Effects of Different Ammonium-N Application Rates of Biogas Wastewater on Rice Cultivation

Huynh Van Thao[1], Vo Thi Cam Tien[2], Nguyen Van Cong[1], Nguyen Vo Chau Ngan[1], Le Vo Khanh Linh[3], Nguyen Tan Thinh[3], and Huynh Cong Khanh[1*]

[1]College of Environment and Natural Resources, Can Tho University, Can Tho City 900000, Vietnam
[2]Graduate student, College of Environment and Natural Resources, Can Tho University, Can Tho City 900000, Vietnam
[3]Undergraduate student, College of Environment and Natural Resources, Can Tho University, Can Tho City 900000, Vietnam
**Corresponding Author E-mail: hckhanh@ctu.edu.vn*

ABSTRACT

Biogas wastewater (BW) is a by-product discharged from anaerobic biogas digesters and is characterized by a high nutrient content, particularly nitrogen (N), in which ammonium (NH_4^+-N) is the dominant form. In the Mekong Delta, pig manure-based biogas systems are widely used at the household scale, making pig manure-derived BW one of the most common organic waste streams in rural farming systems. Previous studies have demonstrated the potential of BW as an alternative fertilizer source for rice cultivation, and fertilizer management based on NH_4^+-N concentration can yield higher rice productivity than recommendations based on total nitrogen content. However, information on the optimal NH_4^+-N application rate for rice cultivation remains limited, particularly under practical farming conditions, where reducing BW volume while maintaining grain yield is important. Therefore, this study aimed to identify the optimal NH_4^+-N application rate from pig manure-based BW for rice cultivation while maintaining grain yield comparable to that of conventional chemical fertilization. The experiment consisted of four treatments with three replications: one applied chemical fertilizer (CF) at 150 kg N ha^{-1} (CF-150), while three used BW as a substitute nitrogen source at NH_4^+-N rates of 100, 150, and 200 kg N ha^{-1} (BW-100, BW-150, and BW-200). Results showed that grain yields in BW-150 and BW-200 were not significantly different from CF-150 ($p > 0.05$), with yields of 691 ± 63 g m^{-2}, 718 ± 50 g m^{-2}, and 692 ± 50 g m^{-2}, respectively, whereas BW-100 produced a significantly lower grain yield of 473 ± 83 g m^{-2}. Plant height and grain number per panicle increased with increasing NH_4^+-N application rate. The results demonstrated that pig manure-based BW achieved grain yield comparable to chemical N fertilizer when applied at an equivalent NH_4^+-N rate of approximately 150 kg N ha^{-1}, although BW also supplied additional organic N, phosphorus, and organic carbon. A key contribution of this study is developing an NH_4^+-N-based fertilization approach for BW application, rather than conventional recommendations based on total nitrogen (TN) or wastewater volume. This approach enables farmers to estimate the appropriate BW application rate using simple NH_4^+-N test kits, facilitating field-scale adoption, reducing excessive wastewater use, and promoting sustainable, biosafe recycling of livestock waste in rice production systems.

Keywords: Biogas wastewater/ Rice production/ NH_4^+-N application rate/ Pig manure/ Sustainable fertilization

1. INTRODUCTION

Rice (*Oryza sativa* L.) is a staple food crop that feeds nearly half of the world's population and plays a central role in Vietnam's agricultural economy [1, 2]. The Mekong Delta is the country's most important rice-producing region, contributing more than half of national rice output and the overwhelming majority of rice exports, and therefore plays a critical role in national food security [3, 31]. Sustaining high, stable rice productivity in this region depends heavily on adequate N nutrition, the dominant factor governing tillering, leaf area development, photosynthesis, and ultimately grain yield [4, 5]. In conventional practice, mineral fertilizers meet this N demand almost entirely, but intensive and often excessive chemical N use has increased production costs and contributed to soil degradation, nutrient imbalances, and pollution of surface and groundwater [6].

