

Communication

Regulatory Promotion and Benefit Analysis of Biogas-Power and Biogas-Digestate from Anaerobic Digestion in Taiwan's Livestock Industry

Wen-Tien Tsai

Graduate Institute of Bioresources, National Pingtung University of Science and Technology, Pingtung 912, Taiwan; wtttsai@mail.npust.edu.tw; Tel.: +886-8-770-3202

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Abstract: The objectives of this paper were to summarize the status of the livestock (pig and cattle) industry and its waste management in Taiwan. The Water Pollution Control Act authorized the reuse of liquor and digestate from anaerobic digestion (AD) as fertilizers for agricultural lands on 24 November 2015. A large number of official databases and literature have been surveyed and analyzed to address the characterization of the biogas (AD-based) digestate and the potential benefits of biogas-to-power in Taiwan. On the promulgation of the Act, the central ministries have jointly managed the applications of livestock farms for reusing the AD-based liquor and digestate as fertilizers for farmlands. The survey findings revealed that the biogas digestate from a pig farm in Taiwan contained significant amounts of nitrogen, phosphorus, and other soil nutrients such as calcium and magnesium. However, it is necessary to control zinc present in the biogas digestate from pig-raising farms. A preliminary analysis based on 123 large-scale pig farms with a total of 1,223,674 heads showed the annual benefits of methane reduction of 6.1 Gg, electricity generation of 3.7×10^7 kW-h, equivalent electricity charge saving of 4.0×10^6 US\$, and equivalent carbon dioxide mitigation of 152.5 thousand tons (Gg). Obviously, the integration of AD and biogas-to-power for treating animal manure is a win-win option for livestock farms to gain environmental, energy, and economic benefits.

Keywords: digestate; anaerobic digestion; biogas-to-power; agricultural fertilizer; regulatory promotion; circular economy

1. Introduction

Taiwan is a small island country, posing a maritime climate with high humidity and warm temperatures due to its geographical location in tropical/subtropical zones. More significantly, this country has a high population density (i.e., about 650 people per km²) because its geographical area is only about 36,000 km², where two-thirds is mountainous and around 24% of Taiwan's land is used for farming. Therefore, the patterns of livestock industry and crop production are small-scale, and concentrated in the central-south region of the island. With continuous economic development and improved living standards, the domestic demand for animal protein, especially of pork and beef, has increased in recent years, making the livestock industry one of the main agricultural industries in Taiwan.

Over the past few years, livestock (e.g., pigs and cattle) waste (i.e., excrement and manure), due to its high levels of biodegradable matters and inorganic nutrients [1], has caused adverse impacts on environmental quality when they are discharged into surface water bodies or agricultural soils without adequate treatment, such biological treatment [2]. In this regard, the livestock sector contributes a significant share to anthropogenic greenhouse gas (GHG) emissions, especially in

methane (CH₄) [3]. On the other hand, it was found to be seriously polluted in terms of suspended solids (SS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), and ammonium–N (NH₄⁺-N) and phosphate–P (PO₄⁻³-N) concentrations in the pig-farming wastewater system [4]. Therefore, eutrophication may appear in the surface water because of the oversupply of nutrients, leading to structural changes in the ecosystem, such as excessive growth of algae and aquatic plants, depletion of dissolved oxygen and fish species, and deterioration of water and air quality. It is necessary to protect environmental quality from these constituents present in the livestock wastewater [5].

