Exploring the environmental and economic potential for biogas production from swine manure wastewater by life cycle assessment

Meng-Fen Shih1 · Chyi-How Lay2,3 · Chiu-Yue Lin1,2,3 · Shen-Ho Chang4

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Abstract
The development of biofuels to replace fossil fuels with bioenergy systems has attracted attention as an environmental-friendly process. Dealing with biowaste by anaerobic digestion disposes of wastes and produces biogas during the treatment processes for providing the renewable energy source at a low cost while conserving fossil fuel. This study uses life cycle assessment and cost-benefit analysis to evaluate and compare environmental impacts and cost benefits before and after installing a rapid-build anaerobic fermentor module into the three-stage wastewater treatment system that the swine farm initially used. The module helps biogas production as energy recovery in swine farms. The results indicate that the module could help reduce carbon footprint by 22.6%, methane by 51.8%, sulfur oxides by 92.6%, nitrogen oxides by 74.2%, carbon monoxide by 54.7%, nitrous oxide by 28.6%, suspended particulate by 95.4%, and non-methane volatile organic compounds by 80%. Using this module made the reductions of damage impacts were human health 82%, ecosystem quality 59%, and resource scarcity 87%. The daily average biogas production was 46.38 m3, and its annual electricity generation income was 6091 USD. This study allows identifying the lowest environmental impact to support the adoption of sustainable waste treatment and the opportunity for converting waste to be energy and utilization with economic benefits for small-scale swine farms.
Keywords Life cycle assessment · Cost–benefit analysis · Swine manure · Biogas · Environmental impacts · Electricity generation

Introduction

A livestock industry has vast and complex processes, including feeding raw materials, product transportation, slaughtering and meat production, waste generation during breeding, and waste treatment. For the pollutant emission of livestock, about 44% is in the form of methane (CH₄), with the remaining part being almost equally shared between nitrous oxide (N₂O) 29% and carbon dioxide (CO₂) 27%. Issues of environmental impact caused by the livestock industry have been discussed for a long time. In terms of activities, feed production/processing and enteric fermentation from livestock are the two primary sources of pollutant emissions, representing 45 and 39% of total emissions; manure storage and processing representing 10%. The improperly managed may make the disposal of livestock manure become a severe public concern due to its vast potential threat to public health and depletion of natural resources (Bui et al. 2011). With changes in living patterns and demand for diet in recent years, the livestock industry has become one of the leading agricultural industries in Taiwan (Tsai 2018). The livestock industry in Taiwan is under the Executive Yuan’s Council of Agriculture (COA) jurisdiction. The Animal Industry Act is drawn up to regulate and provide guidance to the livestock farming business, preventing pollution and facilitating the development of the livestock industry (Taiwan COA 2010). Due to the limited usable land and high population density in Taiwan, the livestock industry and crop production are small and concentrated in Taiwan’s central and southern regions.

Furthermore, the swine husbandry output value accounts for half of the whole livestock production value in Taiwan has regarded as the most significant agricultural economic project. Therefore, considering both economic development and environmental maintenance, swine manure treatment becomes even more critical. In swine supply chains, the bulk of emissions relates to the feed supply and manure storage in processing, followed by energy consumption (FAO 2020). A three-stage wastewater treatment system including solid–liquid separation, anaerobic digestion, and aerobic treatment is used to treat the swine manure in Taiwan. Its effluent can
meet the discharge standard (Tsai and Lin 2009). Even the industry still has to pay fees for water pollution control due to the authorization of the Water Pollution Control Act of Taiwan (Taiwan EPA 2018). Notably, the energy needs for running the system have no help in reducing energy consumption. Because of the change in the livestock industry worldwide toward more concentrated animal feeding operations, environmentally sound methods for the storage and disposal of manure are required (Cantrell et al. 2008). Meanwhile, the growing concerns regarding depleting fossil fuel reserves and adverse changes in climatic conditions due to ever-increasing greenhouse gas emissions made it essential to explore renewable energy sources (Godbout et al. 2008). The approach of producing bioenergy by biowaste that dealing with the waste problem also bringing benefits by producing energy at the same time.

