Vietnam Journal of Science and Technology ***61*** *(3) (2023) 415-428*

doi:10.15625/2525-2518/16766

A case study of circular economy from waste

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Received: 2 December 2021; Accepted for publication: 22 August 2022

Abstract. This case study focused on zero emission via waste sludge treatment process from a brewery wastewater treatment plant. A perspective solution was based on three main processes, including sludge digestion (40 m^3/day), biogas recovery and purification for generation (20 kWh), and organic fertilizer production for green agriculture. The system is designed to integrate processes and operate fully autocompletively, except for the fertilization of crops. The results of this work showed that the organic content decreased by 55 - 70 % after a sludge retention time (SRT) of 20 days with a methane (CH_4) yield of 55 - 65 %. The contaminants in biogas were purified by a high gravity rotary packed bed (HGRPB) device using an aqueous solution (0.01 M NaOH), giving a CH_4 removal efficiency of 87 %. The remaining CH_4 content met the standard requirements for generator engines or boiler combustion. The digested sludge was combined with other by-products to produce organic fertilizers for green agriculture development. The quality of organic fertilizers was examined and met the provisions of Decree No. 84/2019/ND-CP of the Government: Regulations on fertilizer management. The results obtained from this case study met the harmonious combination of waste treatment, energy recovery and organic fertilizer production that contributes to the direction of circular economy and sustainable development.

Keywords: circular economy, energy recovery, organic fertilizer, sludge management, waste sludge treatment.

Classification numbers: 3.3.2, 3.4.1.

1. INTRODUCTION

Rapid population growth, pressure of economic growth, urbanization, industrialization, demand for fuel and energy have led to overexploitation of natural resources. These are the main contributors to environmental pollution and global climate change. Economic shift towards circular economy, green economy (1), low carbon economy (2) is an inevitable trend of the times accompanied with global agreement and acceptance of countries around the world. The trend of the green industrial revolution of the 21st century is an opportunity for the global community to join hands to fulfill international commitments in the field of environmental protection and reponse to climate change, meeting the requirements of sustainable development.

Recovery and reuse of valuable resources from waste are one of the keys to reducing input raw material consumption (water, fuel, etc.), minimizing waste and improving energy efficiency. This is why the circular economy concept can be applied in industrial activities, especially in wastewater treatment. A circular economy is a system in which waste is reused or recycled, and scrap streams are turned into inputs for further production [1].

Sewage sludge is a solid by-product of the wastewater treatment process, containing high contents of organic matter, pathogenic bacteria, toxic compounds and heavy metals, etc. These contaminants are among the most difficult to remove in wastewater treatment plants (WWTPs), where sludge treatment operations account for 60 % of the total cost of removal [2]. From all of the above, it is essential to find the right technical solutions to convert the waste sludge into useful and friendly products that meet economic and environmental aspects. Waste sludge is generated in large quantities in cities and industrial zones in Viet Nam now, so it should be used for the purpose of energy recovery and organic fertilizer production via anaerobic digestion and composting processes [3].

Anaerobic digestion is a novel process due to its low cost and high recovery efficiency for wastewater with high organic and nutrient content, in which biodegradable compounds could be broken down by microorganisms, releasing biogas in the absence of oxygen. Initially, the raw biogas obtained is a mixture of gases including methane (50 - 70 %), carbon dioxide (30 - 50 %), and other gases such as hydrogen sulfide, nitrogen or hydrogen [4]. Methane (CH_4) is an important and indispensable component of biogas, which is considered a greenhouse gas and should be purified. Purified biogas can be used for electricity generation, heat production and as fuel for machinery among other uses. The methane yield from the sludge varies in the range of 80-377 mL CH_4/g of volatile solids depending on the input material, hydraulic retention time, treatment temperature and pretreatment method used [5 - 7]. Therefore, there seems to be a reason to perform anaerobic digestion to facilitate high benefits [8]. Through an anaerobic digestion process, two WWTPs in Austria generated 106.3 and 107 % of their energy self-sufficiency that they used and sold off the rest [1,9]. Meanwhile, waste treatment plants in Switzerland can produce up to 126 % of the electricity needed to supply the grid [10]. Or in the case of the Marselisborg WWTP in Denmark, it can generate up to 150 % of its energy self-sufficiency with the investment of funds to optimize the treatment process and improve biogas production [11].