In comparison with aerobic (activated sludge) processes for treating livestock wastewater, anaerobic digestion (AD) has attracted much greater attention in recent years because it can save energy for aeration, produce much less sludge, and generate a methane-rich biogas as renewable energy. Therefore, AD is a promising valorization technology for the purpose of converting organic biomass into a highly energetic biogas for the generation of electric power and heat [6]. In Taiwan, the central ministries, including the Ministry of Economic Affairs (MOEA), the Environmental Protection Administration (EPA), and the Council of Agriculture (COA), have given financial support for large-scale pig farms to turn pig-raising wastewater into electricity using the three-step system. Under the authorization of the Renewable Energy Development Act of 2009, the feed-in tariffs (FITs) for promoting electricity generation from AD-based biogas in Taiwan have been announced since 2010, indicating an upward trend, as shown in Figure 1. For example, the tariffs of biogas-to-power in 2010 and 2018 were 2.0615 and 5.0161 NTD\$/kW-h (1 US\$ ≈ 30 NTD\$) [7], respectively, showing an annual average increase of 11.8% from 2010. However, biogas digestate will be produced by the AD process, thus forming a sludge residue [8]. Fortunately, this biosludge is a nutrient-rich substance, which can be used as a fertilizer if it is well handled by proper application operation and control of heavy metals in soils. In other words, the direct reuse of AD-based digestate as a fertilizer or soil conditioner is based on its richness in valuable lignocelluloses and mineral nutrients [9–12].

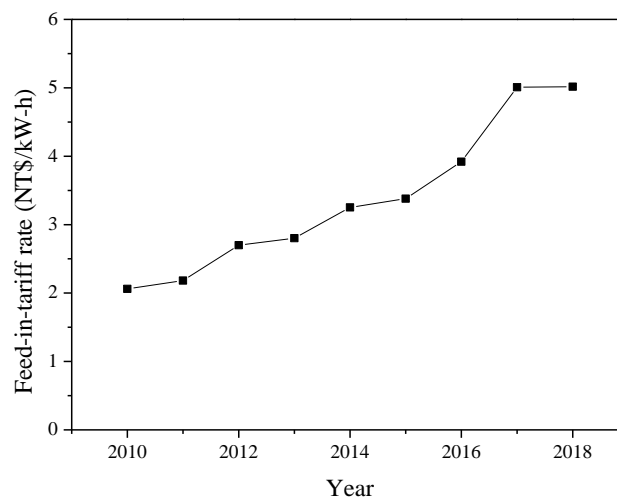


Figure 1. Feed-in-tariff rates of biogas-to-power in Taiwan since 2010.

In the past decades, biogas digestate recycling has been promoted in many European countries. In the literature, however, there are no studies on this issue in Asian countries. In line with the official promotion of the reuse of liquor and digestate from anaerobic digestion (AD) as fertilizers for agricultural lands since 2016, the objectives of this paper were to summarize the status of livestock (i.e., pigs and cattle) industry and its waste management in Taiwan. Further, the characterization of the biogas (AD-based) digestate in Taiwan was summarized to verify its agronomic value. Finally, the preliminary benefit analysis of biogas-to-power and regulatory management measures were briefly addressed in the paper to promote a circular economy in the Taiwanese livestock industry.

2. Materials and Methods

Based on the above-mentioned description, the materials and methods in the present study are briefly summarized below.

- Activity (statistics and current status) of livestock industry

Data on the statistics and current status of the livestock industry in Taiwan were obtained from the official Statistics Yearbook (website: <http://agrstat.coa.gov.tw/sdweb/public/book/Book.aspx>) and promotion brochures (website: <http://english.tlri.gov.tw/page.aspx?path=175>), which were compiled by the COA.

- Preliminary benefit analysis of biogas-to-power

In order to analyze the preliminary benefits of biogas-to-power in the Taiwan's pig-raising industry, the author adopted the official statistics and the emission factors developed by the Intergovernmental Panel on Climate Change (IPCC) [13].

- Characterization of biogas digestate

The data on the characterization of biogas-digestate in Taiwan were extracted from the previous study [14]. They were also used to verify by comparing several literatures [11,15–17].

- Regulatory measures of biogas-digestate recycling

The regulatory measures of biogas-digestate recycling were extracted from the official websites of the central competent authorities, including the COA (<https://eng.coa.gov.tw/>) and the EPA (<https://www.epa.gov.tw/mp.asp?mp=epaen>).

