Environmental Technology & Innovation 27 (2022) 102414

Contents lists available at ScienceDirect

Environmental Technology & Innovation

journal homepage: www.elsevier.com/locate/eti

Valorization of bio-fertilizer from anaerobic digestate through ammonia stripping process: A practical and sustainable approach towards circular economy

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ARTICLE INFO

Article history:
Received 7 September 2021
Received in revised form 4 January 2022
Accepted 6 February 2022
Available online 11 February 2022

Keywords:
Biogas digestates
Bio-based fertilizer
Ammonium sulfate
Ammonia stripping
Economic analysis

ABSTRACT

Anaerobic digestion is a technology, which converts biological wastes into biogas and biogas digestates (DIG); the latter is considered the main challenge for biogas producers. Recently, nutrient recovery technology from these DIG for bio-fertilizers production as an alternative for traditional chemical fertilizers is receiving increasing attention. This study aims to use two different biofertilizers based on DIG using ammonia striping technique which are liquid bio-based ammonium sulfate (BAS-L) and solid bio-based ammonium sulfate (BAS-S) fertilizers, besides the raw DIG and the conventional urea compound fertilizer (UCF) is used as a chemical fertilizer for comparison to produce solanaceous plants (eggplant). The agronomic effectiveness and economics of using these fertilizers are listed, and the results indicated that the eggplant yields using UCF and BAS-L were 62.65 tons/ha and 63.42 tons/ha, respectively, representing 24.5 % and 27.9 % higher than BAS-S and DIG, respectively. The agronomic efficiency (AE_N) and the apparent recovery efficiency (ARE_N) of BAS-L fertilizer were the highest, reaching 44.8 kg $_{DM}$/kg $_N$ and 7.9 %, respectively, which were significantly higher than the corresponding values of BAS-S and DIG. Furthermore, the economic benefits of various fertilizer applications were estimated and compared. The results showed that the theoretical net revenue of BAS-L fertilizer was 86065.03 $/ha, while BAS-S fertilizer and UCF were lower than BAS-L (56.7 % and 48.5 %, respectively), and the theoretical net revenue of direct application of DIG was 36958.95 $/ha. Therefore, BAS-L fertilizer has the best comprehensive fertilizer effect and economic benefits.

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1. Introduction

Synthetic mineral nitrogen (N) fertilizers are an important guarantee for maintaining adequate food supplies for the growing world population. However, most fertilizer production is still based on mineral deposits and fossil fuels (Chojnacka et al., 2019b). Moreover, due to a large amount of nitrogen loss in crop production and the growing independence between planting and breeding industries, it is difficult to form a closed loop of the nitrogen cycle in

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https://doi.org/10.1016/j.eti.2022.102414
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Abbreviation

DIG	Biogas digestate
BS	Biogas slurry
BR	Biogas residue
BAS-L	Bio-based ammonium sulfate liquid fertilizer
BAS-S	Bio-based ammonium sulfate solid fertilizer
UCF	Urea compound fertilizer
CSP	Calcium superphosphate
PS	Potassium sulfate
TN	Total nitrogen
TOC	Total organic carbon
EC	Electrical conductivity
DM	Dry matter
AVR	Ammonia volatilization rate
NUE	Nutrient use efficiency
AE_N	Agronomic efficiency of nitrogen
ARE_N	Apparent recovery efficiency of nitrogen

the agricultural system, resulting in unbalanced nitrogen flow, which threatens the sustainability of agriculture in the environment and economy (Luo et al., 2021).

Waste, especially biomass waste, is a large resource library that can be recycled by different technologies and used to manufacture various fertilizers (Chojnacka et al., 2019a). Therefore, the shift from a fossil-based economy to a bio-based and circular economy, maximizing the recovery of valuable nutrients from bio-waste streams in a sustainable and environmentally friendly manner has become an important issue (Usmani et al., 2020). Bio-based nitrogen fertilizer extracted from livestock and poultry waste can replace synthetic mineral nitrogen fertilizer, which helps form a closed loop of agricultural nitrogen flow and is more sustainable agriculture in line with the circular economy.

Anaerobic digestion (AD) is a promising technology through which the bio-waste (agricultural and animal wastes) are recycled safely to generate biogas which is a significant established form of renewable energy (Eraky et al., 2021). China's interest in AD technology is increasing. According to the National Energy Administration of China, China is the second-largest biogas producer in the world. The annual biogas production will exceed 10 billion m^3 by 2025 and 20 billion m^3 by 2030. At the same time, with the development of biogas projects, a large number of biogas digestate (DIG) have also been produced.

Several studies have found that DIG is a high-quality bio-organic fertilizer, which is rich in some essential elements and nutrients, such as nitrogen, phosphorus, potassium, and several trace elements as copper and zinc. Also, the organic matter, amino acids, vitamins, and some beneficial microorganisms, which can improve the content of soil humic substances and lay the foundation for improving soil fertility (Elsayed et al., 2019; Yan et al., 2019). Currently, most DIG is used as bio-fertilizer directly in the field, which is made into bio-organic fertilizer to improve soil fertility (Bella et al., 2019; Chen et al., 2019). However, there are also many problems with the direct application of DIG. Nitrogen in DIG mainly exists in the form of organic nitrogen and ammonium nitrogen ($NH_4{}^+$-N), accounting for 50 ∼80% of total nitrogen (TN), and the slow release of organic bound nitrogen results in lower plant utilization (Gutser et al., 2005). Due to the slow-release phenomenon of DIG, it cannot completely replace quick-acting chemical fertilizers in agricultural production. In addition, direct application of DIG to the soil causes nitrogen loss in the form of ammonia volatilization. The volatilized ammonia nitrogen enters the atmosphere, which causes the increase of nitrogen content in natural soil and water, resulting in eutrophication (Wang et al., 2019). Until now, researchers have reported contradictory results concerning DIG phytotoxicity, indicating that high doses of DIG can inhibit seed germination (Ros et al., 2018), and the concentration of organic acids in DIG is also a limiting factor for plant growth (Möller and Müller, 2012; Jose et al., 2018). These factors have caused some controversy about the effect of the use of DIG on the field.

General Office of the Ministry of Agriculture and Rural Affairs and General Office of the Ministry of Ecology and Environment (2020) requires that livestock manure and organic fertilizer used for direct return to the field must be treated harmlessly and meet the corresponding hygienic indicators. In livestock manure treatment and organic fertilizer application, necessary measures should be taken to reduce nutrient loss and reduce environmental impact. Therefore, recycling nutrients technologies from DIG as a sustainable fertilizer in agriculture has become an important challenge for further developing sustainable agriculture, green chemistry and renewable energy production through anaerobic digestion.

In developed countries, high-value fertilizers based on DIG are increasing, and different upgrading technologies are used to recover nutrients to increase the value of digestion reuse and further process them into solid or high-concentration upgraded products (Thu et al., 2012). Compared with other technologies (such as membrane treatment technology, evaporation concentration technology, biochar adsorption technology and flocculation precipitation technology), ammonia stripping is a more mature and feasible ammonia nitrogen recovery, its treatment technology for DIG with high ammonia nitrogen content (Guštin and Marinšek-Logar, 2011; Provolo et al., 2017; Costamagna et al., 2020). The special advantage of ammonia stripping technology is that it can easily absorb ammonia in the exhaust gas through acid, effectively produce ammonium salt fertilizer, such as ammonium sulfate and ammonium nitrate, and realize the production of value-added by-products (Zhao et al., 2015). Recently, the relatively mature method for tail gas absorption after ammonia stripping of biogas slurry uses a sulfuric acid solution to form an ammonium sulfate solution with N-S fertilizer effect (Laureni et al., 2013). The bio-based ammonium sulfate fertilizer produced by the ammonia stripping process is an inorganic salt that is reusable and can be used as a commercially available quick-acting fertilizer for N and S (Vaneeckhaute et al., 2013b, 2014; Jamaludin et al., 2018). In addition, in nutrient recycling agriculture, bio-based ammonium sulfate fertilizer is a valuable substitute for chemical fertilizers based on fossil resources, which can promote the reduction of chemical fertilizer production; and it is an important part of modern agriculture and the N cycle advocated by the government.