The quality of biogas depends on the source of raw materials involved in the anaerobic digestion processes [12,13]. Impure biogas from an anaerobic digestion system can be further purified and upgraded to produce biological methane which can be a direct product for natural gas or biogas in order to possibly convert it into thermal and electrical energies through cogeneration by a thermal reactor [14]. The biogas purification is essential to obtain the desired biogas quality [15]. Among the contaminants in biogas, the main compound is H_2S, which is both toxic, corrosive, and causes significant damage to pipelines, equipment and instrumentation, so its removal is prioritized [16].

The digested sludge after anaerobic digestion still contains organic matter and nutrients (phosphorus, potassium, and nitrogen) that should be used as a source of compostor fertilizer for agricultural purposes and soil improvement in accordance with the environmental criteria [14]. This study was conducted at a brewing company with a wastewater treatment capacity of 900 m^3 per day and 20 tons of organic sludge being discharged per day. The experimental system was designed and operated according to an automated, energy-saving and emission-reducing process (detailed in Figure 2).

The circular economy development aspect is the goal of this study, whose overall work focuses on anaerobic digestion, biogas purification and production of organic fertilizers from waste sludge treatment. Hence, the obtained results of this study are to contribute to the sustainable development and application of a circular economy model in waste management.

2. MATERIALS AND METHODS

2.1. Research objectives

The research objectives are shown with three main processes: (1) Anaerobic digestion, (2) Biogas purification, and (3) Organic fertilizer production from waste sludge of the WWTP. The research objectives related to all the processes are presented in Figure 1.

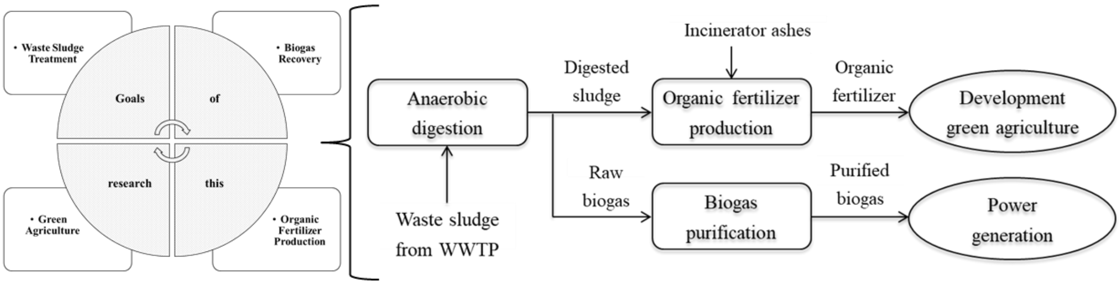

Figure 1. Overall system of the case study.

This study was conducted at a food production company in Dak Lak province, which is the capital of industrial crops, fruits and vegetables in Viet Nam with a wastewater treatment plant of 900 m^3 per day and 20 tons of organic sludge being discharged per day. The waste sludge generated from the factory's wastewater treatment system using A2O technology was a dry waste separated by a sludge conveyor system with a capacity of 3 m^3/h. The dry waste was then collected and transported by a company for processing. Generally, the cost of treating this sludge alone is up to several hundred million a year. In this study, waste sludge generated from the wastewater treatment system of this plant was used as the operating material.

2.2. Technological models

Anaerobic digestion

Anaerobic digestion process to recover biogas is presented in Figure 2. Waste sludge after wastewater treatment was pumped to a 5 m^3 compressed sludge tank and then to a 5 m^3 pre-treatment tank where pH was adjusted. The product generated was pumped to an anaerobic digestion tank of 40 m^3 where raw biogas was recovered for purification as shown in Figure 3 and waste sludge after anaerobic fermentation for composting as shown in Figure 4. The wastewater current was then recovered to come back to the wastewater treatment plant.

