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An Advanced Biogas Plant for Bio-Circular Economy from Pig Manure in Taiwan

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ABSTRACT

Taiwan has more than 7,400 pig farms and 5.5 million pigs. The annual output value is about US$2.3 billion, accounting for 43% of the livestock industry. It is one of the most important agricultural economic sectors in Taiwan. However, due to the large number of herds, a huge amount of pig manure and urine are continuously discharged from the livestock farms. If they are not treated very well, it will seriously affect the environment and ecology. Pig manure contains a large amount of degradable solids, which is a high concentration organic wastewater. This high concentration organic wastewater undergoes a typical anaerobic fermentation process called three-step piggery wastewater treatment (TPWT), and biogas will be generated during the treatment process. Biogas is a combustible gas and its main component is methane, which accounts for 50 to 65% of the volume of biogas. In this study, a commercial scale of two stage anaerobic digestion (AD) treatment is established in central Taiwan. The processes followed the order of regulation, 1st AD, 2nd AD, sedimentation, aeration, and final sedimentation. The most different matter between two-stage AD and TPWT is in the solid-liquid separation process, the two-stage AD can treat wastewater without the solid-liquid separation in a higher solid content. The removal efficiency of chemical oxygen demand (COD) in two-stage AD is 95.7%, which is 12.4% higher than anaerobic fermentation of 83.3% in TPWT. The biogas production or biogas power generation has the benefits of reducing greenhouse gas (GHG) emissions, saving energy expenditure, and improving the quality of discharged water to promote the sustainable operation of the livestock environment. It has been used in overseas pig farming for many years and is one of the best applications of circular economy and biomass energy.

Keywords: Bio-circular economy, biogas production, pig manure, bio-electricity, greenhouse gas emissions.

INTRODUCTION

Agricultural residues and wastes such as rice straws, bagasse, kitchen wastes, animal husbandry wastewater, etc. can generate energy such as electricity and heat through the generation of biogas, and such a technology has been applied in 19,000 large-scale biogas power plants in Europe (Fatih Demirbas, Balat, & Balat, 2011). The two-stage biogas production technology "HyMeTek" developed by Feng Chia University in Taiwan, mainly converts the traditional single-stage biogas production process (acidification and methanation in one reaction tank) into a high-efficiency, two-stage hydrogen and methane production process (hydrogen production and methane production are divided into two reaction tanks to complete the advanced biogas production process) (D.-T. Ta, Lin, & Chu, 2020), and such a technology is the new trend in the current global development of high-efficiency biogas technology (Chu, Vo, & Chen, 2020; Chu & Wang, 2017; Nguyen, Chu, & Ou, 2021; D. T. Ta, Lin, Ta, & Chu, 2020). So far, this technology can increase the traditional biogas production by 8-43% (Schievano, Tenca, Lonati, Manzini, & Adani, 2014).

The biohydrogen research team of Feng Chia University developed HyMeTek technology in batch flasks in the laboratory since year 1998, and then developed a continuous bioreactor to produce hydrogen since year 2000 (Chu, Zheng, Chen, & Bhuyar, 2021; Lee, Lin, & Chang, 2006; Lee, Lo, Lo, Lin, & Chang, 2004). Finally, the team screened an immobilized and optimized biological hydrogen production bacteria in the laboratory, which achieved the world's fastest biological hydrogen production rate (15 m^3/L/hr) and published in an academic paper on International Journal of Hydrogen Energy in 2006 (Chu, Wu, & Shen, 2012; C.-N. Lin, Wu, & Chang, 2006; Wu, Chu, & Yeh, 2013). So far, no international R&D team has exceeded this record. However, the high hydrogen production rate does not mean that the technology can be commercialized (Chu *et al.*, 2011). Therefore, Feng Chia University biohydrogen research team began to develop its commercial technology in 2006, with the support of the Energy Bureau’s projects, combined with the support of the Ministry of Science and Technology, the Ministry of Education and the outstanding projects of Feng Chia University. On the campus of Feng Chia University, the world’s first pilot plant for biohydrogen production was then built in 2006 (Figure 1) (C.-Y. Lin *et al.*, 2010). The plant modified three evolutions with the addition of methane production tanks, biohydrogen refueling stations and other equipment. Feng Chia University has also developed a “mobile biogas synergy power pilot plant" which has been verified onsite at a brewery and food factory in central Taiwan (C.-Y. Lin *et al.*, 2021; Liu, Zheng, Wu, & Chu, 2016). (Figure 2)

Figure 1. The world’s first pilot plant for biohydrogen production on the campus of Feng Chia University, Taiwan.