By exploring the related articles, produced bioenergy using livestock manure has proved that feasibility also has advantages both on environmental and economic concerns. The research by Adeoti et al. (2014) estimates biogas potential from livestock manure in Nigeria and its contribution to climate change mitigation. Roubík and Mazancová (2020), based on practice from other countries, investigate the potential of dealing with animal waste converting to be energy by the small-scale biogas systems and their suitability in rural areas in northern Sumatra. Nasir et al. (2012) review the potential of anaerobic digestion (AD) for biogas production from livestock manure wastes and compare the operational and performance data for various anaerobic process configurations. Ishikawa et al. (2006) have compared an on-farm biogas plant with a centralized biogas plant system totally from the energetics point of view. Various research of livestock manure treatment technologies and management strategies also come out one after another (Alfa et al. 2020). Such as Abdelsalam et al. (2019) use the life cycle assessment to conduct a comparative environmental impact evaluation of manure treatment with different laser radiation times for biogas production that is in order to increase the biogas production from the AD treatment to livestock manure. Biogas produced by AD consists mainly of methane and carbon dioxide. It can be utilized as a renewable energy source in combined heat and power plants, vehicle fuel, or as a substitute for natural gas. The methane in the biogas can also be utilized in industrial processes and raw materials in the industry (Petersson and Wellinger 2009). Therefore, dealing with biowaste by AD not only the appropriate way to dispose of wastes; the process of biogas production also provides renewable energy sources at a low cost while conserving fossil resources such as natural gas or coal.

The life cycle assessment (LCA) has been an accepted international tool to transpose life cycle perspective principles into a quantitative framework for seeking to quantify all relevant emissions, consumptions, depleted resources, and environmental impacts (ISO 14040-14044 2006). Regarding the various biowaste treatment and conversion to bioenergy, a variety of LCA research has been implemented. Börjesson and Berglund (2006) assessed the possible applications of biogas systems with attention to GHG emissions and fossil fuel depletion. Bernsand and La Cour Jansen (2011) carried out an LCA research for comparing three different waste treatment systems and proved biogas production by AD and substitute for the electricity brought the main environmental benefits. Usack et al. (2018) used LCA results to complement measurements and identify the weak points for improvements. It has also been used to examine the environmental sustainability of biofuels to identify the key drivers of the environment profiles, also the benefits of possible new technologies for providing an evidence base for policymakers (Mabee and Saddler 2010). Assessing by LCA application allows environmental improvements to be determined also ranked that presenting environmental improvements, which has been confirmed to be useful (Hellweg and Mila i Canals 2014).

This study adopted a small-scale swine farm in central Taiwan as the research base. It installed the rapid-build equipment system, which calls Smart Green Electricity Product Module (SGEPM), into the three-stage wastewater treatment system commonly adopted by swine farms. The design of SGEPM had an additional fermentation tank for producing biogas from swine manure during the three-stage wastewater treatment system, then introducing biogas into the electricity generator to generate electricity for energy recovery. The recovered energy as electricity and heat provides the swine farm with basic operational needs. Compared with traditional structures by reinforced concrete (RC), SGEPM was easy to implement at a low cost, even could build with recycled materials. There is also no need to consider the cost of patents. It provides the opportunity for converting waste to be energy and utilization with economic benefits for small-scale swine farms in Taiwan, which often obtain no resource or subsidy because they cannot meet government policy norms by farm-scale. The objective of this study was to use life cycle assessment (LCA) and cost-benefit analysis (CBA) tools in evaluating and comparing the potential environmental impacts and cost benefits for the swine farm operation with and without SGEPM. It aimed to (i) understand identifying the lowest environmental impact to support sustainable waste treatment. (ii) Obtain the most appropriate model for small-scale-intensive livestock farms to reduce pollutants and emissions, decrease resource consumption, produce renewable energy, and reduce operating costs to achieve multiple sustainable environments, economy, and energy goals. Moreover, (iii) this could be a suitable reference for developing countries that lack resources and funds, especially when the time or implementation ability does not allow to build large AD plants.
Materials and methods

Biogas production by swine manure wastewater

Swine manure feedstock

The feedstock for the container-mobile anaerobic fermentor was collected from the swine farm in Taichung City, Taiwan. This swine farm-raised about 900 adult swine classify as a small-scale swine farm with less than 1000 heads and used food waste as the main feed. The wastewater was swine manure and floor-washing. The flow rate was about 3–5 cubic meters per day (m³/d, CMD). This swine farm used the three-stage treatment system to deal with the swine manure wastewater, a solid–liquid separator (0.5 mm mesh), an adjustment tank, five anaerobic tanks, two aeration tanks, and a sedimentation tank. The feedstock was the swine manure after solid–liquid separation in the adjustment tank. The characteristics of raw swine wastewater were chemical oxygen demand (COD) 33,190 ± 4660 mg/L, volatile solids (VS) 1690 ± 960 mg/L, total solids (TS) 2540 ± 1680 mg/L, ammonia nitrogen (NH₃-N) 1310 ± 690 mg/L, and pH 6.17 ± 0.7; more details were listed in Table 1 below.