3. Results and Discussion

3.1. Current Status of Livestock Industry in Taiwan

3.1.1. Statistics of Livestock Industry in Taiwan

Hogs

According to the official survey by the COA, pig farms raised about 5440 thousand heads by the end of 2016, as listed in Table 1 [18]. Table 1 also listed the variations of total heads during the past decade (2007–2016), showing a decreasing trend from 6,620,790 heads in 2007 to 5,442,381 heads in 2016. This trend should be mostly attributed to Taiwan entering the World Trade Organization (WTO) on 1 January 2002. Consequently, livestock products in the domestic market suffered from tremendous pressure under global competition. In fact, the historical record of total inventory pigs during the year of 1991 almost reached about 10,089 thousand heads. Unfortunately, the pig industry in Taiwan encountered the foot-and-mouth disease (FMD) event in March 1997; pork was prohibited from being exported. Meanwhile, the Taiwanese government was preparing for the WTO accession, thus assisting medium-scaled or uncompetitive pig farms in business transformation. These efforts attempted to enhance the competitiveness of the industry in the face of strong foreign competition. On the other hand, the excrement discharge from the pig-raising farms was considered one of the main pollution sources in receiving water bodies (e.g., rivers), since the pig-excrement contained nutrients like nitrogen and phosphorus. Therefore, the EPA in Taiwan established several strict measures or permits for effluents from the livestock industry to prevent excrement from polluting water bodies in accordance with the Water Pollution Control Act. In this regard, most small-scaled farms have been driven out of business.

Cattle

As is the case with hogs, a majority of cattle were raised in the central-south region of Taiwan. Currently, three main cattle, including buffalo cattle, yellow and hybrid cattle, and dairy cattle (Holstein), are raised in Taiwan. Table 1 listed the statistics of cattle raised during the past decade (2007–2016) [18]. In Taiwan, most buffalo cattle were used for draft purposes prior to the 1980s. With increasing farm mechanization and a growing demand for beef and milk, buffalo cattle inventories have dropped sharply from 18,600 heads in 1991 to 2037 heads in 2016, only 1.4% of total cattle numbers. Many yellow and hybrid cattle were used for both beef supply and draft purposes. As discussed in the case of buffalo cattle, draft use was declining rapidly. Additionally, beef imports from Australia, New Zealand, and the USA have grown since the 1990s. The number of yellow and hybrid cattle also showed a decreasing trend from 33,699 heads in 1991 to 6968 heads in 2007. In recent years, local citizens liked to eat warm beef, indicating that the yellow and hybrid cattle inventories maintained a stable trend, about 10% of total cattle numbers. With a growing demand for milk since 1970s, dairy cattle numbers have increased from 5723 heads in 1966 to 100,539 heads in 1991. In the past decade, the dairy cattle numbers indicated stable ones over the range from 122 thousand heads to 132 thousand heads, accounting for about 89% of total cattle numbers.

Table 1. Statistics of hog and cattle heads on farms in Taiwan ^a.

Year	Hog	Cattle			Sum
		Buffalo	Yellow/Hybrid Cattle	Holstein	
2007	6,620,790	3452	6986	126,689	137,127
2008	6,427,597	3599	7236	123,115	133,950
2009	6,130,003	3862	7884	121,967	133,713
2010	6,185,952	3844	13,175	122,983	140,002
2011	6,265,546	3627	13,099	127,587	144,312
2012	6,008,317	2951	11,223	129,445	146,186
2013	5,806,237	2511	14,478	130,409	147,398
2014	5,545,010	2437	14,694	128,608	145,739
2015	5,496,216	2311	15,059	132,009	149,379
2016	5,442,381	2037	14,922	129,071	146,030

^a Source Reference [18].