Figure 2. Mobile biogas synergy power pilot plant designed by the Green Energy Development Center, Feng Chia University, Taiwan

The aims of this study is to try to establish one of new anaerobic biogas production system "HyMeTek" in Taiwan and to increase the organic conversion efficiency in the pig farm wastewater treatment process. Since the traditional three-stage wastewater treatment system has poor gas output efficiency, if this new system can work very well and get a promising biogas production rate and COD removal efficiency, this will not solve the odor problem nearby the pig farm and also earn the economy profit by selling the feed-in-tariff rate of the renewable energy set by the government. Under the condition that the input and output are not in line with economic benefits, farmers have little profit and low investment input willingness. But recently, biogas power generation has finally got a new outlook by an advanced biogas production system, the so called "HyMeTek".

SETTING UP THE FIRST ADVANCED BIOGAS POWER GENERATION COMMERCIAL PLANT IN TAIWAN

Nice Garden Company was founded in 1984 in Taiwan which deals specifically in nutrition and health products for aquaculture as well as livestock sectors. The business scope includes animal husbandry, animal nutrition production, food processing, and factories which are also used for sightseeing purposes. Nowadays, pig manure and urine are regarded as a sources of biomass under the concept of circular economy that manure has been effectively returned to farmlands. Not only do they contribute to the reduction of discharged wastewater but also to reduce their GHG emissions and global warming effect. It could provide nutrients for crops as organic fertilizers and can reduce chemical fertilizer expenditures. The biogas can be used for piggery room temperature insulation equipment after converting to electricity by internal combustion engine. After wastewater treatment, the recycled water has reached the discharge standard and can be used to clean the piggery. It is fully in line with the definition of circular economy!

Because of the development of the pork brand of "Choice Pig," Nice Garden Company purchased the 30-year-old "Xin He Xing" pig farm in Nantou county in 2011 as a demonstration field, as well as for educational training and development of products. After the purchase, it was found that the wastewater treatment system was too old, and the generated odor often troubled nearby neighbors. To protect the environment and enhance the brand image, Nice Garden Company decided to invest in the new wastewater treatment system and biogas power generation equipment at the end of 2017.

However, "Xin He Xing" pig farm raises only about 2,000 pigs, and it is not economical to invest in biogas for power generation. Fortunately, the Green Energy Development Center and the Institute of Green Products of Feng Chia University have won four patents on "Two-stage High-efficiency Anaerobic Fermentation Technology, HyMeTek." Nevertheless, each pig can produce about 0.1 cubic meters of biogas per day in their traditional wastewater treatment system. This new-generation biogas power generation technology coupled with two-stage of anaerobic biogas production system can increase the amount of biogas by 30%-40% (Baldi, Pecorini, & Iannelli, 2019), and has good power generation efficiency (Massanet-Nicolau, Dinsdale, Guwy, & Shipley, 2015), which is very suitable for domestic small pig farms. (Figure 3)