Design of smart green electricity product module

The rapid-build anaerobic fermentor set in the Smart Green Electricity Product Module (SGEPM) had an anaerobic fermentation tank. The tank was on a forty-feet open container (W 2.4 m × L12.3 m × H 2.5 m); a large red polyvinyl chloride (PVC) bag (W 2.4 m × L12.3 m × H 3.0 m) was installed inside the container, accompanied with a 2.5 m³ stainless steel outflow trough (W 1 m × L 1 m × H 2.6 m) (Fig. 1). The total capacity of the PVC bag was 80 m³, including liquid working volume 60 m³ and gaseous storage volume of 15 m³. The substrate flow rate was 3 CMD. A part of the produced biogas was pumped into a high-pressure gas storage tank. Fermentation temperature was controlled using an electric water heater through external circulation. Biogas production was recorded using a flow meter—moreover, the biogas engine with a smart-control system to be the generator for the module. Following the concept of net-zero energy construction proposed by Deng et al. (2014), the produced biogas was as energy recovery and combustion to generate electricity for operating the system in situ, which no need to consume extra energy to run the module (Fig. 2).

Table 1  Biohythane production during various periods of continuous cultivation

| Operation period | Continuous 1 (Day 1–32) | Continuous 2 (Day 33–70) | Continuous 3 (Day 71–127) |
|------------------|-------------------------|--------------------------|---------------------------|
| Organic loading  | SMW 3 m³/d              | SMW 3 m³/d + SSW 100 kg/d| SMW 3 m³/d                |
| Biogas production efficiency | Biogas production (m³/d) | 14.89 ± 11.51           | 32.46 ± 10.99             | 46.38 ± 35.19              |
|                   | Biogas production rate (m³/m³/d) | 0.25 ± 0.19           | 0.51 ± 0.17               | 0.57 ± 0.33                |
|                   | Methane production rate (m³/m³/d) | 0.18 ± 0.13           | 0.39 ± 0.14               | 0.39 ± 0.24                |
|                   | Methane production yield (m³/kg VS) | 0.125 ± 0.094       | 0.273 ± 0.098             | 0.222 ± 0.153              |
|                   | H₂ (ppm)                | 15 ± 9                 | 32 ± 43                   | 15 ± 14                    |
|                   | H₂S (ppm)               | 2093 ± 484             | 2206 ± 478                | 2165 ± 301                 |
|                   | CH₄ (%)                 | 71.7 ± 2.8             | 71.4 ± 2.8                | 70.8 ± 2.7                 |
| Wastewater treatment efficiency | COD | 26.21 ± 4.67           | 16.25 ± 5.37             | 25.22 ± 8.12               |
|                   | Effluent (g/L)          | 7.32 ± 0.99            | 8.46 ± 0.89               | 9.54 ± 2.96                |
|                   | Removal efficiency (%)  | 71.5 ± 5.5             | 43.7 ± 12.2               | 50.9 ± 12.1                |
|                   | pH                      | 6.94 ± 0.40            | 6.80 ± 0.19               | 6.21 ± 0.51                |
|                   | Effluent                | 7.46 ± 0.07            | 7.47 ± 0.13               | 7.47 ± 0.11                |
|                   | ΔpH                     | 0.52 ± 0.42            | 0.67 ± 0.16               | 1.26 ± 0.48                |
|                   | TS (g/L)                | 15.83 ± 1.92           | 7.37 ± 1.27               | 13.31 ± 2.08               |
|                   | Removal efficiency (%)  | 77.4 ± 4.6             | 41.0 ± 10.9               | 62.0 ± 11.4                |

*SMW swine manure wastewater, SSM solid swine manure
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**Operation strategy**