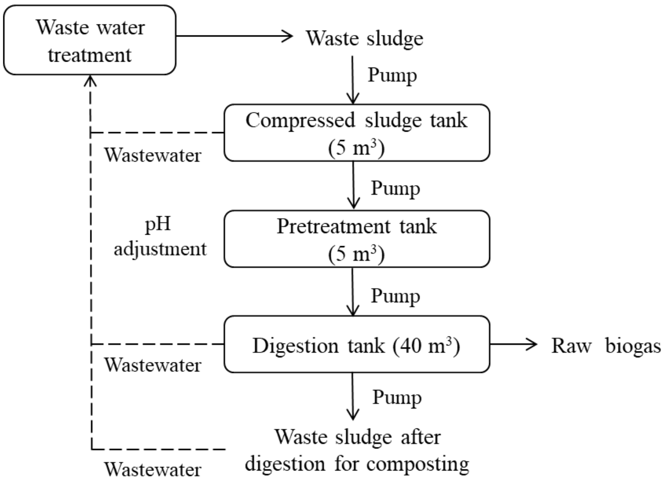

Figure 2. Technological line of anaerobic digestion model for biogas recovery.

Biogas purification

Biogas was finally purified in a tank of 5 m^3 by a high gravity rotary packed bed (HGRPB) device using an absorbent aqueous solution (0.01 M NaOH). Then, the biogas was pressed by a 5 m^3 pressure-regulated tank to a biogas generator to produce 20 kWh of electricity for the plant's operation. All the steps of the biogas purification process are shown in Figure 3.

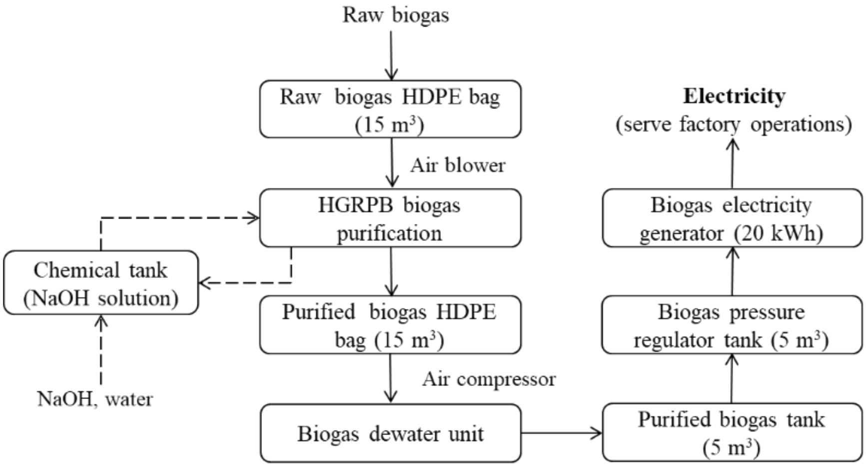

Figure 3. Technological model of biogas purification for power generation.

Organic fertilizer production

The organic fertilizer production process from waste sludge is shown in Figure 4. The waste sludge was pre-treated by adding humidity and controlling pH using a powder of $CaCO_3$ and ash (rice husk, sawdust). Then, the waste sludge was mixed in a mixing tank with additional microbial products. The mixture was composted for 7 to 10 days to form organic fertilizer, whose quality was tested according to national standards for use as compost in agriculture.

