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Use of ammonium-N-based biogas effluent application for sustainable rice production and improved nutrient recycling

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ABSTRACT

The reuse of biogas effluent (BE) represents a sustainable approach for nutrient recycling in agricultural systems, particularly in regions with intensive livestock production. However, its application is often limited by low nutrient concentrations and inefficient management based on total nitrogen content. This study evaluated the effects of BE applied at different ammonium nitrogen (NH_4^+–N) levels (BE-100, BE-150, BE-200) on rice growth, yield, and nitrogen use efficiency under mesocosm conditions, in comparison with synthetic fertilizer (SF-150) and a no-nitrogen control (Ze-N). Results showed that BE significantly improved plant growth and yield, with grain yield increasing from 513 g m^{-2} in the control to 826–898 g m^{-2} in fertilized treatments. The highest yield was observed in BE-200 level, comparable to synthetic fertilizer application. Yield improvements were mainly associated with increased panicle length and spikelets per panicle, while other components showed no significant differences. Nitrogen uptake increased under all fertilized treatments, whereas nitrogen use efficiency did not differ significantly. The findings indicate that NH_4^+–N-based management of BE can maintain rice yield while reducing the effluent volume required. This approach enhances nutrient recycling efficiency and contributes to environmentally sustainable agricultural practices. A key novelty of this study is the development of an NH_4^+–N-based application strategy that enables farmers to estimate the appropriate BE application rate using simple NH_4^+ test kits, thereby facilitating field-scale adoption, reducing excessive wastewater use, and promoting sustainable and biosafe recycling of livestock waste in rice production systems. The results provide practical insights for improving the application of biogas effluent in rice-based systems while reducing the environmental risks associated with excessive effluent application.

Keywords: biogas effluent, ammonium nitrogen, circular agriculture, organic fertilizer.

INTRODUCTION

Rice (*Oryza sativa* L.) plays a key role in ensuring food security and sustaining rural livelihoods in Vietnam, particularly in the Mekong Delta, which accounts for approximately 57% of national rice production (GSOVN 2024). However, intensive rice production systems that rely heavily on synthetic fertilizers have led to increasing environmental concerns, including nutrient losses, water pollution, and ecosystem degradation (Stone and Hornberger, 2016; Peng et al., 2006). Improving nutrient management strategies that maintain productivity while reducing environmental impacts is therefore essential for sustainable rice cultivation.

Biogas technology has been widely adopted in the Mekong Delta as an effective approach to treating livestock waste, generating renewable energy, and producing BE as a nutrient-rich by-product (Ho et al., 2015; Kinyua et al., 2016). BE typically contains substantial amounts of nitrogen (N), phosphorus (P), and potassium (K), making it a promising alternative to synthetic fertilizers. Notably, ammonium nitrogen (NH_4^+–N) is the dominant inorganic nitrogen form in BE due to anaerobic digestion processes (Naik et al., 2014). Given that NH_4^+ is the preferred nitrogen form for rice under flooded conditions, the reuse of BE represents a viable strategy for nutrient recycling within circular agricultural systems. Previous studies have demonstrated that BE can partially or fully replace mineral fertilizers without compromising rice yield and may even improve soil fertility and crop performance (Minamikawa et al., 2020, 2021; Huynh et al., 2022; Maucieri et al., 2023). However, most BE application strategies in previous studies are based on total nitrogen (TN) content, which does not accurately reflect plant-available nitrogen form. A significant proportion of TN in BE exists as organic forms that require mineralization before becoming availability for plant uptake, leading to uncertainties in nitrogen supply and potentially inefficient nutrient use. Consequently, TN-based applications may require excessive effluent volumes, increasing the risk of nutrient leaching and environmental contamination (Nkoa, 2014; Insam et al., 2015).

In contrast, NH_4^+–N represents the readily available fraction of nitrogen in BE and plays a critical role in determining its agronomic effectiveness. Optimizing the BE application based on NH_4^+–N rather than TN could improve synchronization between nitrogen supply and crop demand, and reduce the volume of effluent required for field application. Despite its practical importance, the effectiveness of NH_4^+–N-based BE management has not been adequately evaluated, particularly under controlled experimental conditions that simulate field environments.

Therefore, this study aims to evaluate the effects of BE applied at different NH_4^+–N levels on rice growth, yield formation, and nitrogen use efficiency using a mesocosm system. By focusing on plant-available nitrogen, this study seeks to provide a more accurate and practical approach for BE utilization. The findings are expected to contribute to improving nutrient recycling efficiency and reducing environmental impacts associated with the application of biogas effluent in rice-based systems.