A co-feedstock strategy was applied for starting up the acidogenesis fermentation using the swine manure. In the beginning, the anaerobic organisms of 15 m³ which were collected from a digester of the wastewater treatment plant, and the swine manure 15 m³ was pumped into the mobile-container anaerobic fermentor as the seed inoculum and feedstock, respectively. Then, swine manure was fed at a rate of 3 CMD on the second day. After ten days, the fermentor was switched to a continuous cultivation mode with a hydraulic retention time (HRT) of 20 days. Then, three periods of continuous cultivation (Continuous 1, Days 1–32; Continuous 2, Days 33–70; Continuous 3, Days 71–127) were carried out using the swine manure. The loading for these three periods was manure wastewater 3 CMD with COD of 15.5–37.9 g/L depending on water utilization for cleaning the swine house. The swine manure wastewater (SMW) of 3 CMD with COD concentrations 26.21 ± 4.67 g/L was first fed into the fermentor during Days 1–32 (Continuous 1 period). On Day 33, the solid swine manure (SSW) of 100 kg/d and 3 CMD was added to increase the organic loading. In order to enhance the biogas production by increasing the organic loading rate, the solid manure separated from the first stage of the original wastewater treatment process was collected to mix with the swine manure for the fermentor in the Continuous 2 period during days 33–70. However, after day 71, the extra solid manure addition was stopped because the solid manure was applied (Table 1).

**Monitoring and analyses**

Gas volume was measured using a natural gas meter at temperature (35 °C) and pressure (760 mmHg) (STP). The methane production efficiency including methane content, methane yield (the ability converting wastewater, based on feedstock kg VS, into methane, MY), and methane production rate (the rate of methane production in the reactor, MPR) was evaluated. The ethanol and volatile fatty acids (VFAs) concentrations were detected via a gas chromatograph equipped with a flame ionization detector, glass column (1.6 m × 3.2 mm) which was packed with FON (Shinwa Chemical Industries Ltd) 10%. The running temperature for oven, injection, and detector was 175 °C, 190 °C, 200 °C, respectively. The carrier gas was N₂ with a flow rate of 60 mL/min. The gas composition was analyzed using a CHINA Chromatograph 8700 T equipped with a thermal conductivity detector (oven 40 °C; injection temperature at 40 °C; detector 40 °C; Argon as a carrier gas, packing, Porapak Q (Restek) as the packing material, mesh 80/100). The anthrone/sulfuric acid method was used to measure the hexose concentration.

**Life cycle assessment**

**Assessment goal, system boundary, and functional unit**

The evaluating procedure of LCA followed the guidelines of ISO 14040-14044 (2006) and Guinée et al. (2002). The assessment goal was to assess and compare the change of...
the target swine farm that replaced the original wastewater treatment system (three-stage treatment and direct discharge) with installed the SGEPM to achieve the environmental and cost–benefit considerations. The system boundaries of this study were from the swine house operation to the wastewater treatment. The gate-to-gate assessment included consumption of electricity and water for swine house essential operation, wastewater treatment system operation, and the energy recovery through biogas production with electricity converting for running SGEPM needs in the swine farm. The utilization of the products obtained from the treatment processes was excluded. The system scopes and boundaries of this study for LCA were shown in Fig. 3. The primary data collected from the processes and flows of the swine farm were the year 2019. The inventory of the foreground and background data were summarized in Table 2. According to
Fig. 3 Biohythane production performance at various continuous cultivation periods in the container anaerobic fermentor.
the operation background and conditions, the functional unit was defined as 1 kg live weight of swine at the farm gate.