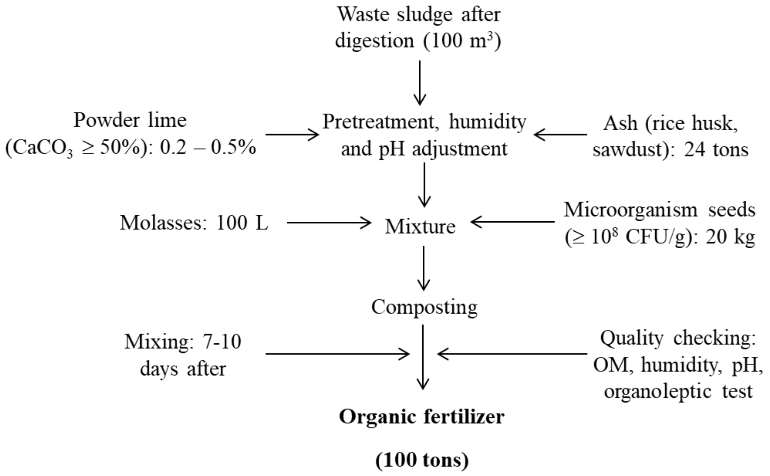

Figure 4. Schematic diagram of organic fertilizer production.

2.2. Research Methods

- The collection and preservation of sludge samples were followed the instructions in TCVN 6663 - 13:2000 and TCVN 6663 - 15:2004. Sludge samples were stored at 4 °C.

+ Chemical oxygen demand (COD) was analyzed according to SMEWW 5200C:2012 - Closed Reflux, Titrimetric Method and Humidity: analyzed according to TCVN 6648:2000 (ISO 11465:1993).

+ Metals (arsenic (As), Zinc (Zn), cadmium (Cd), lead (Pb), barium (Ba), silver (Ag), cobalt (Co), nickel (Ni), selenium (Se), and mercury (Hg)) are analyzed according to Standard Methods 22nd edition [17] and United States Environmental Protection Agency guidance document [18] by Z2000 Atomic Absorption Spectrophotometer equipment, Hitachi, Japan;

+ Chromium(6+) (Cr^{6+}), cyanide (CN^-), phenol, benzen: analyzed according to United States Environmental Protection Agency guidance document [18] by UV-2450 UV-VIS spectrophotometer equipment, Shimadzu, Japan;

+ Benzene was analyzed according to United States Environmental Protection Agency guidance document [18] by GC-2010 Gas Chromatograph equipment, Shimadzu, Japan. Total oil content was analyzed according to United States Environmental Protection Agency guidance document [18];

+ Methane (CH_4): analyzed according to TCVN 8715:2011;

+ Hydrogen sulfide (H_2S): analyzed according to TCVN 10142:2013.

- Analysis of indicators in fertilizer samples was carried out at the laboratory of the Institute of Agricultural Environment where total nitrogen (N_{total}), total phosphorus (P_{total}), total potassium (K_{total}), Humic acid, fulvic acid, Organic carbon, pH_{H2O}, Humidity, *Coliforms and Salmonella* were analyzed according to regulated TCVN methods.

- The obtained data were statistically presented by using Microsoft Excel software. All results of the experimental processes were averaged and repeated 3 times.

- Analytical evaluation method was applied to evaluate the benefits and effectiveness of the research model. The economic efficiency of the model was calculated through the net present value (NPV) as the index, according to the following formula [19, 20]:

$$NPV = \sum_{t=1}^{n} \frac{(B_t - C_t)}{(1+r)^t}$$

where B_t and C_t are the benefits and costs at the year "t", "r" r: discount rate, choose r = 12 % [21] and "t" is the year number calculated.

The internal rate of return (IRR) is indicated as the value to NPV = 0.

3. RESULTS AND DISCUSSION

3.1. Initial composition of waste sludge for biogas recovery, biogas purification and organic fertilizer production

In order to confirm the suitability of using the source of sludge for the purpose of our study, the initial waste sludge was analyzed for parameters inhibiting microbial fermentation. These parameters were humidity, COD, T-N, T-P and heavy metals, CN^-, oil, phenol and benzene according to QCVN 50:2013/BTNMT (Table 1).