MATERIALS AND METHODS

Plant materials and study site

A mesocosm experiment was conducted in a screen-house at Can Tho University, Can Tho, Vietnam (10°01′41″N, 105°45′33″E). The screen-house featured a transparent roof to admit natural light, and its sidewalls were enclosed with fine insect-proof mesh to reduce the impact of external pests. The experiment lasted 91 days, from 20 October 2025 to 22 January 2026. The seed of paddy cultivar 'Dai Thom 8' was purchased from Cuu Long Delta Rice Research Institute in Can Tho.

Soil properties and pig biogas effluent characteristics

Soil was collected two weeks prior to the experiment during the Summer–Autumn season from the plow layer (0–20 cm) of a rice field in An Giang province, Vietnam. The soil had a pH (H_2O) of 5.45, an organic matter content of 7.81%, TN of 3.1 g kg^{-1}, a total phosphorus (TP) of 436 mg kg^{-1}, and a cation exchange capacity (CEC) of 14.99 meq 100 g^{-1}. These properties indicate a moderately fertile soil with relatively high organic matter and nutrient availability.

BE was obtained from a household pig farm located in Thanh Hoa commune, Can Tho city, Vietnam. The farm maintained approximately 40 adult pigs and 20 piglets, and the effluent was collected directly from the anaerobic biogas digester outlet. After collection, BE was transported to the screen-house and stored in sealed 150-L plastic containers prior to use. The effluent was exposed to natural sunlight for approximately two days before application, which may have reduced part of the microbial load and improved the biosafety of the wastewater prior to agricultural reuse. Since this study was conducted under screenhouse conditions, the assessment of microbial density in soil and plants was not included. However, for field-scale application, additional biosafety measures should be considered to minimize potential microbial risks associated with wastewater reuse. Previous studies have suggested thermal treatment at approximately 80 °C (Minamikawa et al., 2021) or disinfection using chlorine-based solutions as practical approaches in future experiments to further reduce pathogenic microorganisms before BE application in agricultural systems.

To ensure homogeneity, the effluent was thoroughly mixed before each application. Samples were collected and analyzed immediately prior to application, and the physicochemical characteristics of BE are presented in Table 1.

Experimental design

The experiment was conducted under screen-house conditions using a completely randomized design with five treatments and three replicates. The treatments included a no-nitrogen control (Ze-N), a synthetic fertilizer treatment (SF-150), and three BE treatments supplying different

Table 1. Characteristics of BE with loading from pig manure

Variable	10 DAS †	25 DAS	40 DAS
pH (H_2O)	7.01	6.93	7.08
NH_4^+ (mg N L^{-1})	325.1	338.2	317.8
Total nitrogen (mg N L^{-1})	376.3	419.1	329.9
Total carbon (mg C L^{-1})	1,035.3	980.4	1,305
Total organic carbon (mg C L^{-1})	716.4	570.0	828.9
Total P (mg P L^{-1})	137.8	160.7	149.8

Note: † Days after sowing.

nitrogen levels based on NH_4^+–N (BE-100, BE-150, and BE-200). All treatments were maintained under continuous flooding conditions to simulate typical lowland rice cultivation.

Each experimental unit consisted of a plastic container (30 × 30 × 35 cm; surface area 0.09 m^2) filled with approximately 23 kg of wet soil. Pre-germinated rice seeds were sown at a density equivalent to 100 kg ha^{-1}.

To better simulate field-like hydrological conditions and minimize temperature fluctuations, each experimental container was placed inside a larger water-filled basin (60 × 40 × 30 cm). This setup helped maintain stable water levels and reduced external temperature effects on the root zone, thereby improving the representativeness of the mesocosm system relative to field conditions. A schematic diagram of the experimental setup is presented in Figure 1.

Fertilizer types and application

In the Ze-N, no nitrogen fertilizer was applied. However, P and K were supplied using single superphosphate (16% P_2O_5) and potassium chloride (61% K_2O), respectively. These fertilizers were applied under flooded conditions at 10, 25, and 40 days after sowing (DAS), following a split application schedule of 50 kg P_2O_5 ha^{-1} (10–20–20) and 60 kg K_2O ha^{-1} (0–30–30).

In the SF-150 treatment, nitrogen was applied as urea (46% N) at a total rate of 150 kg N ha^{-1}, split into three applications at 10, 25, and 40 DAS (30–70–50). P and K fertilizers were applied at the same rates and timings as in the Ze-N treatment to ensure a consistent nutrient supply across treatments, except for nitrogen.

In BE treatments, nitrogen was supplied exclusively through biogas effluent, with application rates calculated based on NH_4^+–N concentration. This approach ensured that treatments differed in plant-available N rather than total N. The effluent was applied at 10, 25, and 40 DAS, consistent with the timing of urea application in the SF treatment.