Currently, most studies on bio-based ammonium sulfate fertilizers focus on bio-based ammonium sulfate liquid fertilizer (BAS-L). The results of Vaneeckhaute et al. (2013c) and Sigurnjak et al. (2016, 2019) show that the replacement of artificial fertilizer with acidic air scrubber water (same as BAS-L) always brings considerable economic and ecological benefits to agricultural scientists in theory and does not affect negatively on the yield in terms of quantity and quality. However, suppose the recovered fertilizers (such as BAS-L or osmotic concentrate) is compared with chemical fertilizers, in that case, the nutrient concentration in the recovered fertilizers is usually lower, with a nitrogen content of about 5∼6%, and some are even lower, but in chemical fertilizers, the nitrogen concentration usually exceeds 20% (Bolzonella et al., 2018). Therefore, there are the same problems as direct fertilization and utilization of DIG for BAS-L; the operator or user must pay a high price for long-distance transportation of fertilizer (Dahlin et al., 2015). Theoretically, based on ammonia stripping, the concentration of bio-based ammonium sulfate solid fertilizer (BAS-S) obtained by crystallization from a saturated solution is higher, similar in composition to BAS-L (Razon, 2012). Although a large amount of energy must be used, the transportation cost and use of BAS-S are lower than BAS-L, and it is more convenient for commercial production and sales (Vaneeckhaute et al., 2013c).

Previous studies on the effectiveness of bio-based fertilizers have mostly focused on energy and leafy crops, and few studies have used them for solanaceous crops cultivation (Vaneeckhaute et al., 2013c; Sigurnjak et al., 2016, 2019). Solanum is the most important horticultural crop globally, especially in Asia and sub-Saharan Africa (Peña and Hughes, 2007). In recent years, with the continuous growth of human consumption demand, the cultivation area of eggplant has gradually expanded, and it has become one of the important vegetables for domestic sales and foreign exchange earning in China. Eggplant is a relatively fertilizer-resistant vegetable and requires a large amount of fertilizer. However, in traditional agricultural production methods, excessive use of mineral fertilizers has caused a large amount of waste of fossil resources. In some areas, using livestock manure instead of mineral fertilizers has further aggravated the pollution of chemical oxygen demand (Zou et al., 2020). Therefore, due to the reproducibility of bio-based fertilizers and its similar fertility characteristics to mineral fertilizers, there is a huge market for bio-based fertilizers in vegetable cultivation.

From the previous literature, we can conclude that few studies on large-scale use of BAS-S, in addition to the lack of scientific publications that explain the difference between BAS-S and BAS-L in terms of technical preparation, characteristics, application effects, and economic benefits. Therefore, the present work investigates the agricultural impacts and economic benefits of applying BAS-S and BAS-L to the soil and eggplant as a field test crop. Additionally, the effects of used BAS-S and BAS-L on eggplant yield and physicochemical characteristics of soil compared with conventional urea compound fertilizer (UCF) are evaluated. Finally, the economic analyses of the cultivation scenarios by bio-based fertilizers (BAS-S and BAS-L) are performed.

2. Materials and methods

2.1. Materials

The experiment was carried out in the experimental greenhouse of Huazhong Agricultural University, Wuhan, China at latitude 30.6°N, longitude 114.1°E and altitude is 23.1 m during April 2019. The soil type is yellow soil and the long purple eggplant (Zilong No. 6, Wuhan Wellford Seedling Co., Ltd.) was selected for planting. The applied fertilizers are biogas digestates (DIG), obtained from the biogas project in Ezhou, Hubei, China, which the raw material for mesophilic anaerobic digestion was swine manure. In this experiment, DIG was separated into a liquid fraction (biogas slurry, BS) and a solid fraction (biogas residue, BR) by decanter centrifuge and applied respectively. The synthetic fertilizer was UCF; the sources of phosphate and potassium are calcium superphosphate (CSP) as phosphate fertilizer and potassium sulfate (PS), respectively.

2.2. Fertilizers preparation

The bio-based ammonium sulfate fertilizer was prepared by ammonia stripping of BS, BAS-L and BAS-S were obtained from the same batch of BS. The process flow chart of ammonia stripping technology used in this study is shown in Fig. 1.

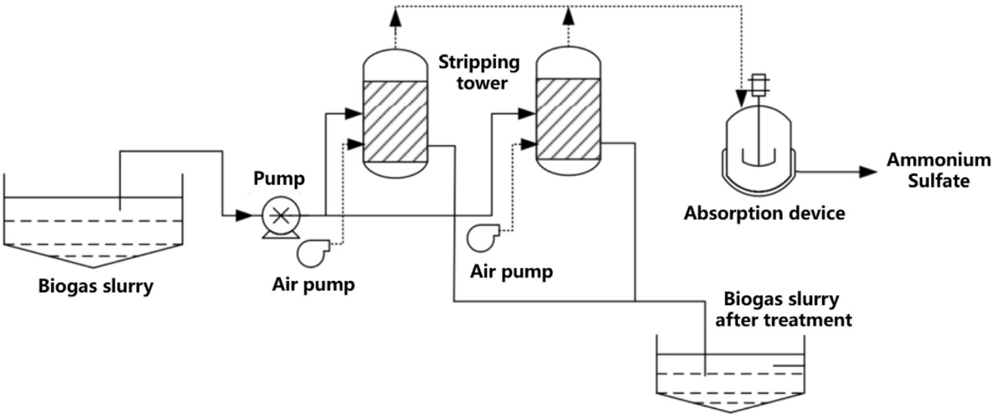

Fig. 1. The process flow chart of ammonia stripping technology.

Table 1
Physicochemical characterization of bio-based products and original soil. Results are expressed on dry weight (DW) basis as means ± deviation of two independent samples. BS: biogas slurry; BR: biogas residue; BAS-L: bio-based ammonium sulfate liquid fertilizer; BAS-S: bio-based ammonium sulfate solid fertilizer.

Test materials	Total N (g/kg)	Total P_2O_5 (mg/kg)	Total K_2O (mg/kg)	TOC (%)	EC (mS/cm)	pH
BS	2.0 ± 0.16	75.9 ± 0.80	1127.0 ± 4.90	0.3 ± 0.01	9.7 ± 0.80	8.2 ± 0.13
BR	4.5 ± 0.10	75.9 ± 0.40	1135.0 ± 5.60	0.3 ± 0.01	5.5 ± 0.70	7.7 ± 0.21
BAS-L	5.0 ± 0.20	ND	ND	ND	3.5 ± 0.60	7.0 ± 0.02
BAS-S	200.0 ± 1.50	ND	ND	ND	3.0 ± 0.70	5.8 ± 0.05
0∼15 cm Soil	1246.0 ± 9.50	49.8 ± 3.40	156.5 ± 5.20	2.2 ± 0.35	128.8 ± 1.30	8.3 ± 0.12
15∼30 cm Soil	1280.0 ± 7.70	48.5 ± 2.60	166.1 ± 4.40	2.4 ± 0.32	112.2 ± 1.10	8.1 ± 0.09

[a] EC and pH of soil and N-S$_{\text{-Crystal}}$ was measured at a 5:1 liquid to dry sample ratio, other (liquid) products were analyzed directly.
[b] ND: Not determined.