In parallel, the rapid expansion of household- and farm-scale livestock production coupled with anaerobic biogas digesters has generated large volumes of nutrient-rich BW, also referred to as biogas

effluent or digestate [7, 8]. Anaerobic digestion (AD) is widely promoted as a renewable-energy and waste-treatment technology, yet the liquid effluent that leaves the digester still carries high concentrations of chemical oxygen demand, nitrogen, and phosphorus that exceed permissible discharge limits; if released directly into canals and ponds, it becomes a major source of eutrophication and water pollution [9, 10, 11]. Because AD converts most of the organic nitrogen of the feedstock into NH_4^+-N without substantial loss of N, phosphorus (P), or potassium (K), BW retains a fertilizer value generally higher than that of raw manure or conventionally composted manure [12, 13, 27, 32].

Pig manure is one of the most common feedstocks for small-scale digesters in the Mekong Delta, making pig manure-derived BW a particularly abundant organic waste stream. A growing body of work has demonstrated that BW can serve as an alternative nutrient source for a range of crops, including maize [14, 35], chili [15], marigold [16], and rice irrigated with cattle-manure effluent [17, 18]. However, most of these studies dosed BW based on TN or on wastewater volume alone. This approach is poorly suited to flooded rice, which preferentially takes up nitrogen as ammonium rather than nitrate, especially during early vegetative growth [3]. Moreover, because ammonia volatilization from BW generally exceeds that from urea, previous work in the Mekong Delta has recommended calculating the nitrogen dose from effluent based on NH_4^+-N rather than total-N concentration [21, 26]. Managing BW application based on its NH_4^+-N concentration is therefore expected to more closely match crop demand and achieve higher productivity than total-N-based recommendations.

Despite this potential, information on the optimal NH_4^+-N application rate for rice remains limited, particularly under practical conditions where farmers need to reduce BW volume while maintaining yield. Excess ammonium can promote luxuriant vegetative growth, lodging, and reduced nutrient-use efficiency, whereas insufficient supply restricts dry-matter accumulation and yield [5]. Establishing the NH_4^+-N rate that maintains a yield comparable to conventional chemical fertilization is thus essential before BW can be recommended for field-scale use [29].

Accordingly, the present study integrates a CF reference with a BW NH_4^+-N dose series under net-house conditions, using the popular high-quality variety Dai Thom 8, to (i) evaluate the response of rice growth, chlorophyll status (Soil Plant Analysis Development, SPAD, value), yield components, and grain yield to different NH_4^+-N application rates from BW, and (ii) identify the optimal NH_4^+-N rate at which BW achieves grain yield comparable to chemical N fertilizer applied at the same N rate, thereby providing a simple, NH_4^+-N based dosing guideline for the sustainable and biosafe recycling of livestock waste in rice production.

2. METHODOLOGY

2.1 Study site and duration

The experiment was conducted from December 2025 to April 2026 (Winter–Spring crop) under net-house conditions at the College of Environment and Natural Resources, Can Tho University, Vietnam. The pot experiment was carried out in the net house located behind the College, allowing close control of irrigation and fertilization while exposing plants to natural light and temperature.

2.2 Experimental materials

Rice was grown in plastic pots measuring 30 cm × 30 cm × 35 cm (length × width × height), giving a cultivated surface area of 0.09 m² per pot. The variety used was Dai Thom 8, a high-quality variety widely grown in the Mekong Delta, with a growth duration of about 100–105 days in the Winter–Spring season and a sowing rate of 10–12 kg seed per 1,000 m². Chemical fertilizers used as the reference were urea (46% N), single superphosphate (16% P_2O_5), and potassium chloride (61% K_2O), purchased from local agricultural suppliers in Can Tho.

Soil was collected from the plow layer (0–20 cm) of a rice field in An Giang province, Vietnam. Before sowing, we thoroughly mixed the soil and collected three representative samples to determine its properties. We air-dried the soil samples, ground them, passed them through a 2 mm sieve, and

analyzed them at the Can Tho University laboratory for pH, total Kjeldahl nitrogen (TKN), total phosphorus (TP), and cation exchange capacity (CEC). The soil had a pH (H_2O) of 5.41, a soil organic matter content of 7.27%, a TN content of 0.31%, a TP content of 0.108% P_2O_5, and a CEC of 16.07 meq 100 g^{-1}.