The required BE volume was calculated as:

$$V_{BE} = N_{target}/C_{NH4^+} \quad (1)$$

where: V_{BE} is the volume of biogas effluent applied (L), N_{target} is the target nitrogen amount (mg N per container), and $C_{N\text{-}NH_4^+}$ is the ammonium nitrogen concentration in the *BE* (mg N L^{-1}).

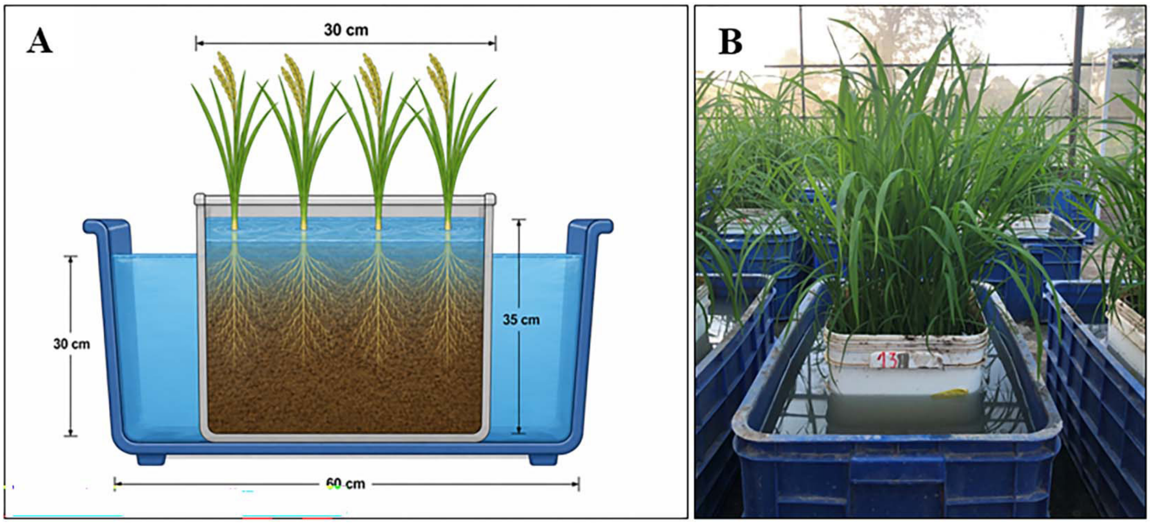

Figure 1. Schematic diagram (A) and photograph (B) of the mesocosm system for rice cultivation
Note: The system consists of an inner container placed within a water-filled basin to simulate field hydrological conditions

The target nitrogen per container was derived from field-equivalent application rates (kg N ha^{-1}) and converted based on the surface area of each experimental unit (0.09 m^2). The calculated BE volumes for each treatment are presented in Table 2.

Measurements and analysis

Biogas effluent analysis

Prior to each application, BE samples were analyzed for pH, TN, NH_4^+-N, and total phosphorus (TP). The pH was measured using a handheld meter (HM-31P, TOA-DKK, Japan). Total nitrogen was determined using the semi-micro Kjeldahl method, while N-NH_4^+ and TP were analyzed using the indophenol blue and ascorbic acid methods, respectively, following standard procedures (APHA, 1998). In addition, total carbon (TC), total organic carbon (TOC), and TN were measured using a total organic carbon analyzer (TOC-L CPH, Shimadzu, Kyoto, Japan) equipped with an ASI-L autosampler.

Plant growth measurements

Plant height and SPAD value were monitored weekly using ten tagged plants per container. Plant height was measured from 7 to 84 DAS, from the soil surface to the tip of the tallest leaf. The SPAD values were recorded from 21 to 84 DAS using a chlorophyll meter (SPAD-502, Konica Minolta, Japan) on the uppermost fully expanded leaf, and averaged per container.

Yield components and biomass

All aboveground rice parts in each container were harvested and separated into straw and panicles. Yield components, including panicle number, spikelets per panicle, filled grain percentage, and 1000-grain weight, were determined. Straw biomass and grain yield were measured after oven-drying samples at 70 °C to constant weight. Grain yield ($GY_{14\%}$) was adjusted to a moisture content of 14%. The harvest index (HI) was calculated as the ratio of grain rice yield (on a dry-weight basis) to total aboveground rice biomass (Wang et al., 2016).