The ammonia stripping process parameters were as follows: 75 L of BS, 75 °C stripping column temperature, 250 L/min airflow, the gas was stripped off for 6 h and the ammonia was absorbed by a 1.5 M H_2SO_4 solution according to Serna-Maza et al. (2015). Due to the low pH value of the original BAS-L, which is not promoted to the field application, the BAS-L was adjusted to pH = 7.0 by ammonia water (25∼28%) to achieve the final application conditions. The BAS-S used in this study was obtained using a rotary evaporator in multiple batches to evaporate BAS-L under the same conditions of 75 °C, −1 atm and 50 rpm/min to precipitate solids, the evaporation capacity of each BAS-L batch is 1 L. Physicochemical characterizations of bio-fertilizers and original soil are listed in Table 1.

2.3. Fertilization strategies and experimental design

To evaluate the bio-fertilizer, an area of 4 m^2 (2 m × 2 m) for each plot was chosen to plant the eggplant, and the space between each plot was 50 cm. Eggplants were planted with 50 cm plant spacing and 35 cm row spacing. 15-day-old eggplant seedlings were planted in each plot. With 5 plants in each row, a total of 15 plants in each plot were planted in three rows.

The amount of nitrogen fertilizer used in this study was referenced to the fertilizer used for horticultural planting (Chen et al., 2004), which is twice the typical amount of nitrogen fertilizer (Chen et al., 2002). The amount of fertilization used for each fertilization treatment was total nitrogen (TN) = 340 kg/ha. This study intends to compare BAS-L and BAS-S obtained by ammonia stripping with the untreated DIG and UCF. A total of 5 groups of fertilization treatments were tested in the experiment: BAS-S, BAS-L, DIG, UCF and blank control (CK, water only without applying any fertilizer).

Each treatment was applied into 10 plots, arranged randomly. Regarding the normal field management method, based on the TN application in the whole process, the fertilization scheme is shown in Table 2. After applying the base fertilizer (10th April, 2019), the soil was mixed and the eggplant seedlings were planted at the next day (11th April, 2019). The first topdressing was when eggplant started to bear fruit on 24th May, 2019. On 11th June, 2019, it entered the fruitful period, and was topdressing for the second time. Topdressing for the third time was on 3rd July, 2019. BS and BAS-L were irrigated on the soil surface, UCF and BAS-S were applied by hole application. The BAS-L and BAS-S were matched with P_2O_5 and K_2O in the same amount as the UCF treatments. In other periods, normal agronomic management was irrigated with clear water.

Table 2
Product and macronutrient dosage per ha applied for the five different fertilization treatments ($n = 2$, plot size = 4 m^2) in this study. BAS-L: bio-based ammonium sulfate liquid fertilizer; BAS-S: bio-based ammonium sulfate solid fertilizer; UCF: urea compound fertilizer (total nutrients = 40%, N: P_2O_5: K_2O = 21: 6: 13); CSP: calcium superphosphate (15% P_2O_5); PS: potassium sulfate (54% K_2O); DIG: biogas digestate; BS: biogas slurry; BR: biogas residue; CK: no fertilizer.

Treatment		Type of fertilizer	Base fertilizer (35%)	Type of fertilizer	The first topdressing (25%)	The second topdressing (20%)	The third topdressing (20%)	Total applied		
			Application amount (kg)		Application amount (kg)	Application amount (kg)	Application amount (kg)	TN (kg)	P_2O_5 (kg)	K_2O (kg)
Bio-based fertilizer	BAS-S	UCF	568	BAS-S	425	340	340	340	97	209
				CSP	160	130	130			
				PS	95	78	78			
	BAS-L	UCF	568	BAS-L	17 000	13 750	13 750	340	97	209
				CSP	160	130	130			
				PS	95	78	78			
	DIG	BR	26 750	BS	43 230	34 585	34 585	340	11	157
Control group	UCF	UCF	568	UCF	405	325	325	340	97	211
	CK	–	–	–	–	–	–	–	–	–

2.4. Eggplant fruit and soil sampling

From the first fruit picking, 10∼15 eggplant fruits were taken at the beginning, full fruit, and end stages of each plot to record the length and weight of fruits; then, it was rinsed with distilled water. The washed eggplant fruits were dried at 105 °C for 30 min and then dried at 65 °C for 48 h. The dry samples were ground and passed through a 100-mesh sieve and stored in sealed plastic bags till tests.

The original soil samples were collected using a 5-point method for shallow tillage soil (0∼15 cm) and deep tillage soil (15∼30 cm) (Aichberger and Back, 2001). After harvesting all eggplants (5th August, 2019), all plots used the 5-point method to collect the shallow and deep soil samples after planting, and removed roots, weeds, soil animals, stones, and other impurities, and then it was mixed well. The samples were air-dried, crushed, sieved through a 100-mesh sieve, and stored for next use.

2.5. Physicochemical analysis

Electrical conductivity (EC) and pH value were determined by using a conductivity electrode (DDS-307 A, INESA Scientific Instrument Co., Ltd, China) and a pH-meter (FE28, Mettler Toledo, USA), respectively. To measure the soil pH value, 10 g soil to 50 mL deionized water was mixed well for 10 min to equilibrium. For solid samples, a ratio of 1:5 dry samples to deionized water was shaked for 1 h and then filtered. P and K were analyzed in plant samples using the SmartChem 200 Discrete Auto Analyzer (AMS-Westco, Italy) and atomic absorption spectrophotometer (AA-6880, SHIMADZU, Japan) after ammonium lactate extraction at pH 3.75 and 0.01 M $CaCl_2$ extraction (Hylander et al., 1995; Van Ranst et al., 1999), respectively. Total organic carbon (TOC) and TN were determined using TOC/TN analyzer (Multi N/C® 2100, Analytik Jena AG, Germany).

After drying eggplant fruit samples, they were digested with $H_2SO_4 - H_2O_2$ to measure the TN by SmartChem 200 (AMS-Westco, Italy).

For ammonia volatilization, the venting method (Wang et al., 2004) was used in this study to determine in-situ ammonia volatilization in the field. The device was made of a polyvinyl chloride rigid plastic tube, with an inner diameter of 15 cm and height of 10 cm. Two sponges with a thickness of 2 cm and a diameter of 16 cm were dipped into 15 mL of phosphoglycerin solution (50 mL of phosphoric acid + 40 mL of glycerol, and the volume was adjusted to 1000 mL), and then placed in a rigid plastic tube. The lower sponge was 5 cm from the bottom of the tube, and the upper sponge was level with the top of the tube. The capture of volatile ammonia in the soil began on the day after the third topdressing. Two capture devices were placed at different locations in each plot, and samples were taken at 17:00 the next day. When taking a sample, the sponge was removed from the lower layer of the ventilation device, and then it was quickly put into a plastic bag according to the test plot, and sealed; at the same time, another sponge was replaced and soaked in phosphoglycerin solution. The upper sponge was replaced once every 3 to 7 days depending on its wet and dry conditions. The recovered sponges were respectively filled into 1L plastic bottles, and 800 mL of 1.0 mol/L KCl solution was added to completely immerse the sponges. After shaking for 1 h at 200 r/min, the ammonium nitrogen (NH_4^+-N) in the leaching solution was measured with a SmartChem 200 Discrete Auto Analyzer (AMS-Westco, Italy), and the volume of the leaching solution was recorded. The ammonia volatilization rate (AVR) of the field soil of each fertilization treatment was calculated through the difference method and according to the following equation (Wang et al., 2004):

$$\mathrm{AVR} = [\mathrm{M}/(\mathrm{A}\times\mathrm{D})]\times 10^{-2} \tag{1}$$

Table 3
Data used for the economic analysis. BAS-L: bio-based ammonium sulfate liquid fertilizer; BAS-S: bio-based ammonium sulfate solid fertilizer.