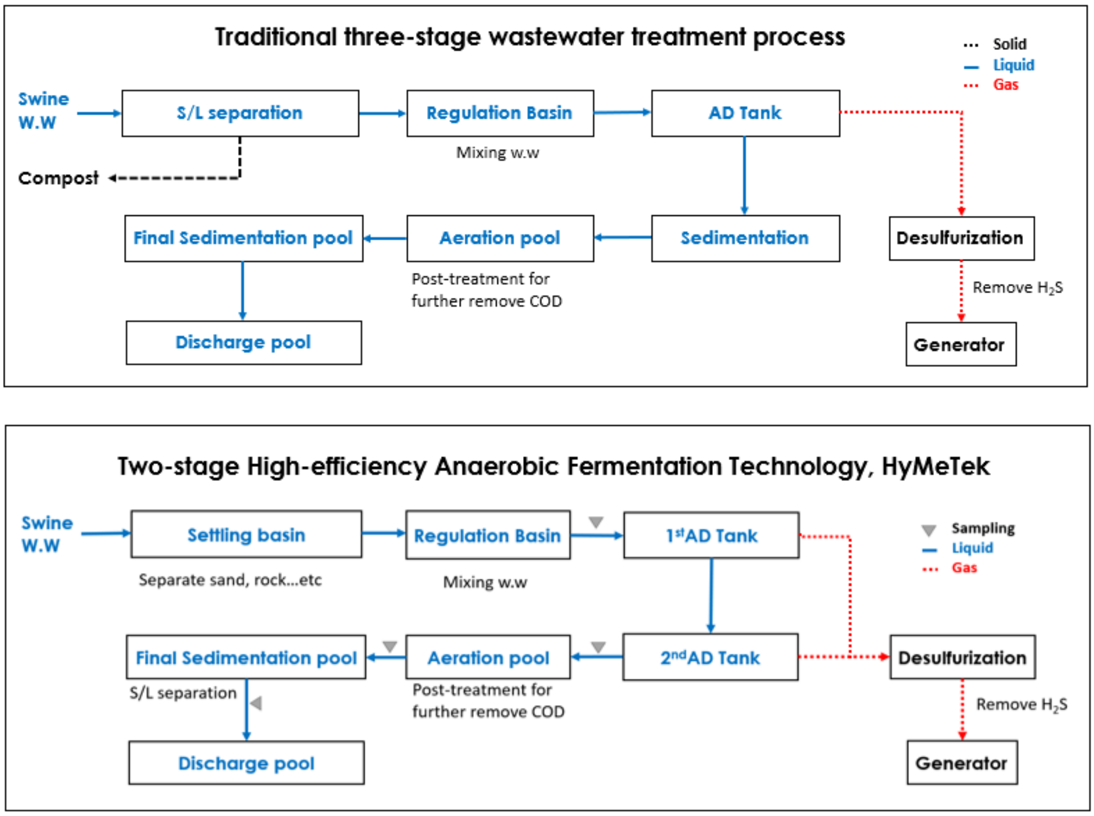

Figure 3. Process comparison between traditional process and HyMeTek

In a traditional three-stage wastewater treatment system, solid-liquid separation is performed to separate solid and liquid matters after collecting pig manure and urine. The solid is used for composting to fertilize the field; the liquid is subjected to anaerobic fermentation to produce biogas. However, the amount of biogas produced was limited without increasing the organic content in the liquid fraction to generate electricity. Feng Chia University research team found that the solid part is rich in organic matter, which can provide anaerobic bacteria fermentation in proper conditions for biogas production. Therefore, the process is changed to keep the solid matter in the mixed well wastewater, the first stage is to fully stir the pig manure and urine, and the second stage is the HyMeTek fermentation process for hydrogen and methane productions. Mixture of the hydrogen and methane gases as a biohythane gas can greatly increase the combustion efficiency, which can be 25% higher than the general biogas power combustion efficiency, and there is almost no odor in the post wastewater treatment process.

With the patent research and development of Feng Chia University, what the receiver also needs is the equipment supplier. Mr. James Tung, CEO of Asia Hydrogen Energy company, has long been devoted to professional equipment for pig wastewater biogas power generator, and has been cooperating with Professor Andrew Chu, Director of Institute of Green Products, Feng Chia University. The advanced biogas technology of a two-stage high-efficiency anaerobic fermentation technology for wastewater system in “Xin He Xing” pig farm was then first realized in Taiwan. Nearly 80% of pig farms are operated on a small-scale mode in Taiwan. Generally, small farmers cannot invest in large amounts of money to support the advanced biogas power generation and wastewater treatment system. Therefore, the entire team of this project has invested regardless of the cost, and hopes to use this case to establish a reference model. The purpose of this project is to demonstrate that affordable clean energy can be achieved by the small-scale farmers so they can see the benefits and have the ability to invest, so that the circular economy can be truly implemented.

Since this two-stage high-efficiency anaerobic fermentation technology was first implemented onsite in Taiwan, the construction process must continue to be fine-tuned according to the onsite conditions. Because the original wastewater treatment tank is used for reconstruction, but the industry of raising pigs cannot be interrupted. Therefore, the temporary storage tank is used to collect the continuously generated wastewater. It took more than a year to complete the civil works. The double layers' biogas holder and the generator are also required for adjustment and technical training. After the construction of the entire hardware equipment, an automation control system that optimizes the biogas power generation system (computer remote digital control system), can remotely monitor and operate various parameters of wastewater treatment and make the most immediate adjustments according to the actual situation (Figure 4).