Nitrogen uptake and use efficiency

Total plant nitrogen uptake was calculated as the sum of nitrogen accumulation in grains, leaves, and stems, determined by multiplying each component's dry biomass by its total nitrogen concentration. Nitrogen use efficiency (NUE) indices, including apparent nitrogen recovery (ANR), agronomic NUE (ANUE), and internal NUE (INUE) were calculated following Cabangon et al. (2011) using the mean values of three replicates per treatment. ANR was calculated as the difference in total N uptake between fertilized and control treatments divided by the amount of N applied. ANUE was calculated as the difference in grain yield between fertilized and control treatments divided by the amount of N applied. INUE was calculated as the ratio of grain yield to total plant N uptake

Statistical analysis

All statistical analyses were performed using SPSS software (version 26.0; SPSS Inc., Chicago, IL, USA). Data were subjected to one-way analysis of variance (ANOVA) to evaluate the effects of nitrogen treatments on plant growth parameters, yield components, grain yield, straw biomass, harvest index, and nitrogen use efficiency indices. Prior to analysis, assumptions of normality and homogeneity of variance were checked. When significant treatment effects were detected ($P < 0.05$), mean comparisons were performed using Duncan's multiple range test at the 5% significance level. Results are presented as mean ± standard deviation (SD) of three replicates.

Table 2. Nitrogen application rate and corresponding BE volume/pot (0.09 m^2)

Treatment	10 DAS (gN/pot)	BE volume (L/pot)	25 DAS (gN/pot)	BE volume (L/pot)	40 DAS (gN/pot)	BE volume (L/pot)	Total (gN/pot)
Ze-N	-	-	-	-	-	-	0
SF-150	0.27	-	0.63	-	0.45	-	1.35
BE-100	0.18	0.554	0.42	1.242	0.30	0.942	0.90
BE-150	0.27	0.830	0.63	1.863	0.45	1.413	1.35
BE-200	0.36	1.107	0.84	2.484	0.60	1.888	1.80

Note: Biogas effluent volume was calculated based on NH_4^+–N concentrations of 325.1, 338.2, and 317.8 mg N L^{-1} for 10 DAS, 25 DAS, and 40 DAS, respectively.

RESULTS AND DISCUSSION

Plant height and SPAD value

Plant growth was positively influenced by nitrogen application, particularly under BE treatments (Figure 2A). Plant height increased steadily throughout the growing period, although differences among treatments were relatively small during the early vegetative stage (0–30 DAS). More pronounced treatment effects emerged after 30 DAS, coinciding with the rapid tillering and stem elongation stages, when crop nitrogen demand substantially increased. Among the fertilized treatments, BE-200 consistently produced the tallest plants, followed by BE-150 and BE-100, whereas the Ze-N treatment remained the lowest throughout the experiment. At 84 DAS, plant height in the BE treatments ranged from 99.1 to 102.3 cm, exceeding that of the chemical fertilizer treatment (SF-150; 95.8 cm). This result suggests that BE supplied sufficient plant-available nitrogen to support vigorous vegetative growth, likely due to the high proportion of NH_4^+-N, which is the preferred nitrogen form under flooded rice conditions. Similar findings were reported by Khanh et al. (2019), who demonstrated that BE application based on NH_4^+-N concentration resulted in greater plant height than treatments calculated using total nitrogen concentration. The enhanced plant growth observed under BE treatments is also consistent with previous studies showing that digestate-derived NH_4^+-N can improve nitrogen availability, stimulate tillering, and promote biomass accumulation in rice systems (Möller and Müller, 2012).

SPAD values were consistently higher in all fertilized treatments than in Ze-N throughout the growing period (Figure 2B), indicating improved leaf nitrogen status and chlorophyll content under nitrogen application. During the active vegetative stage (21–50 DAS), SPAD values in BE treatments were comparable to those in SF-150, suggesting that BE supplied sufficient available nitrogen to maintain chlorophyll synthesis at levels similar to mineral fertilizer. Notably, SPAD values in BE treatments remained relatively stable during mid-growth stages and declined more gradually during the reproductive stage compared with Ze-N. This slower decline suggests a more sustained nitrogen release and prolonged leaf photosynthetic activity under BE application. Similar responses have been reported in previous studies where biogas digestate maintained chlorophyll content and delayed leaf senescence due to gradual nutrient mineralization and improved nitrogen retention in flooded soils (Möller and Müller, 2012; Linquist et al., 2013).