	Factor	Value	Reference
COSTS	Cost artificial N production & packing (\$/kg N)	1.176	Vaneeckhaute et al. (2013b)
	Cost artificial P production & packing (\$/kg P)	0.150	Vaneeckhaute et al. (2013b)
	Cost artificial K production & packing (\$/kg K)	0.537	Vaneeckhaute et al. (2013b)
	BAS-L price (\$/kg)	0.250	Calculation, see section 4.4
	BAS-S price (\$/kg)	0.292	Calculation, see section 4.4

where AVR is the ammonia volatilization rate (kg/(ha·d)), M is the average ammonia measured per capture device (mg), A is the cross-sectional area of the capture device (m^2), and D is the time of each continuous capture (d).

2.6. Nutrient use efficiency

The fate of nitrogen after fertilizer application in the farmland can be divided into three parts: (1) absorbed by crops (the utilization rate of nitrogen fertilizer), (2) residues in the soil, and (3) losses caused by different forms. The utilization rate of nitrogen fertilizer is the main factor that determines the use efficiency of nitrogen fertilizer. In this study, the agronomic efficiency (AE_N) and apparent recovery efficiency (ARE_N) of eggplant fruits were used to evaluate the nutrient use efficiency (NUE) for each fertilization treatment.

The dry matter (DM) content was used to calculate the AE_N of each fertilization treatment through the difference method (Fan et al., 2014):

$$AE_N = (Y - Y_0)/F \tag{2}$$

where AE_N is the agronomic efficiency (kg_{DM}/kg_N), Y and Y_0 are the yields of eggplant in fertilization plot and unfertilized control plot (kg_{DM}), respectively, and F is the quantity of nitrogen applied (kg_N).

Based on the data obtained, the ARE_N is calculated as (Fan et al., 2014),

$$ARE_N = (U - U_0)/F \times 100 \tag{3}$$

where ARE_N is the apparent recovery efficiency (%), U and U_0 are the nitrogen uptake by eggplant fruits in the fertilized plot and in the unfertilized control plot (kg_N), respectively, and F is the quantity of nitrogen applied (kg_N).

2.7. Economic evaluation

The economic and ecological impact of artificial fertilizer production, packing, transport and application was considered. The transport costs were calculated based on the average price of diesel in China (0.94 \$/L) in April 2020 (GlobalPetrolPrices, 2020). In addition, the cost of ammonia stripping in this study only includes the operation cost, not including the construction investment of stripping facilities and the maintenance cost of facilities in the operation stage.

Next to these costs, the economic benefits of digestate derivatives as fertilizer were handled. Obtain the BAS-L by stripping with acidic recovery, BAS-S by stripping with acidic recovery and crystallization. Ammonia stripping reactor consisted of an aerated ammonia stripping tank. The escaped ammonia was absorbed by a 1.5 M H_2SO_4 solution. The crystals were obtained by evaporation crystallization (Han et al., 2014). The data used for the economic analysis is shown in Table 3.

2.8. Statistical analysis

The experimental data were analyzed using SPSS19.0 (Chicago, IL, USA). Based on the physical and chemical data obtained, an analysis of variance (ANOVA) was used to determine the effect of fertilization on soil quality and fertility, as well as the effect on yield and nutrient uptake. When a significant difference between the means was observed, Duncan's test ($p < 0.05$, $n = 3$) was used for additional post hoc evaluation.

3. Results and discussion

3.1. Effects on fruit quantity and yield

The eggplant fruits were harvested on 1st June 2019, then entered the fruit-growing period on 15th June. Finally, the harvesting was ended on 1st August. The length and weight of all picked mature fruits during this period were recorded. As shown in Fig. 2, among the eggplant fruits under different fertilization treatments, the average fruit length of BAS-S application was the longest (31.2 cm), while the average fruit length applied by DIG was the shortest (29.5 cm). In the study of Amalia et al. (2020), they applied fermented compost and N-fertilizer to grow purple eggplant, and the average

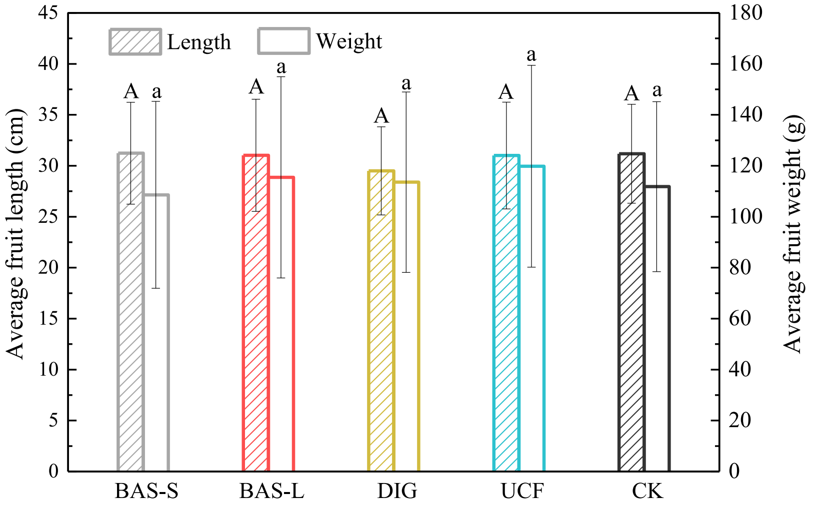

Fig. 2. Average length and average weight of eggplant fruits after different fertilization treatments. BAS-S: bio-based ammonium sulfate solid fertilizer; BAS-L: bio-based ammonium sulfate liquid fertilizer; DIG: biogas digestate; UCF: urea compound fertilizer; CK: no fertilizer. Means with different letters are significantly different according to Duncan's Test, $p < 0.05$. Capital letters mean the average fruit length, small letters mean the average fruit species.

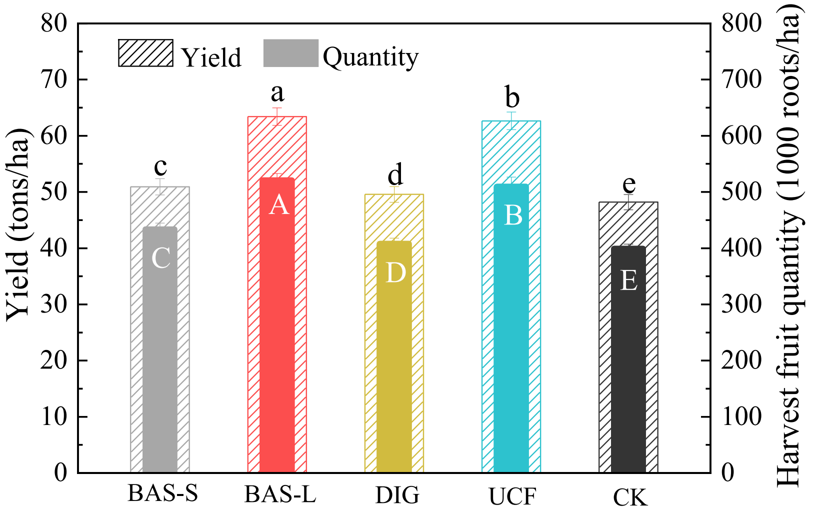

Fig. 3. Yield and quantity of eggplant harvest under different fertilization treatments. BAS-S: bio-based ammonium sulfate solid fertilizer; BAS-L: bio-based ammonium sulfate liquid fertilizer; DIG: biogas digestate; UCF: urea compound fertilizer; CK: no fertilizer. Means with different letters are significantly different according to Duncan's Test, $p < 0.05$. Capital letters mean the harvest fruit quantity, small letters mean the yield.