Table 1. Parameters causing microbial inhibition in waste sludge samples

STT	Parameter	Unit	Result	QCVN 50:2013/BTNMT
1	Humidity	%	99.4	-
2	COD	g/L	30.99	-
3	T-N	mg/L	271.12	-
4	T-P	mg/L	68.16	-
5	Pb	ppm	< LOD = 0.01	263
6	As	ppm	< LOD = 0.01	35.1
7	Hg	ppm	< LOD = 0.01	3.51
8	Zn	ppm	80.8	4382.5
9	Cd	ppm	< LOD = 0.01	8.77
10	Ba	ppm	< LOD = 0.01	1753
11	Ag	ppm	< LOD = 0.01	87.7
12	Co	ppm	< LOD = 0.01	1402.4
13	Ni	ppm	7.43	1227.1
14	Se	ppm	< LOD = 0.01	17.53
15	Cr^{6+}	ppm	< LOD = 6.0	87.7
16	CN^-	ppm	< LOD = 0.061	517.1
17	Total oil content	ppm	< LOD =50.0	876.5
18	Phenol	ppm	< LOD = 5.0	17530
19	Benzen	ppm	< LOD = 0.001	8.77

Note: LOD: limit of detection

The obtained data of the pollutant concentrations in terms of all parameters were within the allowable limits compared with the National technical regulation on hazardous thresholds for sludges from water treatment (QCVN 50:2013/BTNMT). It was confirmed that the waste sludge generated from the plant's wastewater treatment system was not hazardous and could be used for other purposes such as biogas recovery for electricity generation, biogas purification to reduce pollution, and production of organic fertilizer by composting.

3.2. Efficiency of the biogas purification and the applied models from waste sludge

These applied technologies showed that the system of this case study was perfect stages including waste sludge supply, pH increase, anaerobic digestion for biogas recovery, biogas purification, sludge compression, electricity generation, and organic fertilizer production. Power generation was automated through the control system. All components in the system were calculated for the most suitable and effective performance under the climatic conditions in Viet Nam. The models were practically connected to the central controller to operate conveniently and reduce labor costs.

Different from the traditional batch-based anaerobic digestion technology, these technologies were not only applied in continuously operated processes but also ensured undisturbed technology models, fully meeting the requirements of environmentally sustainable development. Technical parameters for the highest biogas recovery from waste sludge after the decomposition process ensured an easy balance of basic components for bio-organic fertilizer production by COD content and purified biogas using an HGRPB device and an absorbent solution of NaOH.

The obtained results showed that the COD content before the decomposition process was 30994.49 ± 4989.19 mg/L, and after the decomposition was 9624.86 ± 1639.39 mg/L. With 40 m^3 of the sludge treated, the total amount of biogas obtained was 105.59 m^3, so the biogas production yield was 0.31 L/g COD. If COD consumption was completely converted into CH_4, 1 kg of COD could produce 0.35 m^3 of CH_4 [22]. Thus, in this study, a conversion efficiency of up to 88.5 % was achieved. Moreover, under anaerobic conditions, the organic matter was converted to CH_4 gas, each kg of COD removed could produce about 13.5 MJ of CH_4 energy, and yield 1.5 kWh of electricity with an electric conversion efficiency of 40 % [23].

Moreover, in the study, the generated raw biogas from the anaerobic digestion model was cleaned to ensure the biogas composition for electricity generation. The high-speed centrifugal rotation technique was applied using an HGRPB device (Figure 5). This technique can produce high centrifugal acceleration with a large contact area between the liquid and gas phases [24]. According to Ramshaw, 1995 [25], this technique is an effective technological solution, significantly reducing the size of the device and giving high efficiency in biogas purification. Moreover, with a simple and compact structure, this device can be easily moved and installed at required locations.

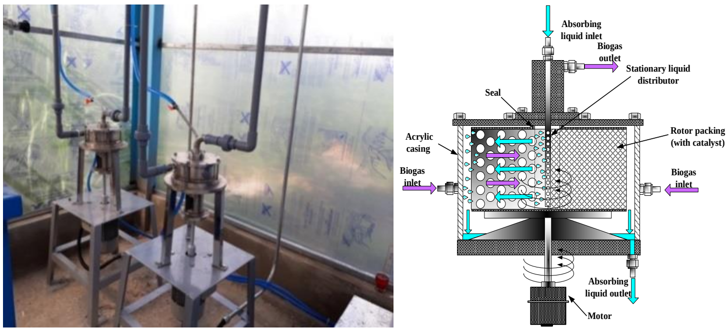

Figure 5. Gas absorption principles by HGRPB.