Rice yield components

Rice yield components were partially influenced by nitrogen treatments (Table 3). Panicle

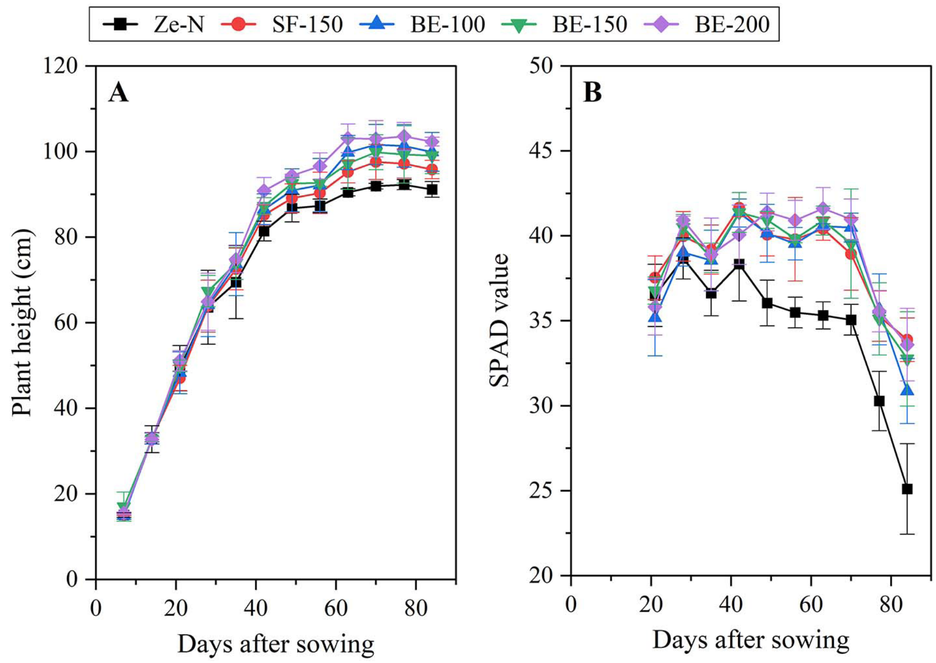

Figure 2. (A) Plant height and (B) SPAD value as affected by N treatment

length increased significantly from 20.4 cm in the Ze-N treatment to 21.9–22.7 cm in fertilized treatments. Likewise, spikelets per panicle increased markedly from 91 in the control to 103–122 in fertilized treatments, with BE-200 achieving the highest value (122 spikelets per panicle). In contrast, panicle number ranged from 611 to 863 m^{-2}, filled grain percentage from 77.0% to 85.7%, and 1000-grain weight from 24.1 to 25.6 g, with no significant differences among treatments ($p > 0.05$). Although slight increases were observed under fertilized conditions, these parameters appeared less responsive to nitrogen input. The results indicate that nitrogen application primarily enhanced reproductive traits associated with yield formation, particularly panicle size and spikelet number. Similar findings have been reported by Peng et al. (2006) and Jiang et al. (2026), where nitrogen fertilization increased spikelet number without significantly affecting grain filling or grain weight.

Grain yield, straw biomass, and harvest index

Grain yield was significantly increased by nitrogen application, rising from 513 g m^{-2} in the Ze-N treatment to 826–898 g m^{-2} in fertilized treatments (Table 4). Among these, BE-200 achieved the highest yield (898 g m^{-2}), slightly exceeding SF-150 (871 g m^{-2}), although differences among fertilized treatments were not statistically significant. Straw biomass followed a similar trend, increasing from 977 g m^{-2} in the control to 1.224–1.593 g m^{-2} in fertilized treatments, with BE-200 producing the highest biomass (1.593 g m^{-2}). Harvest index ranged from 0.346 to 0.400 and did not differ significantly among treatments, indicating relatively stable biomass partitioning regardless of nitrogen source. The relatively small differences among fertilized treatments suggest that nitrogen was not strongly limiting under the experimental conditions. This plateau response is commonly observed in rice systems with sufficient background soil fertility, where additional nitrogen inputs do not yield proportional increases in yield (Peng et al., 2006). Similar findings have been reported in studies using digestate and biogas slurry, where yields under organic nutrient sources were comparable to those obtained with chemical fertilizers (Maucieri et al., 2023; Liu et al., 2024).

Although BE treatments achieved grain yields comparable to SF-150, important differences were observed in application efficiency and practical feasibility. The chemical fertilizer treatment supplied 150 kg N ha^{-1} in a highly concentrated form, requiring minimal application volume, whereas substantially larger volumes of BE were needed to deliver equivalent nitrogen inputs. For example, BE-150 and BE-200 required approximately 45.6 and 60.9 m^3 per 1000 m^2, respectively, to achieve target N levels. This reflects a major practical limitation of BE use under field conditions, particularly with respect to transportation, storage, and uniform field application. Synthetic fertilizers, therefore, remain more convenient and efficient from a logistical perspective due to their high nutrient concentration and ease of handling. Despite these constraints, BE maintained comparable grain yield and biomass production, indicating that it can effectively substitute for mineral fertilizers when properly managed. Moreover, BE provides additional agronomic and environmental benefits beyond crop productivity alone. As a recycled organic resource, BE contributes to nutrient recycling, reduces dependence on synthetic fertilizers, and supports sustainable livestock waste management. The comparable yield achieved at lower BE