3.1.2. Current Status of Livestock Waste Management in Taiwan

It is well known that livestock excrement and manure contain lots of organic matter and dissolved nutrients such as nitrogen and phosphorus. Therefore, livestock waste has an agronomic value or fertilizer value. Although a good way to treat livestock waste is to return it into the soil by proper application, the primary concerns are aesthetic odor and heavy metals (e.g., copper and zinc). In Taiwan, the limits for zinc, copper, nickel, cadmium, mercury, lead, arsenic, and chromium in the organic fertilizers have been set by the COA to protect soil quality and hence crop quality. As described earlier, the discharge of wastewater (or livestock slurry) from pig-raising farms into surface water bodies without biological treatment had caused serious water pollution in the past. This means that the livestock waste treatment focuses on the compliance cost reduction of meeting the regulatory requirements (e.g., effluent standards and water pollution control fee) in accordance with the Water Pollution Control Act. The approach for the reuse of AD-based liquor and digestate as agricultural fertilizer changed previous perceptions about slurry. This innovative measure will raise its value as a useful resource that can increase soil fertility and also produce biogas for fuels, while reducing the amount of slurry entering water bodies. The author roughly performed an analysis of the benefits of reusing digestate as fertilizer, showing that about 5 million packs of fertilizer and 6.0×10^7 US\$/year (40 kg, 16% N) can be made by using the following factors: 20 g N/head·day, 5 million pig heads, and 12 US\$/pack. Therefore, the EPA has jointly ventured with the COA to implement the plan of reusing

AD-based liquor and digestate as fertilizers for farmlands under the amendments of the “Water Pollution Control Measures and Test Reporting Management Regulations” on 27 December 2017. Figure 2 compared the flow-sheet of the traditional three-step system with innovative circular system in the pig-farming wastewater treatment plant, showing that the AD system can reduce air/water pollution and mitigate GHG emissions from the livestock sector through bioenergy production [19].

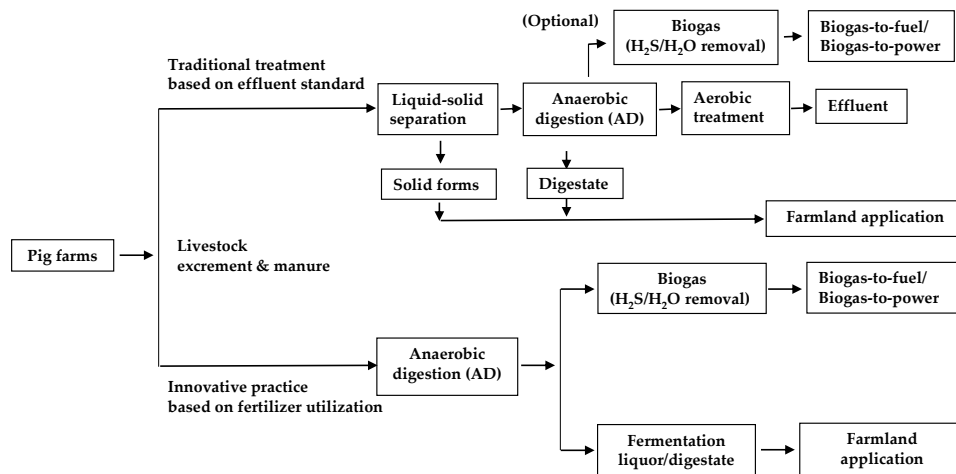


Figure 2. Flow-sheet comparison of traditional treatment to innovative practice in pig-farming wastewater management.

Currently, the three-step system has been adopted as the most suitable excrement and manure treatment system in Taiwan. In most cases, when operated under proper conditions, the treated wastewater can meet the effluent standards, which include biochemical oxygen demand (BOD) of 80 mg/L, chemical oxygen demand (COD) of 600 mg/L, and suspended solid (SS) of 150 mg/L. The three-step process for treating livestock wastewater is briefly described as follows [20].