Impact assessment methods and outputs

The Life Cycle Impact Assessment (LCIA) was conducted using ReCiPe2016 methodology (Huijbregts et al. 2017) characterization model incorporated with ecoinvent database v3.0 and referred to Weidema et al. (2013) and SimaPro v8.4 software (2017). The Endpoint characterization factors were directly related to the three areas of protection (human health, ecosystem quality, and resource scarcity) derived from Midpoint characterization factors per impact category used. The endpoints in ReCiPe2016 through different weighted indicators and specific parameters, each protection area, had its unit was showing the definition of damage impacts. DALYs (disability-adjusted life years), relevant for human health, represent the years lost or that a person was disabled due to a disease or an accident. The unit for ecosystem quality was species × year, which means the local species loss was integrated over time. The unit for resource scarcity was USD2013, which represents the extra costs involved for future mineral and fossil resource extraction (by US Dollars). The evaluation value of ReCiPe2016 after the weighting directly showed the impacts on human health and the environment. The global warming potential was commonly referred to as carbon footprint and was used to assess the potential impact of different gaseous emissions on climate change (IPCC 2013). Considering the direct impact of the swine industry on gaseous pollutant emissions, the Greenhouse Gases Protocol was used to assess the emission contributions of carbon footprint. In addition, effects of gaseous pollutants, such as sulfur oxides (SOX), nitrogen oxides (NOX), carbon monoxide (CO), and suspended particulate matter (PM), were using the Selected LCI indicators methods in SimaPro v8.4. Using scenarios of before and after installing SGEPM into the three-stage wastewater treatment system of the swine farm were all evaluated in this study.

Cost-benefit analysis

Cost-benefit analysis (CBA) is one of the critical parameters in commercializing the technology. An economic analysis was applied for the full-scale anaerobic digestion process under the optimal condition in this study. The main cost of an anaerobic digestion process includes capital investment (CI), operation and maintenance (O&MC). Therefore, the internal rate of return (IRR), payback time (PBT), and sensitivity analysis was used as the decision-making tools for evaluating the economic feasibility (Choudhary et al. 2020). All the calculations for these indices were in USD. IRR is a critical evaluation criterion and was calculated using the equation:

$$\sum_{t=0}^{T} \frac{C_t}{(1 + IRR)^t} - \sum_{t=0}^{T} \frac{CI}{(1 + IRR)^t} = 0$$

(1)

The PBT was applied as another assessment criteria for decision-making and a different way to evaluate the period in which the expected cumulative cash flow would match the initial CI. PBT was calculated by Eq. 2 (Choudhary et al. 2020), where NCF was the expected net cash flow (USD). The PBT was defined as the discrepancy in the project’s earnings and operation and maintenance cost every year:

$$PBT = \frac{CI}{NCF}$$

(2)

Results

Biogas production in anaerobic mobile-container fermentor

The biogas production performances, including the content of biogas (H2, H2S, and CH4), methane production rate, and methane production yield at various continuous cultivation periods, were shown in Fig. 4 and Table 1. During days 1–32 (Continuous 1 period), the biogas production rate, methane production rate, and methane production yield were 0.25 ± 0.19, 0.18 ± 0.13 m³/m³/d, and 0.125 ± 0.094 m³/kg VS, respectively, with biogas having H2 15 ± 9 ppm, H2S ppm 2093 ± 484 ppm and CH4 71.7 ± 2.8%. H2 was suddenly increased to 140 ppm, but methane was maintained at about 70% at Day 36. The biogas production rate, methane production rate, and methane production yield during Days 33–70 (Continuous
period) increased to 0.51 ± 0.17 m³/m³/d, 0.39 ± 0.14 m³/m³/d, and 0.273 ± 0.098 m³/kg VS, respectively, with biogas content of H₂ 32 ± 43 ppm, H₂S 2206 ± 478 ppm and CH₄ 71.4 ± 2.8%. Due to an SSM shortage, the organic loading for the fermenter was switched back to SWW 3 CMD with COD 25.22 ± 8.12 g/L. This COD concentration was much higher than the COD 16.25 ± 5.37 g/L in the Continuous 2 period, which resulted from the rainy season causing low COD and SS concentrations. Therefore, the H₂ content increased rapidly to 103 ppm, and HPR reached 1.25 m³/m³/d at Day 72. However, the average BPR, MPR, and MY in Continuous 3 period (Days 71–127) were 0.57 ± 0.33 m³/m³/d, 0.39 ± 0.24 m³/m³/d, and 0.222 ± 0.153 m³/kg VS, respectively, which closed to those values in the Continuous 2 period. The COD and TS removal efficiencies reached 43.7–71.7% and 41.0–71.4%, respectively, during the continuous cultivation.