fruit length of the best experimental group was only 26.21 cm. As for the fresh weight of eggplant fruit, the application of BAS-L is almost the same as that of UCF, both reached about 120.0 g, and the fresh weight of DIG and BAS-S were about 115.0 g for both. In Amalia et al. (2020)'s study, the average fresh weight of eggplant fruit is more than 160 g. But that should be because the experiment used different varieties of eggplant. These results indicated that the fruit length and fresh weight of eggplants using BAS-L and BAS-S were slightly better than those using DIG directly. However, there was no significant difference in fruit length and fresh weight distribution between different fertilization treatments ($p > 0.05$).

Therefore, the main factor affecting the yield of eggplant was not fresh weight of individual eggplants; it was the harvested amount of eggplant fruits by different treatments. As shown in Fig. 3, there was a significant difference between the eggplant yield and the quantity of harvested eggplants under different treatments ($p < 0.05$). The number of fruits harvested with BAS-L and UCF increased significantly, exceeding 500,000 roots/ha, while the number of fruits harvested by CK was only 400,000 roots/ha, and the number of fruits harvested by BAS-S and DIG groups was only slightly higher than that of CK, which were 430,000 roots/ha and 410,000 roots/ha, respectively. In addition, there was a significant correlation between yield and fruit number ($r = 0.99$). The yields of BAS-L and UCF applications were significantly higher

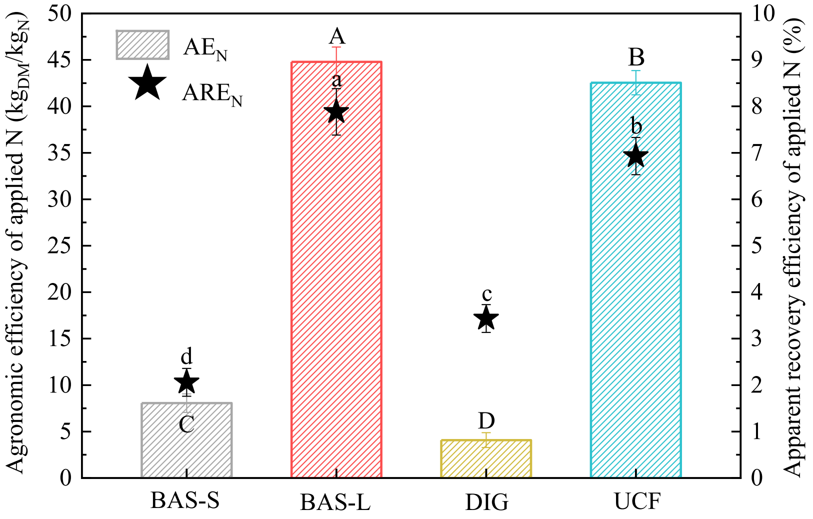

Fig. 4. Agronomic efficiency (AE$_N$) and Apparent recovery efficiency (ARE$_N$ ★) of applied N in different fertilization treatments. BAS-S: bio-based ammonium sulfate solid fertilizer; BAS-L: bio-based ammonium sulfate liquid fertilizer; DIG: biogas digestate; UCF: urea compound fertilizer. Means with different letters are significantly different according to Duncan's Test, $p < 0.05$. Capital letters mean the AE$_N$, small letters mean the ARE$_N$.

than other applications, 63.42 tons/ha and 62.65 tons/ha, respectively. It was significantly higher than the yield of 34.6 t/ha obtained by El-Mageed et al. (2021) in the eggplant planting experiment and the yield of 49.2 t/ha obtained by Amalia et al. (2020). Other studies have reported similar results, Vaneeckhaute et al. (2013c) reported a small improvement in maize yield when air scrubber water and a mixture of digestate and liquid fraction of digestate was applied as N-source compared with mineral N. In terms of harvested quantity and fresh weight, BAS-L and UCF also have only small differences, indicating that bio-based products can replace mineral fertilizers without adversely affecting productivity.

It is worth mentioning that Sobhi et al. (2020) measured the composition of ammonium sulfate produced by ammonia stripping, and the results showed that the produced ammonium sulfate was pure and free of impurities, which also showed that it could completely replace chemical fertilizers. This process helps to achieve the goal of reducing the amount of chemical fertilizer used in organic recycling agriculture. However, the yield of eggplant due to BAS-S application was significantly lower than that of BAS-L application, which was only 50.29 tons/ha, which may be related to the different fertilization methods of the two fertilizers. Zhang et al. (2020) showed that under the condition of fertilizer hole application, the nitrification of ammonium nitrogen was not only affected by soil water content, pH and time factors, but also strongly inhibited by high concentration nutrients in the fertilizer layer, which delayed the transformation of ammonium nitrogen to nitrate nitrogen. Nitrate nitrogen can be directly absorbed by eggplant, but ammonium nitrogen needs to be converted into nitrate nitrogen to be absorbed by most. This is consistent with the distribution of the number of fruits in each group, the yield of DIG was the lowest, only 49.58 tons/ha. This is might because the ammonium nitrogen in DIG that can be used by crops in a short time is very easy to volatilize, while organic nitrogen takes a long time to decompose into a form that can be used by crops (Gutser et al., 2005). From the results of the eggplant fruit quantity and yield of different groups, it was found that when DIG was applied as the nitrogen source, the nitrogen utilization rate and hence, the growth rate of the eggplants were lower than the plants that used the nitrogen from the bio-based ammonia sulfate fertilizers. Therefore, the nitrogen utilization of bio-based nitrogen fertilizer prepared by recovering N from DIG through the ammonia stripping process is better than that of DIG, improving fertilizer utilization and crop yield.

3.2. Nutrient use efficiency of bio-fertilizers

As shown in Fig. 4, the AE$_N$ of the BAS-L application was the highest (44.8 kg_{DM}/kg_N), which was slightly higher than the UCF (42.5 kg_{DM}/kg_N) and significantly higher than the DIG application (4.1 kg_{DM}/kg_N) ($p < 0.05$). Additionally, the level of AE$_N$ applied with different fertilizers is consistent with the yield level distribution. Furthermore, there were significant differences in the ARE$_N$ of different fertilization treatments. The ARE$_N$ of BAS-L application was slightly higher than UFC application, which was 7.9% and 6.9% for BAS-L and UCF application, respectively. It was significantly higher than the DIG application which yielded 3.4%. The ARE$_N$ value in this study was lower than 10∼50% from the single-season ARE$_N$ value given by some other research results, and this may be related to the different experimental crops (Bella et al., 2019).