- The first step is the solid-liquid separation. After the operation, the recycled solid material is often collected for composting in the subsequent utilization.
- The second step is called anaerobic fermentation or anaerobic digestion (AD). During the anaerobic treatment, biogas is generated as a valuable by-product. Raw biogas is mainly composed of methane (60–75 vol %) and carbon dioxide (19–33 vol %) [21]. It also contains small amounts of hydrogen sulfide (H₂S), ammonia (NH₃), and water vapor. In order to prevent damage of biogas utilization units, the desulfurization (H₂S removal) of raw biogas is crucial in the subsequent reuses such as fuel sources for the stove, water heater, piglet warming, water pump, electricity generation, automobile, etc. [22]. In addition, the biogas digestate formed during the AD process is another valuable by-product since it constitutes a bio-fertilizer with increased availability of soil nutrients like nitrogen and inorganic minerals. However, the study by Czubaszek and Wysocka–Czubaszek [23] showed a relatively low impact of the emissions of CO₂ and CH₄ from the field fertilized with biogas digestate on total emission from agriculture.
- The third step is an aerobic treatment. The activated sludge process is used to further treat the anaerobically treated wastewater. The excess sludge generated in this step is dehydrated and directly used as a fertilizer. Occasionally, the spent activated sludge and recycled biosolid generated in the first step are processed into organic fertilizers.

3.2. Preliminary Benefit Analysis of Biogas-to-Power in the Taiwan’s Pig-Raising Industry

In Taiwan, the biogas from swine manure management was viewed as a valuable energy source because it contains a high proportion of methane, one of the major GHGs. Currently, the gaseous fuel provides a unique green energy for auxiliary power. To upgrade the integrated biogas-to-power system

and promote the circular economy in the livestock waste management, a US\$84 million (NTD\$2.6 billion) “Pig Industry Modernization Project” in Taiwan was officially launched by the EPA in early 2017. Pig farms with more than 5000 heads will be subsidized by official funds to build biogas-to-power plants in the coming three years (2017–2020). According to the reasonable activity data in Taiwan and available factors, as described below:

- Pig-raising farms of over 5000 heads: 123 farms with 1,223,674 heads, as seen in Table 2 [18].
- Methane emission factor: 5 kg CH₄·head⁻¹·year⁻¹ (equivalent to 11.75 m³ biogas head⁻¹·year⁻¹ based on methane concentration of 65% in biogas) [13].
- Electricity generation factor: 0.626 m³ biogas per kW-h (based on 5500 kcal·m⁻³ heating value, 25% energy efficiency) [24].
- Electricity purchase charge (FIT): 0.172 US\$ per kW-h, seen in Figure 1.
- Global warming potential for methane: 25 (100-year time horizon) [25].

The potential for quantitative benefits of biogas-to-power from the pig-raising industry is summarized below:

- Methane reduction: 1,223,674 head × 5 kg CH₄·head⁻¹·year⁻¹ × 10⁻⁶ Gg·kg⁻¹ ≈ 6.1 Gg·year⁻¹.
- Electricity generation: 6.1 × 10⁶ kg·year⁻¹ × 2.35 m³ kg⁻¹ ÷ 0.626 m³ kW-h⁻¹ ≈ 2.3 × 10⁷ kW-h·year⁻¹.
- Equivalent electricity charge: 2.3 × 10⁷ kW-h·year⁻¹ × 0.172 US\$ kW-h⁻¹ ≈ 4.0 × 10⁶ US\$·year⁻¹.
- Equivalent carbon dioxide mitigation: 6.1 Gg·year⁻¹ × 25 ≈ 152.5 Gg·year⁻¹.

Overall, about 55 biogas plants with total installed capacity of 3.9 MW are being operated in connection with large-scale pig farms, concentrated in the Southern Taiwan (Table 3).

Table 2. Statistics of hog heads on farms classified by scale in Taiwan ^a.

Scale (Heads)	Farms	Percentage (%)	Heads on Farms	Percentage (%)
1~99	2354	31.8%	70,323	1.3%
100~199	824	11.1%	124,727	2.3%
200~299	404	5.5%	98,567	1.8%
300~499	613	8.3%	245,349	4.5%
500~999	1528	20.6%	1,156,265	21.3%
1000~1999	1067	14.4%	1,488,771	27.4%
2000~2999	203	2.7%	494,451	9.1%
3000~4999	141	1.9%	530,549	9.8%
5000 or more	123	1.7%	1,223,674	22.5%
Sum	7407	100.0%	5,432,676	100.0%

^a Source Reference [18]; statistics to the end of November 2017.