Environmental impacts evaluated

Contribution of carbon footprint

These swine farm’s total carbon footprint emissions were 28.19 and 21.83 kg CO₂-eq when using the three-stage treatment system and after installing the SGEPM, respectively (Table 3). Figure 5 shows the contribution assessment of carbon footprint inventory for these two systems. The results showed that the fossil-related factor significantly impacted the three-stage system (25.89 kg CO₂-eq). The same emission from the system with SGEPM was 5.24 kg CO₂-eq which was only one-fifth of the three-stage system. Notably, the system with SGEPM had an enormous contribution to the biogenic CO₂ emission of 11.67 kg CO₂-eq which reached about eight times higher than that of the three-stage system. The CO₂ emission by land transformation and the CO₂ uptake was in similar values by two systems (Fig. 5).

Table 3 Contributions of gaseous pollutant emissions by the three-stage wastewater treatment system and SGEPM (unit: mg/kg)

| Impact category | SOₓ | NOₓ | N₂O | CO | TSP | CH₄ | NMVOC |
|-----------------|-----|-----|-----|----|-----|-----|-------|
| Three-stage system | 8221 | 5109 | 478 | 3382 | 7496 | 10,258 | 705 |
| SGEPM           | 603 | 1319 | 341 | 1532 | 344 | 4950 | 141 |
Contribution of gaseous pollutant emissions

The results of the equivalence of pollution factors emissions were shown in Table 4 with total suspended particulate (TSP) and gaseous pollutants. The swine industry was constantly criticized for methane (CH$_4$) emissions, and this indeed was seen from these results with emitting 10.26 g per kg live weight swine. Based on the general weight of an adult swine as 250 kg, the average emission would reach 2.57 kg per swine. In contrast, when the system installed SGEPM, the CH$_4$ emissions were significantly reduced to 4.95 g per kg live weight swine, which value was only half...
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Table 4 Contribution in three damage impact sections of swine farm operating by three-stage wastewater treatment system (original operating) and the SGEPM (transform operating). Assessed by ReCiPe2016 at the endpoint level

| Damage category | Unit        | Original operating | Transformation operating |
|-----------------|-------------|--------------------|--------------------------|
| Human health    | DALY        | 7.70E−05           | 1.39E−05                 |
| Ecosystems      | species.yr | 1.94E−07           | 7.90E−08                 |
| Resources       | USD2013     | 1.28               | 0.17                     |

Fig. 6 Comparison of damage impacts of the original three-stage wastewater treatment system and the SGEPM at the endpoint level

of that of the three-stage system. The reduction of CH₄ emissions was 1.33 kg per adult swine.

In addition, SOₓ and TSP were the other two categories with more significant emissions discrepancies after installed the SGEPM that the emission reductions were 92.65% for SOₓ and 95.41% for TSP. Moreover, the emissions of NOₓ, CO, and N₂O were also reduced by 74.18, 54.70, and 28.56%, respectively. On the other hand, although the emission of non-methane volatile organic compounds (NMVOC) was small, it was reduced by 80% after installed the SGEPM.

Environmental impacts evaluated by ReCiPe2016 midpoint

The evaluation results for the relative contribution of the swine farm using the three-stage wastewater treatment system and after installed the SGEPM had shown in Fig. 6. After installing the SGEPM into the three-stage wastewater treatment system, the ionizing radiation (IRP) section got the highest reduction on the impact value, which was reduced from a former value of 3.20E-08 to 5.74E-10 DALY, which is only 2% of the former value. The subsequent high reduction was water consumption potential (WCP) and fine particulate matter formation (PMFP). There were three sub-sections in WCP: human health, terrestrial and aquatic ecosystems. The values of WCP-human health, WCP-terrestrial ecosystem, and WCP-aquatic ecosystem were reduced from 2.05E-06 to 8.64E-08 DALY, 1.25E-08 to 5.25E-10 species × year, and 5.59 E-13 to 2.35E-14 species × year, respectively. For the PMFP, it was reduced from 3.92E-05 to 1.68E-06 DALY. After installing the SGEPM into the original treatment system, the WCP and PMFP values were only 4% of those using the three-stage treatment system.

Fossil resource scarcity (FFP) and mineral resource scarcity (SOP) were the following two sections with high emission reductions after installed SGEPM into the treatment system with reduction values of 13% and 15%, respectively. The global warming potential (GWP) effects on human health, terrestrial ecosystems, and freshwater ecosystems were reduced to 24%; the photochemical oxidant formation effect on human health and ecosystem quality (HOFP, EOFP) was also reduced to 26%. The impacts related to ecotoxicities, such as terrestrial ecotoxicity (TETP) and freshwater (FETP), and marine ecotoxicity (METP), were reduced to 28% to 36%. The terrestrial acidification potential (TAP) was also reduced to 39%. According to the assessed results on the midpoint, installed the SGEPM into the three-stage wastewater treatment system carried out huge benefits to environmental impacts.