In general, with the increase of nitrogen application, the crop yield increased and the nitrogen use efficiency significantly decreased. Recently, the nitrogen use efficiency of crops in European countries has generally decreased to about 120 kg/ha. In comparison, the nitrogen application rate of crops in each season in eastern China has generally exceeded 250 kg/ha, making the yield per unit area is relatively high, as the nitrogen utilization efficiency is lower

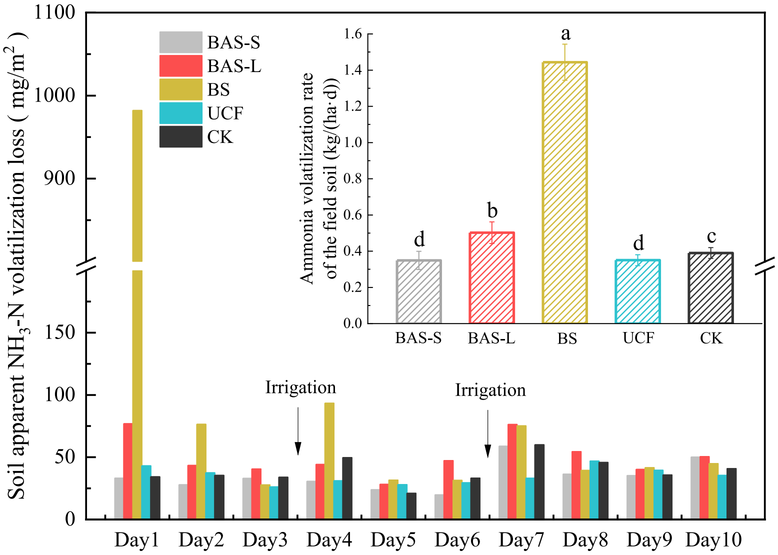

Fig. 5. Soil apparent NH_3-N volatilization loss under different fertilization treatments after the third topdressing. BAS-S: bio-based ammonium sulfate solid fertilizer; BAS-L: bio-based ammonium sulfate liquid fertilizer; BS: biogas slurry; UCF: urea compound fertilizer; CK: no fertilizer. Means with different letters are significantly different according to Duncan's Test, $p < 0.05$.

(Silva et al., 2020). In the report of the Asian Vegetable Research and Development Center, the typical nitrogen fertilizer application for eggplant is 170 kg/ha nitrogen (Chen et al., 2002). However, in China, the amount of nitrogen fertilizer used for horticultural planting is generally higher than 170 kg/ha. The amount of nitrogen fertilizer used in this study is a reference to the amount of fertilizer used for horticultural planting, which is twice the typical amount of nitrogen fertilizer; hence the lower ARE_N belongs normal range. Moreover, the AE_N and ARE_N of the BAS-L group were the highest, which further confirmed the efficient fertilizer utilization rate of BAS-L.

However, an unexpected result is that the nitrogen use efficiency between BAS-L and BAS-S is very different. The results showed that the AE_N and ARE_N of BAS-S were 8.1 kg_{DM}/kg_N and 2.1%, respectively, which was not only significantly lower than BAS-L treatment, but also ARE_N was lower than DIG treatment. Vaneeckhaute et al. (2013a) also carried a field experiment and reported that the application of bio-fertilizers had significant effects on NUE and plant nitrogen uptake. Treatments that completely used air wash water showed the highest NUE and plant nitrogen uptake, and a strong correlation was also found between NUE and DW biomass production. Whereas the nitrogen utilization rate of BAS-S treatment was significantly lower than that of BAS-L treatment in our research. At present, similar results or reasonable explanations have not been found in other references. Based on the differences in fertilization methods, it can be concluded that this may be related to the different fertilization methods of the two fertilizers. The conventional fertilization method used in BAS-L treatment is to directly irrigate BAS-L into the ditch on the ground's surface, while the hole fertilization used by BAS-S is to pour BAS-S into the soil holes dug near the roots of the crop. However, in general, bio-based ammonium sulfate fertilizer has higher NUE than DIG and has no difference with UCF in fertilizer utilization efficiency. This is consistent with related research results, which show that using wastewater from an acidic air scrubber for NH_3 removal in agriculture as a sustainable substitute for chemical fertilizer N can result in higher N use efficiencies and less N leaching. In addition, the more the chemical N was replaced by air scrubber water, the higher the observed phosphorus utilization efficiency and apparent P recovery (Vaneeckhaute et al., 2014). Therefore, bio-based ammonium sulfate fertilizer is a reliable substitute for synthetic chemical fertilizers, but the optimal application method of different forms of bio-fertilizers needs further study.

Besides, the capture of volatile ammonia in the soil began on the day after the third topdressing. As illustrated in Fig. 5, on the first day after topdressing, the ammonia volatilization of the treatment with BS topdressing was significantly higher than that of other treatments and then significantly reduced. BAS-L topdressing treatment was the second, but it was still significantly lower than the DIG application. After the second irrigation, the ammonia volatilization of BAS-S, BAS-L, and UCF application increased slightly compared to the previous 6 days. There were also significant differences in AVR in the soil with different topdressing treatments. The AVR applied by BS was the highest, which reached 1.44 kg/(ha d), followed by BAS-L, which was 0.50 kg/(ha d). BAS-S and UCF were similar in AVR; both were 0.35 kg/(ha d). The AVR in the CK group was 0.39 kg/(ha d), this is because the process of microbial metabolism in the soil will produce ammonia and some unstable ammonium substances, coupled with additional external forces such as watering, change the pore structure of the soil and allow ammonia to escape from the soil (Zhu et al., 2020). Therefore, it can be considered that the ammonia volatilization loss after the application of BAS-S and UCF is negligible, while most of the ammonia volatilization after the

Table 4
The physical and chemical characteristics of the soil after different fertilization treatments and their relation to the original soil as being 100 % in the respective soil depth (Adjusted). Results are expressed on dry weight (DW). BAS-S: bio-based ammonium sulfate solid fertilizer; BAS-L: bio-based ammonium sulfate liquid fertilizer; DIG: biogas digestate; UCF: urea compound fertilizer; CK: no fertilizer.

Soil depth	Treatment	Total N (mg/kg)	*Adj.*	Total P_2O_5 (mg/kg)	*Adj.*	Total K_2O (mg/kg)	*Adj.*	TOC (%)	*Adj.*	EC (uS/cm)	*Adj.*	pH	*Adj.*
0∼15 cm	Original soil	1246.0	*100*	49.8	*100*	156.5	*100*	2.2	*100*	128.8	*100*	8.3	*100*
	BAS-S	1677.0	*135*	110.3	*221*	257.7	*165*	1.9	*86*	337.5	*262*	6.7	*81*
	BAS-L	2520.0	*202*	90.4	*182*	388.6	*248*	2.2	*100*	699.0	*543*	6.3	*76*
	DIG	1248.0	*100*	120.5	*242*	151.7	*97*	1.9	*86*	247.5	*192*	6.5	*78*
	UCF	977.0	*78*	115.9	*233*	205.1	*131*	1.6	*73*	380.2	*295*	5.5	*66*
	CK	1092.0	*88*	40.4	*81*	131.1	*84*	2.0	*91*	112.0	*87*	6.7	*81*
15∼30 cm	Original soil	1280.0	*100*	48.5	*100*	166.1	*100*	2.4	*100*	112.2	*100*	8.1	*100*
	BAS-S	924.0	*72*	44.1	*91*	97.5	*59*	1.4	*58*	143.0	*127*	7.5	*93*
	BAS-L	904.0	*71*	37.5	*77*	163.8	*99*	1.7	*71*	216.2	*193*	7.2	*89*
	DIG	1621.0	*127*	76.3	*157*	103.7	*62*	1.7	*71*	130.0	*116*	7.4	*91*
	UCF	1793.0	*140*	61.6	*127*	147.2	*89*	1.4	*58*	197.5	*176*	7.0	*86*
	CK	1048.0	*82*	50.4	*104*	110.3	*66*	1.8	*75*	104.0	*93*	7.3	*90*

application of BAS-L comes from the soil itself instead of ammonium sulfate. In the DIG group, AVR was significantly higher when BS topdressed than other fertilization treatments, which showed that DIG application had the highest nitrogen loss, reduced the ammonia nitrogen directly available to its crops and led to low AE_N and ARE_N in the DIG group and affect crop yields. Therefore, compared to the direct application of DIG, it is a better choice to use the ammonia stripping process to store N from DIG in a more stable form before applying.