Figure 4. HyMeTek biogas plant with a remote-control system established in Central Taiwan for 1,500 pigs farm in 25 kW power generator

IMPACT TO THE SMALL FARMERS

The use of organic wastewater or agricultural and animal husbandry wastewater to generate electricity is not a new technology, but Feng Chia University has made technological breakthroughs and developed the "anaerobic two-stage biohythane gas production technology, HyMeTek," the anaerobic two-stage refers to the production of methane after hydrogen production. This two-stage biohythane gas production system not only has higher energy recovery efficiency, but also can make the better combustion efficiency of the internal combustion engine in the generator. But any technology must go out of the laboratory to really bring help to the industry and people's livelihood. The Feng Chia University team with the technology met the Xin He Xing Ranch in Nantou County with the intention of improving the environmental pollution of the pig industry. The two parties hit it off together and jointly built the world's first pig farm biohythane power station. The system operated in the beginning of year 2020. In 2020, a yearly income was about US$3,000, but based on the data during April to June 2022, the yearly income had reached around US$9,000.

Besides financial profit, there is also a good performance in removal efficiency at biochemical oxygen demand (BOD), chemical oxygen demand (COD) and suspension solids (SS). The overall removal efficiency of BOD, COD and SS can reach 99.5, 98.8 and 99.5%, respectively (Table 1). The odor problem of the wastewater was solved, and the farm could receive about US$9,000 in electricity sales every year. Table 2 shows the COD removal efficiency between two-stage of HyMeTek and the single-stage of traditional TPWT process. Su and Chen (2018) reported that three farm-scale anaerobic piggery wastewater digesters in northern, central, and southern Taiwan which used the traditional TPWT process, and its COD removal efficiency were 76.7, 74.3, and 83.3%, respectively. It is proved that the two-stage of HyMeTek shows better performance in COD removal efficiency.

Table 1. Summary of performance in BOD, COD and SS removal efficiencies

Process	BOD (mg/L)	COD(mg/L)	SS(mg/L)
Original W. W.	11,000	20,900	14,200
Before AD	34,300	72,100	33,800
After AD	174	907	332
After aeration	256	3,330	2,470
Discharged water	50	261	77
Overall removal efficiency	99.5%	98.8%	99.5%

Table 2. The COD removal efficiency between single-stage and two-stage at different location in Taiwan.

Field	Type of AD	COD (mg/L)			Reference
		Influent	Effluent	Efficiency	
Northern Taiwan	Single-stage	7,397	1,727	76.7%	(Su & Chen, 2018)
Central Taiwan	Single-stage	13,038	3,354	74.3%	(Su & Chen, 2018)
Southern Taiwan	Single-stage	7,225	1,208	83.3%	(Su & Chen, 2018)
Xin He Xing pig farm	Two-stage (HyMeTek)	20,900	907	**95.7%**	This study

CONCLUSIONS

Since this was the first large-scale pig wastewater treatment in Taiwan by using two-stage anaerobic fermentation technology, coupled with a computer remote digital control system, there were still several problems during the commissioning phase, but it still shows a good performance in COD removal efficiency of 95.7%. This study is to demo a successful practice case, and drives the domestic industry to invest together, so that the circular economy is no longer a distant dream, but a regenerative value that can be concretely practiced. At present, Xin He Xing pig farm in Nantou was equipped a designed power generation with a capacity of 25 kW. It is estimated that about US$30,000 can be recovered annually if appropriate operation and management of biogas power plant. The "two-stage high-efficiency biogas production technology HyMeTek" developed by Feng Chia University could not only treat wastewater and agricultural wastes with high organic matters, but also generate bioenergy and sell electricity to the government to generate economic value (Chu, Unpaprom, Ramaraj, & Chen, 2021; Chu *et al*., 2020; Nguyen *et al*., 2021; Panin, Setthapun, Sinsuw, Sintuya, & Chu, 2021). It could also enhance the green image of the industry by selling "carbon credits" that reduce the accumulation of carbon dioxide is arguably the most compact bioenergy technology in the future.

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AUTHOR'S CONTRIBUTIONS

Concept and design of study: Tsung-Hsien Chen, Chen-Yeon Chu.
Acquisition of data: Tsung-Hsien Chen.
Analysis and/or interpretation of data: Tsung-Hsien Chen, Chen-Yeon Chu.
Drafting the manuscript: Tsung-Hsien Chen.
Revising the manuscript critically for important intellectual content: Chen-Yeon Chu.

COMPETING INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.