Damage impacts evaluated by ReCiPe2016 endpoint

A comparison of before and after installing the SGEPM into the three-stage wastewater treatment system in three damage impact sections had depicted in Fig. 6. All three damage impacts gave a significant reduction after installing the SGEPM. In terms of human health (HH), ecosystem quality (ED), and resource scarcity (RA), the reductions were 82%, 59%, and 87%, respectively. It was evident that the SGEPM could improve the damage impacts caused by the three-stage treatment system in the swine farm and averagely reduced the damage impacts by 80%. Table 5 summarizes the contribution assessment results of these two treatment systems in three damage impact sections.

Economic evaluation

In terms of cost-benefit analysis, this study started from the discrepancy in operating these two systems, compared them with the concept of relevant information, and explained overall system planning. First, because the SGEPM system was directly grafted to the original wastewater treatment system, there was no increase in raw material and salary costs. Further, the cost of installing the SGEPM system was 70,000 USD, and the estimated durability was 25 years without a disability. Under the condition of value, the annual increase in depreciation costs was 2800 USD. Next, the cost
of utility electricity was calculated based on utility posted price, including the use of a substrate pump (1500 W) for 45 min per day and the use of a hybrid pump for 30 min per day (550 W). The use of an intelligent control system for 12 h per day (250 W) and the total electricity consumption was about 0.1 USD/kWh (about 280 USD per year). In addition, the maintenance cost was calculated at 15% of the depreciation cost, and it was 420 USD per year that made the annual increase in relevant costs was 3500 USD. Therefore, the estimated annual benefit of installing the SGEPM system was 2591.13 USD. Based on the useful life of 25 years, the cash expenditure of 70,000 USD was invested in the SGEPM system at the beginning of the period. The subsequent cash inflows were evaluated, with the IRR being 6.55% and the expected recovery period being 12.94 years.

Next, based on the biogas production rate, a calculation of the power generation revenue was done. Based on the posted price issued by CPC at 0.36 USD/d-m³ (CPC Corporation 2020), the daily biogas production through the SGEPM system was 46.38 m³, and the daily gas production income was 16.69 USD. From these results, using the SGEPM system would increase the annual electricity generation income by 6091.85 USD. This result was crucial in making a decision. Table 5 lists the cost–benefit estimate.

### Discussion

#### Reduce the potential for carbon footprint emissions by installing the SGEPM

The carbon footprint evaluation result shows that installing the SGEPM into the three-stage wastewater treatment system could reduce 22.56% emissions. Observing the total emission on SGEPM, which evaluated each operating unit, was 1.02 kg CO₂-eq/kg higher than the original three-stage system. However, considering the whole swine farm operation included energy consumptions and energy recovery by electricity generation through biogas converting, the emissions were reduced by about 35% in the end. It gave a positive response for reducing carbon footprint while applying the SGEPM to produce biogas and recycling as electricity generation. In addition, due to the carbon fixation of biomass in the life cycle (Ducat and Silver 2012), for carbon footprint accounting purposes, biogenic carbon is considered a CO₂ reduction or a negative emission (ISO 2018). From this perspective, the carbon footprint emissions under the SGEPM system would be -5.30 kg CO₂-eq indicating no carbon footprint emissions. It proved that using bio-sourced waste converting to bioenergy having a more significant opportunity to decrease carbon footprint emissions.

### Mitigation for gaseous pollutant emissions

Gaseous pollutants such as SOₓ, TSP, and NMVOC were significantly reduced after using the SGEPM system and NOₓ, CH₄, CO, and N₂O emissions. Grossi et al. (2018) had shown that these materials are the primary gaseous pollutants emitted from the livestock industry. Due to the installation of SGEPM, the pollution factors that generally escape into the air during the initial wastewater treatment processes would be significantly reduced by the anaerobic fermentation process in SGEPM, included the contents of the treated wastewater that returned to the original system for discharging. This treatment brought many benefits to the environmental impacts, primarily directed to freshwater and soil acidification, furthermore for crops.