BW was collected from the outlet of pig manure-fed biogas digesters operating stably in the Can Tho area. Effluent was sampled when the digester was producing gas well, and the gas bag was fully inflated; it was stored in 30 L plastic containers and used within 1 to 2 days. Leaf chlorophyll status was measured with a SPAD-502 Plus chlorophyll meter (Konica Minolta, Japan); ten leaves were measured per pot and averaged, with readings taken between 07:00 and 09:00 to ensure data consistency.

2.3 Experimental design and treatments

The experiment used a completely randomized design with four treatments and three replications. The treatments combined a CF reference dosed at the recommended N rate with a BW NH_4^+-N dose series, as summarized in Table 1. All treatments received mineral phosphorus and potassium at the same recommended rates. The treatments were designed to be equivalent in NH_4^+-N, not total N. Because BW also contains organic N, phosphate, and organic carbon, the BW treatments received additional non-ammonium N, P, and C beyond the target NH_4^+-N rate.

Table 1. Description of the experimental treatments.

Treatment	Nitrogen source	NH_4^+-N rate (kg N ha^{-1})
CF-150	Chemical fertilizer applied at a nitrogen rate of 150 kg N ha^{-1}	150
BW-100	Irrigation with post-digester BW at a nitrogen rate of 100 kg N ha^{-1}	100
BW-150	Irrigation with post-digester BW at a nitrogen rate of 150 kg N ha^{-1}	150
BW-200	Irrigation with post-digester BW at a nitrogen rate of 200 kg N ha^{-1}	200

Note: For the BW treatments, the applied volume was calculated from the measured NH_4^+-N concentration in the effluent to ensure the target ammonium-nitrogen rate was met.

2.4 Crop and water management

Before sowing, the soil was soaked for about two weeks to soften its structure, then tilled to produce a loose, well-aerated medium. Dai Thom 8 seeds were soaked overnight, incubated for two days to initiate germination, and sown directly into the pots. Throughout the experiment, water was managed to keep the pots saturated, with the water level maintained about 5 cm below the pot rim and replenished two to three times per week. Two drainage events were imposed at 15 and 30 days after sowing (DAS) to stimulate tillering, after which the saturated condition was restored until the end of the experiment.

2.5 Fertilization and biogas-wastewater dosing

The total target nitrogen rate of 150 kg N ha^{-1} (equivalent to 15 g N m^{-2}, or 1.35 g N per 0.09 m^2 pot) was split into three applications at 10, 25, and 40 DAS, corresponding to the seedling/recovery, active-tillering, and panicle-initiation stages. For the biogas-wastewater treatments, we computed the volume applied at each split from the measured NH_4^+-N concentration of the freshly collected effluent. For example, to deliver 0.27 g N per pot at an NH_4^+-N concentration of 322 mg L^{-1}, the required volume was (0.27 × 1000) / 322 = 0.84 L. To ensure an equal irrigation volume across treatments at each split, all pots received a common total volume, with tap water added to make up the difference; biogas wastewater was applied in the late afternoon to limit ammonia volatilization.

2.6 Sampling and chemical analysis

We sampled biogas wastewater three times (at 10, 25, and 40 DAS) to determine its chemical composition. We stored one-liter samples in plastic bottles at 4 °C and analyzed them at the laboratory of Can Tho University. Table 2 summarizes the analytical methods.

Table 2. Methods used for the chemical analysis of biogas wastewater (APHA, 1998).

Parameter	Unit	Analytical method
NH_4^+-N	mgN L^{-1}	Indophenol-blue method
TKN	mgN L^{-1}	Semi-micro Kjeldahl method
Total organic carbon (TOC)	mgC L^{-1}	TOC-L CPH analyzer (Shimadzu, Japan)
PO_4^{3-}-P	mgP L^{-1}	Ascorbic acid method

At harvest, plant samples were separated into straw and panicles. Twenty panicles per pot were selected at random from all hills in the pot (including both main-stem and tiller panicles, but excluding damaged or incompletely emerged panicles), and these panicles were used to determine yield components (panicle length, number of grains per panicle, and percentage of filled grains), while the remaining panicles were threshed, separated into filled and unfilled grains, and oven-dried to constant weight to determine grain yield. A 1,000-grain sub-sample of filled grains was weighed to obtain the 1,000-grain weight. Plant height and SPAD were recorded weekly from 21 DAS to harvest.