Raw biogas was fed into the device at a steady rate and allowed to flow through a regulator (Q_G = 2.5 L/min), with Q_G/Q_L (gas flow rate/liquid flow rate) = 20, rotating speed = 1200 rpm. The NaOH absorbent solution was supplied to the center shaft of the device by a pump. Under the action of the rotating motor in the middle shaft, the NaOH solution moved centrifugally at a high speed, increasing the contact between the solution and the incoming gas stream. In the process, H_2S gas combined with NaOH solution according to reactions (1) to (4) as below [26, 27]:

$$H_2S_{(aq)} + NaOH_{(aq)} \rightarrow Na_2S_{(aq)} + 2H_2O \quad (1)$$

$$H_2S_{(aq)} + NaOH_{(aq)} \rightarrow NaHS_{(aq)} + H_2O \quad (2)$$

$$Na_2S_{(aq)} + H_2S_{(aq)} \rightleftharpoons 2NaHS_{(aq)} \quad (3)$$

$$Na_2S_{(aq)} + H_2O \rightleftharpoons NaHS_{(aq)} + NaOH_{(aq)} \quad (4)$$

At the same time, NaOH also reacted with CO_2 presented in biogas according to reactions (5) and (6):

$$NaOH_{(aq)} + CO_{2(aq)} \rightarrow NaHCO_{3(aq)} \quad (5)$$

$$NaHCO_{3(aq)} + NaOH_{(aq)} \rightarrow Na_2CO_{3(aq)} + H_2O \quad (6)$$

with high centrifugation speed, the NaOH adsorbent solution was not pulled out with the gas stream, so that the treated gas stream had a low moisture content, meeting the standards for power generation. Figure 6 shows biogas composition before and after cleaning by HGRPB technique of this case study. After the treatment process, the H_2S gas was completely cleaned. Some research results in the world also achieved the content of H_2S purified after processing by different methods with the allowable value within standard limits [28, 29]. In other researches, the quality of biogas after complete cleaning also met the requirements of the standards [30, 31].

The experimental results showed that the removal efficiency of H_2S using HGRPB was completely achieved, that is, no trace of H_2S was detected after the purification process. Meanwhile, the CH_4 composition increased to 87.6 %, completely meeting the requirements of biogas standards for power generation purposes [31]. After removing CO_2 and H_2S, the total volume of CH_4 in the biogas increased from 60.61 m^3 to 92.50 m^3 after being purified, which greatly contributed to the improvement of biogas quality.

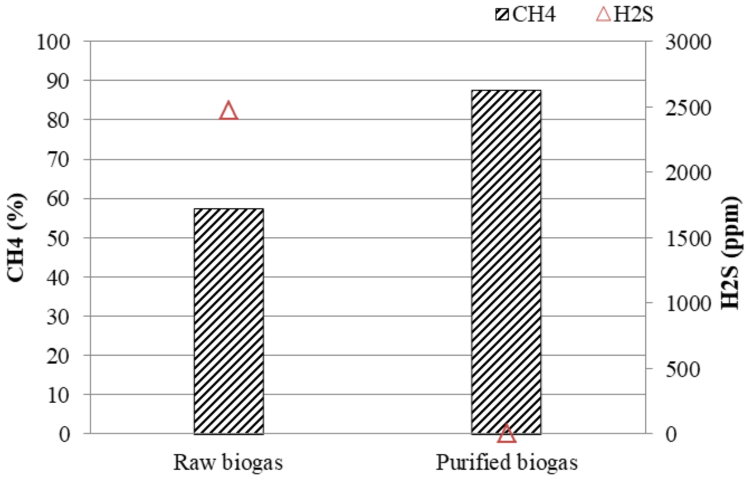

Figure 6. Components (CH_4, H_2S) of raw and purified biogas.