### Environmental assessment for damage impacts

The damage impacts assessment considered the impacts on human health, environment, and resource consumption with time-length factors, such as consideration by 20 or 100 years for the influence duration. Therefore, the comparison results of damage impact evaluation were more prominently presented before and after installing the SGEPM than other evaluation results.

According to the feeding in swine farms, to maintain stable and good swine feeding efficiency and growth performance, high-protein formulas are often used in swine husbandry feeds. However, if it were not effectively used and decomposed, approximately 60–70% of unused nitrogen in feeding would be excreted in manure again and caused pollution (Dourmad et al. 1999). Nitrogen-containing substances in manure include undigested dietary nitrogen such as protein, endogenous nitrogen, and microbial nitrogen. Manure microorganisms rapidly convert undigested protein into relatively unstable nitrogen-containing or sulfur-containing...
substances, such as ammonia, nitrate, nitric oxide, hydrogen sulfide. The discharge of these substances into the environment would affect the surrounding environment. In addition, the livestock industry in Taiwan is dominated by intensive farming to facilitate centralized management, shorten the raising time, and fast obtained as the objective. Excessive heavy metals might be added to the feeds, and the livestock wastewater might contain heavy metals and chemical residues. These materials could cause terrestrial pollution during recharging agricultural land. Therefore, the livestock raising and fattening process, wastewater treatment, and recycling are the keys to improve the industry and its environmental impacts. After installing the SGEPM into the three-stage wastewater treatment system, the reductions in NOₓ, SOₓ, and relevant gaseous pollutant emissions had an extent reduction. As IRP was relevant to metal residues of treated wastewater, HOFP and EOFP were relevant to the emission of CO, NOₓ, N₂O, CH₄, and TSP. The reductions of TETP, FETP, METP, and TAP were relevant to the decrease of NOₓ and SOₓ, showing the interactive reaction in the midpoint and endpoint results by reductions in each impact category. All of those results pointed to after installing the SGEPM brought environmental and economic benefits. There were (i) turning waste to be energy while dealing with swine manure wastewater; and (ii) the energy-recovery supporting the needs of SGEPM operation and swine farm essential operation, reducing the impacts of SOP and FFP. Among all the endpoint (damage impacts), resource scarcity (RA) had the most significant impact reduction after installing the SGEPM, showing that the SGEPM was greatly helpful in reducing resource consumption.

**Investment and operation/benefits and feasibility of SGEPM**

Under the operational guidance of the government, most large-scale swine farms (with more than 2000 heads) in Taiwan have installed a wastewater treatment system and biogas power generator (COA 2016). The actual benefit of biogas power generation is only a quarter of the estimated value by the government. The results from the customary raising model of using groundwater for flushing swine houses in Taiwan result in the dilution of swine manure wastewater and then lowering biogas production. In addition, the current methods and models used in commercializing biogas power generation and electricity sales are more suitable for large-scale swine farms. The costs of equipment and generators are much too high for most of the small and medium-scale swine farms in Taiwan.

Furthermore, swine farmers need to pay more time and workforce in negotiating and coordinating the specifications and installation procedures of different equipment with various manufacturers for installing and operating biogas power generation systems. Therefore, the SGEPM proposed in this study had easy-to-install and easy-to-move equipment planning and design, which could be adopted to local conditions for small-scale swine farms. It could solve possible equipment and assembly requirements and meet the economic considerations that could be seen by cost–benefit evaluation. This system can achieve the closed cycle of material and energy flow in swine farms and is suitable for small and medium-scale intensive swine farms to achieve the goals of enterprise self-reliance, resource recycling, economic improvement, reduction of environmental impacts, and energy sustainability.

**Conclusions**

The environmental and economic performance of installing the SGEPM into the three-stage wastewater treatment system had been analyzed with the detailed assessments conducting on environmental impacts and cost-benefit analysis. The SGEPM system was shown as the tremendous appropriate module for small-scale-intensive livestock farms, and it could efficiently reduce carbon footprint and relevant gaseous pollutants. Installing the module also could reduce damage impacts on human health, ecosystem quality, and resource scarcity and bringing economic benefits by daily producing biogas for energy recovery and increasing an annual electricity generation income of 6092 USD.

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**Declarations**

**Conflict of interest** There is no conflict of interest to claim in this study.

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