Table 3. Statistics of biogas-to-power systems installed by pig farms in Taiwan ^a.

Location	Farms	Heads on Farms
Northern Taiwan	6	~19,000
Central Taiwan	10	~114,000
Southern Taiwan	39	~308,000
Sum	55	~441,000

^a Surveyed by the Council of Agriculture (COA); total installed capacity: ~3.9 MW; statistics to the end of 2018.

3.3. Characterization of Biogas Digestate in Taiwan

The AD process is a promising valorization technology due to its ability to convert livestock waste into a highly energetic biogas for the generation of electric power and/or heat. However, biogas digestate will be produced in the AD process, thus forming a sludge residue or biosolid. Although

the primary concerns are toxic contaminants (e.g., heavy metals), the AD residue is often utilized as a fertilizer or soil conditioner based on its richness in mineral nutrients [8].

In order to study the characterization of biogas digestate, the fresh biogas digestate was obtained from a livestock farm at the National Pingtung University of Science and Technology (Pingtung County, Taiwan) [14]. This pig farm was designed to deal with excrement and manure from a maximum 1500 pig heads. According to a previous study [14], the dried biosolid comprised a large percentage of ash (i.e., 23.03 wt %), thus causing a relatively lower calorific value (i.e., 16.64 MJ/kg). However, the nitrogen and sulfur contents (i.e., 4.56 and 1.49 wt %, respectively) of the feedstock were relatively high. Other thermochemical properties of the digestate sample included the contents of inorganic nutrients and contaminants. It showed that the macronutrients Ca and P were significantly high in the sample. On the other hand, this biosolid also contained some micronutrients, including Al, Cu, Fe, K, Mg, Mn, Na, Si, Sr, Ti, and Zn. These aforementioned findings were in accordance with the literature data [15,16]. Moreover, the concentrations of heavy metals (i.e., Cd, Ni, Cr, and Pb) were not observed (below the method detection limits), while Cu and Zn were found to be more concentrated in the digested sediment. Therefore, these nutrients and heavy metals may be easily leached from soils [12,15–17], suggesting that AD residue should be carefully monitored in case of its application to agricultural soils.

3.4. Regulatory Measures of Livestock Waste Recycling in Taiwan

Regarding a regulatory framework for livestock waste management in Taiwan, it was developed by a ministerial joint-venture to protect environmental quality and a promote circular economy. Since 2014, the EPA and the COA have jointly managed the applications of pig farms to utilize AD liquor and digestate as organic fertilizers in nearby soil. Under the authorization of the Water Pollution Control Act, the EPA announced amendments to the “Water Pollution Control Measures and Test Reporting Management Regulations”, adding a new chapter on the plan for implementing AD liquor and digestate as fertilizer for farmlands. The plan of reusing AD-based liquor and digestate as fertilizer for farmlands must be submitted to the COA for application. Upon approval, the permit should be further reported to the local competent authorities for reference in accordance with the contents of registration (e.g., application rate, monitoring and verification) in the implementation stage.

It was reported that the concentrations of dissolved nitrogen (N) and phosphorus (P) in the pig-raising wastewater ranged from 1500 to 15,200 mg N/L and from 70 to 1750 mg P/L, respectively [26]. In addition, the discharge may contain dissolved organics in terms of COD and BOD. Consequently, wastewater from livestock farms is considered to be the main water pollution source, resulting in eutrophication and/or water body deterioration.

