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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-

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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. About 22 M households have small scale biogas plants which produce 9.5 km^3 biogas, and there are 3800 large-scale biogas plants which produce 318 hm^3 biogas, but most of the animal manure in China is not treated [6]. If all the livestock manure was treated to produce biogas, the total energy would be 3.77 EJ, the total energy consumption of China in 2006 was 72.1 EJ, so 5.23% of China's energy could be met from 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 hydroelectricity 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 m^3 underground digesters (fermentation tanks) and two 300 m^3 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