Table 3. Yield components of rice plants

Treatment	Panicle length^{φ} (cm)	Panicle number (m^{-2})	Spikelets per panicl^{e}φ	Filled grains^{φ} (%)	1000-grain weight† (g)
Ze-N	20.4±0.6^{b}	611±40.0^{ns}	91±1.9^{c}	85.7±3.6^{ns}	24.4±0.2^{ns}
SF-150	21.9±0.7^{a}	863±156^{ns}	103±4.8^{bc}	77.0±1.0^{ns}	25.6±1.2^{ns}
BE-100	22.7±0.8^{a}	785±276^{ns}	113±16.2^{ab}	78.4±2.5^{ns}	24.8±1.9^{ns}
BE-150	22.2±0.8^{a}	759±85.0^{ns}	114±5.5^{ab}	78.5±0.7^{ns}	24.3±0.1^{ns}
BE-200	22.7±0.3^{a}	752±178^{ns}	122±5.5^{a}	77.5±2.9^{ns}	24.1±0.3^{ns}

Note: ^{φ} Calculated on 60 rice panicles of each treatment (20 samples per replicate). Data presented as mean ± standard deviation (SD; n = 60), † Calculated on a dry-weight basis. Data presented as mean ± SD (n=3), Different letters within the same column indicate a significant difference at $P < 0.05$ by Duncan. “ns” indicates no significant difference between all treatments ($p > 0.05$).

Table 4. Grain yield, straw biomass, and harvest index

Treatment	Grain yield † (g m⁻²)	Straw biomass (g m-2)	Harvest index ‡
Ze-N	513±63^{b}	977±141^{c}	0.346±0.06^{ns}
SF-150	871±108^{a}	1.342±183^{ab}	0.394±0.01^{ns}
BE-100	827±190^{a}	1.224±96^{bc}	0.400±0.04^{ns}
BE-150	826±119^{a}	1.286±208^{b}	0.392±0.01^{ns}
BE-200	898±147^{a}	1.593±104^{a}	0.359±0.03^{ns}

Note: † Expressed as 14% moisture content, ‡ Calculated on a dry-weight basis, Data presented as mean ± SD (n=3), Different letters within the same column indicate a significant difference at $P < 0.05$ by Duncan. “ns” indicates no significant difference ($P > 0.05$).

application rates, particularly BE-100 (approximately 30.4 m³ per 1000 m²), further suggests that optimizing NH_4^+-N-based application strategies may improve practical feasibility while maintaining crop performance. Overall, these findings highlight the trade-off between nutrient concentration and environmental sustainability, suggesting that integrating BE into rice nutrient management systems could provide a balanced approach that combines productivity, resource recycling, and sustainable agricultural intensification.

Nitrogen uptake and use efficiency

Total plant nitrogen uptake increased significantly from 14.83 g N in the Ze-N treatment to 22.22–24.73 g N in fertilized treatments (Table 5), confirming that both biogas effluent (BE) and synthetic fertilizer effectively enhanced nitrogen acquisition by rice plants. The highest N uptake values were observed in BE-200 (24.73 g N) and SF-150 (24.38 g N), indicating that BE supplied sufficient plant-available nitrogen to sustain crop growth and productivity. Similar findings were reported in rice-based systems, where the application of digestate or biogas slurry increased plant N uptake due to the high proportion of readily available ammonium nitrogen and improved soil nutrient availability (Insam et al., 2015; Lu et al., 2024). In particular, Lu et al. (2024) reported that partial substitution of chemical fertilizer with biogas slurry significantly increased N uptake in both rice grain and straw while improving fertilizer utilization efficiency and soil fertility.

Apparent nitrogen recovery (ANR) ranged from 0.49 to 0.74 g g^{-1}, with BE-100 exhibiting the highest value, although differences among treatments were not statistically significant. The greater ANR under moderate BE application suggests improved synchronization between nitrogen release and crop demand, thereby enhancing nitrogen recovery efficiency. However, ANR tended to decline at higher BE application rates, likely because excessive nitrogen inputs increased NH_3 volatilization, denitrification, and other nitrogen loss pathways under flooded paddy conditions. Similar responses have been reported in rice production systems receiving organic digestates or slurry amendments, in which moderate substitution rates improved NUE, whereas excessive inputs reduced recovery efficiency (Peng et al., 2006). Lu et al. (2024) also observed that replacing approximately 30% of chemical fertilizer with biogas slurry yielded the highest NUE, whereas higher substitution rates reduced the efficiency gains.