3.3. Effect of bio-based fertilizers on soil quality and fertility

Table 4 illustrates the physicochemical properties of the soil before and after different fertilization treatments; NPK content in the soil changed significantly after planting. The application of BAS-L and BAS-S increased the TN in shallow soils and decreased it in deep soils. For example, after applying BAS-L, the TN of shallow soil increased from 1246.0 mg/kg to 2520.0 mg/kg, while in deep soil, it decreased from 1280.0 mg/kg to 904.0 mg/kg. However, the TN of shallow soils decreased after UCF application and the TN of deep soils increased. The change of TN of the soil after DIG application was not significant. In addition, the P_2O_5 content in the soil after applying the bio-based ammonium sulfate fertilizer was lower in both the shallow and deep soils. Although, in the shallow soil, the P_2O_5 content of the four fertilization groups was increased with little difference, as in deep soils, the P_2O_5 content of the BAS-S and BAS-L groups was significantly decreased, from 48.5 mg/kg to 44.1 mg/kg and 37.5 mg/kg, respectively. Overall, the NPK content of the BAS-S and BAS-L groups increased in the 0∼15 cm soil layer after the end of planting, as it decreased in the 15∼30 cm soil layer, which is slightly different from the soil after UCF application. This may be due to the different nutrient flow conditions in the soil after applying different fertilizers.

It is worth noting that although the focus of the previous discussion is the utilization of N, the results show that the residual P in the soil of bio-based ammonium sulfate fertilizer was the smallest. This indicates that the crop has a better absorption effect on TP. Some studies have also concluded that when the chemical fertilizer is completely replaced by the air scrubber wastewater, the plant's P absorption is significantly higher (Vaneeckhaute et al., 2013c). The higher P-uptake in these scenarios may be attributed to the higher dosage of NH_4–N in the bio-based ammonium sulfate fertilizer. NH_4^+ was absorbed by the root. Nitrification of NH_4^+ to NO_3^- is an acidification process; it can increase soil P mobilization and rhizosphere absorption (Diwani et al., 2007). Although DIG contains a high NH_4–N content, after application, the ammonia volatilization loss is significantly higher than bio-based ammonium sulfate fertilizer, especially in eggplant cultivation. The higher temperature is suitable for eggplant growth during the planting period accelerated the volatilization rate of ammonia.

In addition, the P_2O_5 and K_2O applied by the DIG treatment were the least, but the residual amount of P_2O_5 was found to be the highest in the soil after planting. This is due to the slow decomposition of the organic P of DIG. At the same time, the NUE of the crop is low, and the combined effect is caused. On the other hand, Vaneeckhaute et al. (2013c) and Coban et al. (2015) reported that when digestive derivatives are used as fertilizer, more organic carbon is added to the soil, and additional carbon supply can significantly improve soil structure. However, the results of the present study showed that in each fertilization treatment, the TOC content of the soil decreased, and the application of DIG did not have a significant effect on soil improvement in the short term.

In addition to NPK, sulfur (S) is an essential macronutrient for plants. When the S demand by crops was higher than the supply of S applied fertilizer, which may lead to the extraction of S from the soil (Vaneeckhaute et al., 2013c). Bio-based ammonium sulfate fertilizer not only increases the absorption of P by crops but also provides S for plant growth. When applying bio-based ammonium sulfate fertilizer, its S supply is higher, beneficial to crop growth. While at the same time, this may cause S surplus in the soil balance, excessive levels of sulfate may also cause salt accumulation in the soil (Alexander, 2008; Ai et al., 2020). Therefore, special attention was paid to the effects of applying bio-based ammonium

Table 5
Costs analysis for the ammonium sulfate considered. All costs are in $/m^3 of digestate treated (*the cost of electrical energy was considered 0.072 $/kWh in China, sulfuric acid was considered 86.520 $/t).

Cost item	Stripping ($/m^3)	Stripping + crystallization ($/m^3)
Energy consumed	0.532	0.532 + 0.009
Chemicals	0.182	0.182
Total estimated costs	**0.714**	**0.723**

Table 6
Economic analysis of the cultivation scenarios. BAS-L: bio-based ammonium sulfate liquid fertilizer; BAS-S: bio-based ammonium sulfate solid fertilizer; DIG: biogas digestate; UCF: urea compound fertilizer; CSP: calcium superphosphate; PS: potassium sulfate.

($/ha)	BAS-S	BAS-L	DIG	UCF
UCF production	184.98	184.98	–	448.31
BAS-L production	–	11 165.05	–	–
BAS-S production	322.44	–	–	–
CSP	9.45	9.45	–	–
PS	72.38	72.38	–	–
Transport	0.15	1.70	4.75	0.15
Total economic cost	**589.40**	**11 433.56**	**4.75**	**448.46**
Biogas sales	1 533.94	52 219.20	1 566.58	
Eggplant sales	36 363.52	45 279.38	35 397.12	44 734.46
Theoretical net revenue	**37 308.06**	**86 065.03**	**36 958.95**	**44 285.99**

sulfate fertilizer and DIG on soil EC and soil pH value. This study showed that the EC value of shallow soil after different fertilization treatments was significantly higher than that of deep soil, while the pH value was lower than that of the deep soil, indicating the greater impact of fertilizer application on shallow soil.

Additionally, the most obvious changes were EC and pH value of the 0∼15 cm soil. The EC value of the BAS-L application was increased, reaching 699.0 μS/cm, and the pH value was decreased to 6.3. The EC value of BAS-L treated soil was 5.4 times higher than that of the original soil and pH decreased to 24.1%. After applying UCF to the soil, a significant increase in EC value and a decrease in pH value (5.5) were observed. This illustrates the fertilizer properties of bio-based ammonium sulfate, which are similar to traditional chemical fertilizers. Although higher soil EC and pH values are beneficial for crops to absorb certain nutrients such as P, long-term high EC and low pH values may have a negative impact on the abundance of soil flora and soil aggregates (Wang et al., 2020). In our previous study (Ai et al., 2020), it was found that it would affect the form of heavy metals in soil, thereby enhancing the absorption of heavy metals by crops and the loss of heavy metal ions. Long-term effects may have a negative impact on the food safety of crops and groundwater safety. However, the changes in EC and pH value are related to the growth characteristics of different crops and different combinations of fertilizers (Sigurnjak et al., 2019). These possible negative effects can be avoided by crop rotation or combined application of organic and inorganic fertilizers.

3.4. *Fertilizer markets and economic analysis*

Bolzonella et al. (2018) described mass balance for the stripping process, treating up to 130 m^3/d of digestate, the installed power was around 40 kW working 24 h/d, chemicals used in the stripping system is sulfuric acid (273 kg/d) for ammonium sulfate recovery, and then 370 kg ammonium sulfate were produced. The electricity cost was therefore 0.532 $/m^3 according to the prices in 2019. Costs for chemicals were estimated to be 0.182 $/m^3 of digestate. Han et al. (2014) investigated a double-effect mechanical vapor re-compression (MVR) evaporation system taking ammonium sulfate wastewater as the treated solution. The circulating-pump power was taken into consideration, the specific power consumption of the model at an evaporation temperature of 70 °C was 41.5 kWh/t. The crystallization efficiency was set at 87%. The production cost of bio-fertilizer is listed in Table 5, electricity costs are the power of equipment multiplied by time, and the chemical costs are the price of chemical reagents multiplied by the amount of use.

