio for fermentation was approximately 20:1 to 30:1 [25]. The C:N ratio of the dry matter is 13.72:1 for pig manure and 22:1 for water hyacinth (Table 3). Thus, mixing water hyacinth with pig manure increased the C:N ratio of the fermentation substrate, which could accelerate the growth of fermentation bacteria, resulting in more biogas production [26]. Third, water hyacinth materials contain high concentrations of metal ions such as Fe³⁺, Zn²⁺, Ni²⁺, Co²⁺, and Cu²⁺ (Table 3), which can facilitate the fermentation process to produce more biogas [27].

Why did the biogas production not continue to increase with the increase in water hyacinth proportion even though the C:N ratio of the fermentation substrates did? This was probably because of the high lignin content of water hyacinth. As the proportion of water hyacinth in the fermentation substrates increased, so did the lignin content. It has been documented elsewhere that high lignin content could reduce biogas production [18]. So, the overall effect of adding water hyacinth on biogas production in our experiment was determined, to a large extent, by the balance between the positive effect of increasing the C:N ratio and the negative effect of increasing lignin content. As a result, the optimal substrate mixture that gave rise to the highest biogas production emerged around 15% of the feedstock being water hyacinth.

4.2. Social benefits

The project created 8 jobs, including one administrative person and seven workers. It also stimulated the development of the pig farming industry. The number of breeding pigs in the Tongren Pig Farm increased from 150 in 2001 to 472 in 2005, producing 10,000 commercial pigs. Meanwhile, the number of employees of the pig farm increased by 20% each year. Because Haining was located in a rapidly developing region of China, energy supply was in high demand. The electricity generated by the biogas facility helped alleviate the problem of electricity shortage, especially during the summer time.

Table 2 – Effect of solar-powered water heating on pig manure fermentation.

<table>
<thead>
<tr>
<th>Group</th>
<th>Pig manure (GJ)</th>
<th>Solar converted energy (GJ)</th>
<th>Biogas (GJ)</th>
<th>Pig manure energy convection rate (%)</th>
<th>Increasing (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot water</td>
<td>286</td>
<td>45</td>
<td>27.5</td>
<td>9.63</td>
<td>36.4</td>
</tr>
<tr>
<td>Cold water</td>
<td>286</td>
<td>/</td>
<td>20.2</td>
<td>7.06</td>
<td></td>
</tr>
</tbody>
</table>
4.3. Environmental benefits

From an ecological standpoint, the Haining biogas generation project helped improve several local environmental conditions through integrative and multiple utilization of pig manure and the invasive species of water hyacinth. For example, the transformation of livestock wastes into usable energy significantly reduced the level of pollution in neighboring lands and water bodies. Second, because pathogenic microorganisms in pig manure were killed in the process of organic manure processing before being exported from the facility, an important threat to human health was greatly reduced. Third, the use of solid and liquid organic manure produced by the biogas generation process prevented the heavy application of chemical fertilizers, which further reduced non-point pollution. In addition, previous studies have shown that such organic manures could improve soil structure and fertility [30–35]. Fourth, using solar energy instead of fossil fuel to provide heated water could save about 9.93 t of standard coal.

5. Conclusion

The Haining sustainable and bioresource engineering project of integrative biogas production was quite successful based on our benefit analysis considering ecological and social factors. There are, however, a couple of technical aspects of the project that still needs further improvement: (1) reduction (or replacement) of diesel fuel in the electricity generation process would be desirable, and (2) some measures need to be developed to make sure that the solar-powered water-heating system operates uninterruptedly and adequately even in frequently cloudy winter months. Overall, the experimental study provided not only valuable empirical data for optimizing biogas production using mixtures of pig manure and water hyacinth, but also highlights some key components of a sustainable and bioresource engineering project. As the most populous country in the world, China is faced with a myriad of environmental problems from the rapid economic growth across the country. Integrated approach and bioresource engineering that simultaneously consider environmental, economic, and social factors will play an increasingly important role in the rehabilitation and improvement of China’s environment at local and regional scales. Our project is just one such example, and many more will be needed in the future.

Acknowledgement

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### Table 3 – Chemical compositions of water hyacinth (dry matter, %) and pig manure (dry matter, %) [28,29].

<table>
<thead>
<tr>
<th>Chemical Properties</th>
<th>C</th>
<th>N</th>
<th>P</th>
<th>K</th>
<th>Ca</th>
<th>Mg</th>
<th>Na</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water hyacinth</td>
<td>23.0</td>
<td>35.0</td>
<td>1.6</td>
<td>0.3</td>
<td>3.8</td>
<td>1.7</td>
<td>0.6</td>
</tr>
<tr>
<td>Pig manure</td>
<td>13.7</td>
<td>31.6</td>
<td>2.3</td>
<td>1.2</td>
<td>1.6</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

### References