Based on the calorific value of biogas and the amount of electricity measured in each test period, the total biogas energy and the total electrical energy generated (kJ) were calculated representing the power generation efficiency. The amount of electricity generated (kWh) was measured by a 10/40A single-phase meter network (kWh) with CV140 glass lid with calculation formulas according to the instructions of the document [32]. The test results showed that the average calorific value of biogas was 27808.41 kJ/m^3. According to Alexandrina *et al.* [33], the calorific value of biogas with a methane content greater than 80 % would fall in the range of more than 25000 kJ/m^3, so our results were completely consistent with their study. The average power generation efficiency is 34 %. Normally, when biogas is burned and converted into electricity, 65 % of energy is lost as heat. Therefore, the power generation efficiency of the biogas engine will be about 30 - 34 % [34]. If a thermoelectric cogeneration engine is used, it is possible to recover the lost heat and give an efficiency of up to 96 %. This result was similar to the power generation efficiency of some other previous studies [33]. The average total amount of biogas generated was 105.59 m^3 and the electricity generated was 263.98 kWh, so 1 m^3 of biogas generated 2.5 kWh of electricity. This result was consistent with the information in the book Biogas - Green Energy [35].

3.3. Organic fertilizer production technology from waste sludge

Table 2. Sludge composition before and after composting for 30 days.

No.	Parameter	Unit	Result		Decree No 84/2019/ND-CP, QCVN 01-189:2019
			Before composting	After composting	
1.	N_{total}	%	1.38	1.84	-
2.	K_{total}	%	0.13	0.13	-
3.	P_{total}	%	0.04	0.06	-
4.	Humic acid	%	4.47	4.22	Humic + Fulvic acid ≥ 2
5.	Fulvic acid	%	6.86	10.57	
6.	Organic carbon	%	29.72	21.42	≥ 15
7.	Humidity	%	60	29.4	-
8.	pH_{H2O}	-	7.5	7.8	-
9.	As	mg/kg	Not detected	Not detected	≤ 10.0
10.	Hg	mg/kg	Not detected	Not detected	≤ 2.0
11.	Pb	mg/kg	Not detected	Not detected	≤ 200.0
12.	Cd	mg/kg	Not detected	Not detected	≤ 5.0
13.	*Coliforms*	CFU/g	2.8×10^3	Not detected	Not detected
14.	*Salmonella*	CFU/g	Not detected	Not detected	Not detected

According to applied research models, the waste sludge after biogas purification was used for composting and was added with some materials to ensure the nutrient ratio in the composting process which lasted at least 30 days. The waste sludge after biogas purification was also sampled to check and evaluate its composition. The results of the sludge composition after anaerobic digestion process of the composting are presented in Table 2.

The results in Table 2 showed that, after the incubation composting process, the organic carbon content in the raw materials reached 21.42 %, the moisture decreased sharply to 29.4 %, the total N and total P increased, while limiting factors such as heavy metals (As, Hg, Pb, Cd), *Coliforms* and *Salmonella* were undetected. The reason is that the high temperature of the composting pile caused the loss of water vapor in the pile and at the same time the accelerated metabolism of organic compounds, which inhibited and killed pathogenic microorganisms, thus reducing the risk of environmental pollution by contaminants. The obtained results confirmed that the organic fertilizer product from waste sludge after biogas purification got quality assurance according to Decree No. 84/2019/ND-CP and National technical regulation on fertilizer quality (QCVN 01-189:2019) in Viet Nam and met the demand of using environmentally friendly products in agriculture such as organic fertilizer from waste sludge.

After that, the organic fertilizer product was tested for the growth of beans and applied in DakLak (experiment sample). The control sample was prepared with TRIBAT cow manure from Sai Gon Xanh company: organic content: 23.6 %, humidity: 24 %, nutrient: 1.57 %. This manure was cleaned from pathogens and harmful insects. The results were used to evaluate the benefits of the experiments using fertilizer for bean growth compared with the control as shown in Table 3 and Figure 7.

Table 3. Economic accounting model of growing common beans with organic fertilizers.