Agronomic nitrogen use efficiency (ANUE) decreased with increasing nitrogen input, from 31.40 g grain g^{-1} N in BE-100 to 19.24 g grain g^{-1} N in BE-200, indicating diminishing yield returns at excessive nitrogen application rates. This decline in ANUE at high N input levels has been widely documented in intensive rice systems because excessive nitrogen supply often exceeds crop demand and increases nutrient losses to the environment Biyensa et al., 2024).

Internal nitrogen use efficiency (INUE) remained relatively stable across treatments (34.76–36.94 g grain g^{-1} N uptake), suggesting that once nitrogen was absorbed, the efficiency of converting absorbed nitrogen into grain production was relatively unaffected by fertilizer source or application rate.

Different letters within the same column indicate a significant difference at $P < 0.05$ by Duncan. “ns” indicates no significant difference ($P > 0.05$).

Overall, these findings indicate that moderate BE application rates may provide a more favorable balance between nitrogen uptake and nitrogen use efficiency than excessive nitrogen inputs. While higher BE rates increased total N uptake and

Table 5. Nitrogen use efficiency indices in the mesocosm experiment

Treatment	Total plant N uptake (g N)	ANR † (gN_{uptake} $g^{-1}N_{applied}$)	ANUE ‡ (g_{grain} $g^{-1}N_{applied}$)	INUE ¶ (g_{grain} $g^{-1}N_{uptake}$)
Ze-N	14.83±1.2^{b}	–	–	34.76±4.9^{ns}
SF-150	24.38±3.0^{a}	0.64±0.2^{ns}	23.83±7.2^{ns}	35.73±1.9^{ns}
BE-100	22.22±3.2^{a}	0.74±0.32^{ns}	31.40±19^{ns}	36.94±3.1^{ns}
BE-150	22.53±3.6^{a}	0.51±0.24^{ns}	20.85±7.9^{ns}	36.75±1.3^{ns}
BE-200	24.73±2.5^{a}	0.49±0.13^{ns}	19.24±7.3^{ns}	36.19±2.5^{ns}

Note: † Ratio of difference in total N uptake between fertilized and control treatments to the total N application rate in the fertilized treatment, ‡ Ratio of difference in grain yields between fertilized and control treatments to the total N application rate in the fertilized treatment, ¶ Ratio of grain yield to total N uptake, – Not determined.

biomass production, they did not proportionally improve grain yield or NUE, highlighting the importance of optimizing nitrogen supply rather than maximizing fertilizer application. Similar conclusions were reported in previous studies, which emphasized that partial replacement of chemical fertilizer with digestate or biogas slurry can improve rice productivity, nutrient recovery, and soil fertility while reducing environmental nitrogen losses (Insam et al., 2015; Nkoa, 2014; Lu et al., 2024).

CONCLUSIONS

BE effectively improved rice growth, yield, and nitrogen uptake, with performance comparable to chemical fertilizer when application was optimized based on NH_4^+–N. Among the tested treatments, BE-100 showed the most balanced performance by maintaining grain yield comparable to SF-150 while requiring substantially lower application volume than BE-150 and BE-200. Although BE-200 achieved the highest grain yield and biomass, the additional yield gain was relatively small compared with the increased effluent volume required. These results suggest that moderate NH_4^+–N application rates are more suitable for improving agronomic efficiency and practical feasibility. Overall, NH_4^+–N-based management of BE represents a promising strategy for enhancing nutrient recycling and reducing dependence on synthetic fertilizers in rice-based systems.

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REFERENCES

1. APHA. (1998). *Standard methods for the examination of water and wastewater. 20th ed*. American Public Health Association, American Water Works Association, Water Environmental Federation, Washington, DC, US.
2. Biyensa, G., Stefania, C., Amanda, J., Ashworth, R. P. U., Valeria, C., Alessio, I., Dominique, S., Flavio, F., Andrea, D. G., Ester, F. P., Giuseppe, C., (2024). Short term effects of digestate and composted digestate on soil health and crop yield: Implications for sustainable biowaste management in the bioenergy sector. *Science of the Total Environment, 906,* 167208.
3. Cabangon, R. J., Castillo, E. G., Tuong, T. P. (2011). Chlorophyll meter-based nitrogen management of rice grown under alternate wetting and drying irrigation. *Field Crops Research, 121*(1), 136–146.
4. GSO (2024). Statistical Yearbook of Vietnam; General Statistics Office of Vietnam, *Statistical Publishing House:* Hanoi, Vietnam.
5. Ho, T. B., Roberts, T. K., Lucas, S. (2015). Small-scale household biogas digesters as a viable option for energy recovery and global warming mitigation-Vietnam case study. *Journal of Agricultural Science and Technology A 5*, 387–395.
6. Huynh, C.K., Minamikawa, K., Nguyen, V.C.N., Nguyen, H.C., Nguyen, V.C. (2022). Effects of cattle biogas effluent application and irrigation regimes on rice growth and yield: A mesocosm experiment. *JARQ, 56*(4), 341–348.