In order to further increase the utilization efficiency of livestock waste, Taiwan’s EPA simplified the management (application) and review (verification) procedures according to the “Water Pollution Control Measures and Test Reporting Management Regulations” on 27 December 2017. In addition, the EPA requested pig and cattle farms registered after the amendments to recycle at least 10% of their discharged wastewaters. Other pig and cattle farms, those that discharge wastewater to the surface water body, shall meet the recycling ratios as follows:

- Large-sized farms with more than 2000 pig heads or 500 cattle heads will meet at least 5% of recycling wastewater generated in 5 years, and 10% of recycling wastewater generated in 10 years from 27 December 2017.
- Medium-sized farms with 20–2000 pig heads or 40–500 cattle heads will meet at least 5% of recycling wastewater generated in 8 years, and 10% of recycling wastewater generated in 12 years from 27 December 2017.

On the other hand, the EPA further revised and announced the Regulations to reduce water pollution. The main points of the amendments for livestock waste management are summarized below:

- Defining the plan for implementing AD-based liquor and digestate as fertilizers for farmlands. It refers to the liquor and digestate generated from livestock excrements, or the livestock excrements collected by the management operator of livestock waste treatment center (or biogas recycling center) after anaerobic fermentation or aeration treatment, and then used on farmlands for fertilization.
- Expanding the scope of suitable users of liquor and digestate from the AD process as organic fertilizers for agricultural lands. In addition, agricultural land is clearly defined as land registered under a general or specific agricultural zone.
- Adjusting the groundwater background values and test items for agricultural soil quality on which AD-based liquor and digestate are used as fertilizers. It means that testing for $\text{NH}_4^+ \text{-N}$ in AD-based liquor and digestate, pH, nitrate nitrogen, total phosphorus, copper, and zinc in groundwater, and pH and total phosphorus in soil are no longer required.
- Simplifying the application procedures for reusing AD-based liquor and digestate as agricultural fertilizers. The agricultural competent authorities (i.e., the COA and local governments) have been authorized to determine the minimum number of days for the anaerobic fermentation of livestock waste based on the review of case plan. On-site inspections of the plan for implementing AD-based liquor and digestate as fertilizers for farmlands will be conducted on a flexible basis.

Furthermore, livestock farms, those that discharged wastewater to the surface water body, are required to pay fees for water pollution control starting from 1 January 2017 under the authorization of the Water Pollution Control Act. This fee is calculated based on the farm-scale classification and the water quality items of treated wastewater (effluent) such as COD and SS. To avoid illegal discharge and improve surface water quality, the EPA will strengthen livestock effluent control and inspection, and promote the reuse of AD-based liquor and digestate as fertilizers for farmlands.

4. Conclusions and Prospects

The livestock sector contributes to the release of GHGs (i.e., methane) and water/air (odor) pollution. In this regard, anaerobic digestion (AD) processes for treating livestock manure provides a cost-effective valorization technology because of its advantages of energy saving, reduced digestate yield, and electricity (biogas-to-power) generation. In Taiwan, there were about 5442 thousand pig heads and 146 thousand cattle heads raised in livestock farms by the end of 2016. To upgrade environmental, agricultural, and energy sustainability, the Environmental Protection Administration (EPA) and the Council of Agriculture (COA) have jointly managed the applications of livestock (pig and cattle) farms for reusing AD-based liquor and digestate recycling as fertilizers or soil conditioners for agricultural lands. This recycling regulation was motivated by the authorization of the Water Pollution Control Act on 24 November 2015. Obviously, the integration of AD and biogas-to-power has a better performance compared to the existing three-step system, as it requires less time and cost to complete the cycle. Furthermore, these AD-based by-products (liquor and digestate) contain soil nutrients, which could be reused as green fertilizers in farmlands. Based on 123 large-scale pig farms with about 1223 thousand heads in Taiwan, a preliminary analysis showed the annual benefits of methane reduction of 6.1 Gg, electricity generation of 3.7×10^7 kilowatt-hour (kW-h), equivalent electricity charge saving of 4.0×10^6 US\$, and equivalent carbon dioxide mitigation of 152.5 thousand tons (Gg). Thus, the production of biogas and digestate from the AD process is a win-win option for livestock farms to gain environmental, energy, and economic benefits.

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