Content	Unit	Experiment			Control		
		Count	Unit price (Million Vietnamese dong)	Price (Million Vietnamese dong)	Count	Unit price (Million Vietnamese dong)	Price (Million Vietnamese dong)
Seedlings	kg	20	0.5	10	20	0.5	10
Manure	m^3				25	0.8	20
Organic fertilizer from sludge waste	ton	10	2	20			
NPK fertilizer	kg	130	0.01	1.3	130	0.01	1.3
Plow	ha	1	10	10	1	10	10
Electricity	kWh	1000	0.002	2	1000	0.002	2
Wage labor	Labor	220	0.2	44	220	0.2	44
Plant protection products	liter	1	1	1	1	1	1
Total cost	Million Vietnamese dong			88.3			88.3
Income				188			176
Benefits				**99.7**			**87.7**
Differential				**+12.0**			

Figure 7. Model of using organic fertilizer for bean cultivation.

The test results showed that the yield of bean cultivated in the experimental and control models was different and was 23.5 and 22.0 tons/ha, respectively. There was a marked difference between the value of the products obtained, whereby the selling price per ha of the experimental batch was higher than that of the control and the final income reached 12 and 8 million Vietnamese dong, respectively. The model of using organic fertilizer from digested sludge brought higher profits for vegetable cultivation up to 12 million VND/ha. In terms of environmental protection, organic fertilizer from sludge after anaerobic digestion can completely compete with other organic fertilizers on the market to serve agricultural development, particularly in high-tech agriculture.

The material balance for the anaerobic process of waste sludge from the WWTP in this case study is shown in Figure 8.

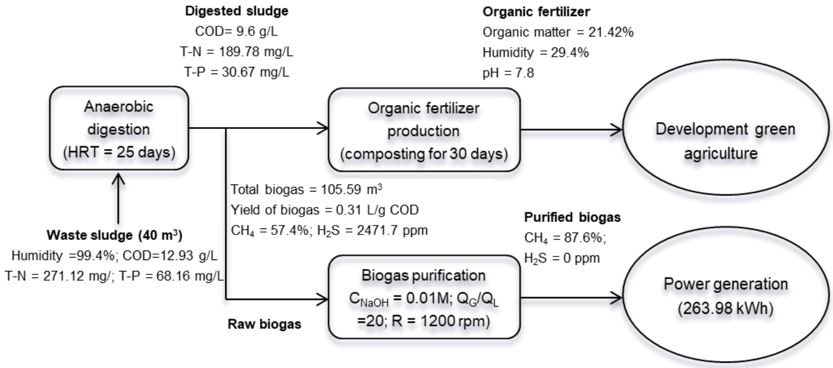

Figure 8. Material balance for anaerobic process of waste sludge from WWTP in this case study.

4. CONCLUSIONS

There is an appropriate technical solution that has been demonstrated to convert waste sludge into energy and green agricultural products. This case study has initially built a circular economy model from waste to friendly products such as purified biogas, electricity, organic fertilizer, and organic farming products.

The results indicated that the organic fertilizer met the quality according to Decree No. 84/2019/ND-CP and QCVN 01-189:2019; the biogas obtained after purification met the standards as biofuel for power generation with CH_4 content ≥ 85 % and no H_2S detected; the electricity generation could achieve a high capacity of 20 kW; the risk of environmental pollution from waste was reduced and contribution to sustainable agricultural development were achieved.

Acknowledgements. The authors would like to thank the Vietnam Academy of Science and Technology and the Institute of Environmental Technology for providing financial support through the project code TN18/C07 and other supports.

CRediT authorship contribution statement. Do Van Manh: Methodology, Investigation, Funding acquisition. Nguyen Tuan Minh 2: Formal analysis. Le Xuan Thanh Thao 3: Formal analysis, Methodology. Huynh Duc Long: Formal analysis. Luong Huu Thanh, Vu Dinh Ngo: Formal analysis, Investigation. Dang Thi Thom, Do Van Manh: Writing and finishing the manuscript.

Declaration of competing interest. 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.

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