7. Insam, H., Gómez-Brandón, M., Ascher, J., 2015. Manure-based biogas fermentation residues – Friend or foe of soil fertility? *Soil Biology and Biochemistry 84*, 1–14.
8. Khanh, H. C., Hosen, Y., Loc, N. X., Nam, T. S., & Chiem, N. H. (2019). Using effluents from biogas digesters of cow-dung for rice grown on alluvial soil. *Journal of Can Tho University*, *55*, 142–148.
9. Linquist, B. A., Liu, L., Chris van Kessel, C. V., Kees Jan van Groenigen, K. J. V. (2013). Enhanced efficiency nitrogen fertilizers for rice systems: Meta-analysis of yield and nitrogen uptake. *Field Crops Research*, *154*. 246–254
10. Jiang, Y., Shi, B., Xue, R., Li, H., Li, B., Wang, L., Li, N. (2026). Biogas slurry substitution for chemical fertilizer under fertigation enhances soil fertility and maize yield sustainability: A meta-analysis. *Journal of Environmental Management*, *405*, 129748.
11. Liu, W., Yao, B., Xu, Y., Dai, S., Wang, M., Ma, J., Ye, X., Liu. D. (2024). Biogas digestate as a potential nitrogen source enhances soil fertility, rice nitrogen metabolism, and yield. *Field Crops Research*, *318*, 109568.
12. Maucieri, C., Barbera, A. C., Giannini, V., Caruso, C., Dalla Costa, L., Borin, M., (2023). Agronomic and environmental performance of crops under digestate fertilization. *Archives of Agronomy and Soil Science, 69*(15), 3422–3437.
13. Minamikawa, K., Khanh, H.C., Hosen, Y., Nam, T.S., Chiem, N.H. (2020). Variable-timing, fixed-rate application of cattle biogas effluent to rice using a leaf color chart: microcosm experiments in Vietnam. *Soil Science and Plant Nutrition, 66*(1), 225–234.
14. Minamikawa, K., Khanh, H.C., Hosen, Y., Nam, T.S., Chiem, N.H. (2021). Cattle biogas effluent application with multiple drainage mitigates methane and nitrous oxide emissions from a lowland rice paddy in the Mekong Delta, Vietnam. *Agriculture, Ecosystems and Environment 319*, 107568.
15. Möller, K., Müller, T., (2012). Effects of anaerobic digestion on digestate nutrient availability and crop growth: A review. *Engineering in Life Sciences*, *12*(3), 242–257.
16. Naik, L., Gebreegziabher, Z., Tumwesige, V., Balana, B. B., Mwirigi, J., Austin, G. (2014). Factors determining the stability and productivity of small scale anaerobic digesters. *Biomass and Bioenergy 70*, 51–57
17. Nkoa, R., (2014). Agricultural benefits and environmental risks of soil fertilization with anaerobic digestates: A review. *Agronomy for Sustainable Development, 34*, 473–492.
18. Peng, S., Buresh, R.J., Huang, J., Yang, J., Zou, Y., Zhong, X., Wang, G., Zhang, F., (2006). Strategies for overcoming low agronomic nitrogen use efficiency in irrigated rice systems in China. *Field Crops Research*, *96*, 37–47.
19. Stone, E. C., Hornberger, G. M. (2016). Impacts of management alternatives on rice yield and nitrogen losses to the environment: A case study in rural Sri Lanka. *Sci. Total Enviro*n., *542*, 271–276.
20. Wang, Z., Zhang, W., Beebout, S. S., Zhang, H., Liu, L., Yang, J., Zhang, J. (2016). Grain yield, water, and nitrogen use efficiencies of rice as influenced by irrigation regimes and their interaction with nitrogen rates. *Field Crops Research, 193,* 54–69.
21. Lu, Y., Xiao, Q., Wu, S., Yuan, H., Gao, T., Cai, T., Wu, X., Ma, Y., Liao, X. (2024). Partial substitution of nitrogen fertilizer with biogas slurry increases rice yield and fertilizer utilization efficiency, enhancing soil fertility in the Chaohu lake basin. *Plants*, *13*(15), 1–17.