Since the BAS-S and BAS-L groups in this experiment were treated with urea compound fertilizer as the basic fertilizer, the production costs of the BAS-S and BAS-L groups in Table 6 include a portion of the UCF production costs. The total production cost of different fertilizers was the cost per hectare which was determined based on the illustrated application amount in Table 2 and the calculated unit cost in Table 5. Besides, the transportation cost of fertilizer was calculated per kilometer. Because the total amount of BAS-S and UCF was small, a 2.5-ton truck can be loaded in one car, and the fuel consumption of this truck was 0.08 L km^{-1}. The total amount of BAS-L and DIG was large; hence a 10-ton truck was used for transportation. Based on these calculations, the BAS-L and DIG require 5 and 14 vehicles, respectively, and the fuel consumption of this truck is 0.18 L/km.

The transportation cost (Table 6) is the product of the fuel consumption of these two trucks and the corresponding number of vehicles. In addition, suppose that the fermentation material is pig manure with a total solid content of 3%, the dry matter in the material is degraded by 60% in the anaerobic reaction stage and enters biogas slurry about 10% after solid–liquid separation. The dry matter is converted into biogas residue, 30% of the total amount. Gas production per kg of pig manure (dry matter) is 0.43 m^3/kg. The cubic meter of methane can generate electricity of 2.3 kWh (Zhang and Xu, 2020). The current Chinese policy applicable to biogas power generation is the Renewable Energy Law (2005). The comprehensive feed-in tariff is 0.11 $/kWh, and the market price of eggplant is calculated at 0.714 $/kg. The income listed in Table 6 is the biogas power generation income converted from the biogas slurry and biogas residue used for the fertilizer applied per hectare of arable land and the sales income of eggplant per hectare. It should be noted that ammonia stripping is only one part of the post-treatment of biogas slurry. The economic analysis of this study did not consider the benefits of utilizing the biogas slurry after ammonia stripping or the process cost of the biogas slurry up-to-standard discharge treatment.

Vaneeckhaute et al. (2013c) concluded that in the cultivation of energy crops, bio-fertilizers could bring considerable economic benefits to agricultural workers, as well as ecological benefits through energy use and reduction of greenhouse gas emissions. In the eggplant cultivation of the present study, the use of BAS-L fertilizer instead of synthetic fertilizer did not reduce the cost of fertilizer use; the cost of BAS-L has reached 25.4 times of UCF. However, the calculated theoretical net income is higher than the theoretical net income using UCF, reaching 86065.03 $/ha, close to twice the income using UCF (Table 6). The main reason for the higher cost of BAS-L was the N content of BAS-L was much lower than that of UCF; hence it was necessary to use a larger volume of BAS-L to ensure the equality of nitrogen content, which led to a significant increase in production costs.

Furthermore, calculation revealed that the transportation cost of this type of liquid bio-fertilizers with low nutrient content such as BAS-L and DIG was indeed high. In Europe, it was particularly difficult for large-scale biogas plants to find sufficient arable land for allowed digestion application; therefore the operators of these biogas plants must pay a high price for long-distance transportation to fertilize areas that require nutrients (Vaneeckhaute et al., 2013b), this is also an important constraint in China. However, benefitting from the higher eggplant yield applied by BAS-L and the higher biogas sales income before BAS-L production, the theoretical net revenue of BAS-L fertilizer is significantly higher than the other three fertilizers. Additionally, there are some uncalculated economic benefits of applying BAS-L. For example, it can effectively save fresh water for agriculture, and in drip irrigation technology, as the impurities in BAS-L are significantly less than raw BS, the phenomenon of blocking in the drippers and network can be reduced, thus reducing the maintenance cost of the whole irrigation system.

In contrast, for BAS-S and DIG, although their total cost was not high, their net revenue was only about 85% of UCF. Mainly because their eggplant production was significantly lower than UCF, which directly led to a decline in sales income and cannot achieve the purpose of increasing net revenue. On the other hand, the obtained results reveal that the application of BAS-S produced by nutrient recovery technology can increase the net benefit by about 350 $/ha compared to the direct application of DIG (Table 6). Moreover, for bio-fertilizers put on the market, producers believe that the consistency of nutritional ingredients is necessary to produce standardized products, and farmers believe that granular products are particularly easy to use. Their similarity to mineral fertilizers makes it possible to use their existing spreading machinery as one of the advantages of bio-based solid fertilizers (Dahlin et al., 2015). In this regard, BAS-S has better fertilizer efficiency than DIG and has better attributes than BAS-L as a commercial fertilizer. It is closer to traditional chemical fertilizers and can better achieve the purpose of replacing chemical fertilizers. Therefore, through optimization of its application mode, it still has good market value potential. However, in theory, BAS-S is an ideal bio-based product. The production of BAS-S has increased a lot of cooling and energy consumption, and the application mode of BAS-S is not economical enough, making its benefit lower than BAS-L.

Thus, in the subsequent research, it is necessary to further study the reasonable application method of BAS-S and the efficient and low-cost application method of BAS-L. It is also necessary to adopt full life cycle assessment methods to comprehensively evaluate the benefits and impacts of bio-based fertilizer projects. In general, a bio-based fertilizer project centered on a biogas project is easier to achieve circular economy and sustainable development, because biogas projects themselves can produce the two most important production bases, energy and raw materials. Therefore, if nutrient recovery technologies with low energy demand (e.g., ammonia stripping) can be combined with the energy and heat generated by biogas in biogas projects, a closed loop of nutrients and energy can be formed and lower carbon and energy-saving fertilizer production technology can be realized.

4. Conclusion

Two different bio-fertilizers (BAS-S and BAS-L) were recovered from DIG to add value and economic use of biogas digestates; these bio-fertilizers were compared with mineral fertilizers to investigate the agricultural impacts and economic benefits of applying them to the soil.

The results showed that from the perspective of yield and fertilizer utilization, the effect of applying BAS-L was significantly better than BAS-S and DIG and slightly higher than UCF. Compared with UCF, the higher NH_4–N dosage in bio-based ammonium sulfate fertilizer promoted the process of soil acidification, thereby increasing the mobilization of phosphorus and rhizosphere absorption. In addition, the theoretical net income of BAS-L fertilizer (86 065.03 $/ha) was significantly higher than the other three fertilizers, which was 94% higher than UCF.

This study provides a reference for the application value of bio-ammonium sulfate in fruit and vegetable cultivation and supports better classification of these bio-based products. Furthermore, more planting experiments and more comprehensive systematic evaluations are needed in the future to verify the hypothesis in this study.

CRediT authorship contribution statement

Keda Jin: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft. **Andrea Pezzuolo:** Writing – review & editing. **Shaban G. Gouda:** Writing – review & editing. **Shijiang Jia:** Investigation. **Mohamed Eraky:** Formal analysis. **Yi Ran:** Resources, Project administration. **Mengdi Chen:** Formal analysis, Methodology. **Ping Ai:** Supervision, Funding acquisition, Writing – review & editing.

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.

Acknowledgments

This work was financially supported by the National Natural Science Foundation Program of China (No. 31972611), Agricultural Science and Technology Innovation Program (ASTIP) of Chinese Academy of Agricultural Sciences (1610012020004_01900), Key Laboratory on Development and Application of Rural Renewable Energy, China, and Central Universities Fundamental Research Funds, China (No. 2662020GXPY006). The authors gratefully acknowledge their supports.

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