2.7 Yield calculation and data analysis

Grain yield was expressed on a dry-weight basis and adjusted to a standard moisture content of 14% using $Wa = Wb \times (100 - Hb) / (100 - Ha)$, where Wa is the moisture-adjusted yield, Wb the measured yield, Hb the actual grain moisture content, and Ha the standard moisture content (14%). Data were processed in Microsoft Excel and analyzed using one-way analysis of variance (ANOVA), with treatment means compared by Duncan's multiple-range test at the 5% significance level, in IBM SPSS Statistics 13.0.

3. RESULTS AND DISCUSSION

3.1 Nutrient composition of pig manure-based biogas wastewater

The pig manure-based BW was nutrient-rich (Table 3). The NH_4^+-N concentration was high and relatively stable over time, ranging from 321.6 to 332.0 mg L^{-1} with a mean of 325.27 ± 5.84 mg L^{-1}. This reflects intense ammonification under anaerobic digester conditions, along with limited nitrification, leading to ammonium accumulation as the dominant nitrogen form, which flooded rice absorbs most readily [3, 10]. TKN averaged 403.06 ± 35.91 mg L^{-1}; NH_4^+-N accounted for about 81% of TKN, confirming that most of the nitrogen in the effluent was present as NH_4^+-N, while the remaining ~19% was mainly organic N.

Phosphate (PO_4^{3-}P) varied more strongly over time, increasing from 190.88 mg L^{-1} at 10 DAS to 261.27 mg L^{-1} at 40 DAS (mean 217.26 ± 38.37 mg L^{-1}), consistent with the progressive release of phosphorus during the decomposition of organic matter. Total organic carbon remained high (mean 353.13 ± 35.44 mg L^{-1}), indicating incomplete mineralization during anaerobic digestion. Overall, these high and time-variable nutrient concentrations confirm that direct discharge of the effluent would pose a real risk of water pollution and eutrophication, whereas controlled application can valorize it as a crop nutrient source [9, 11].

Table 3. Chemical composition of pig manure-based biogas wastewater at three sampling times (DAS = days after sowing).

Parameter	Unit	10 DAS	25 DAS	40 DAS	Mean
NH_4^+-N	mgN L^{-1}	332.0	321.6	322.2	325.27 ± 5.84
PO_4^{3-}-P	mgP L^{-1}	190.88	199.62	261.27	217.26 ± 38.37
TOC	mgC L^{-1}	385.4	315.2	358.8	353.13 ± 35.44
TKN	mgN L^{-1}	447.7	378.3	387.8	403.06 ± 35.91

3.2 Chlorophyll status (SPAD)

SPAD readings provide a rapid, non-destructive estimate of leaf chlorophyll content and are closely correlated with leaf nitrogen status and photosynthetic capacity in rice [5, 19, 20]. During the early stage (≤ 21 DAS), SPAD values differed little among treatments because seedlings relied mainly on seed reserves. After 21 DAS, when plants entered a more vigorous vegetative phase, differences emerged: SPAD rose markedly following the top-dressings at 25 and 40 DAS, confirming the strong link between applied nitrogen and leaf chlorophyll content (Figure 1).

Before heading (around 35 DAS), the CF-150 recorded the highest SPAD values, peaking at about 43.3, reflecting the rapid availability of soluble mineral nitrogen. After heading, however, CF-150 declined more sharply, and from about 63 DAS onward the biogas-wastewater treatments — particularly BW-200 — sustained SPAD values comparable to CF-150. This is consistent with the gradual mineralization of the organic N and C supplied with BW and of soil organic matter, which provides a steadier and more prolonged nitrogen supply than soluble mineral fertilizer [8]. Among the BW treatments, SPAD tended to increase with the NH_4^+-N application rate, with BW-200 generally the highest and BW-100 the lowest. By the end of the monitoring period (84 DAS), all treatments converged to about 34 as nitrogen was remobilized to the grain, yet remained at or above the deficiency threshold (SPAD = 32), which is regarded as sufficient for high-yielding rice [20].

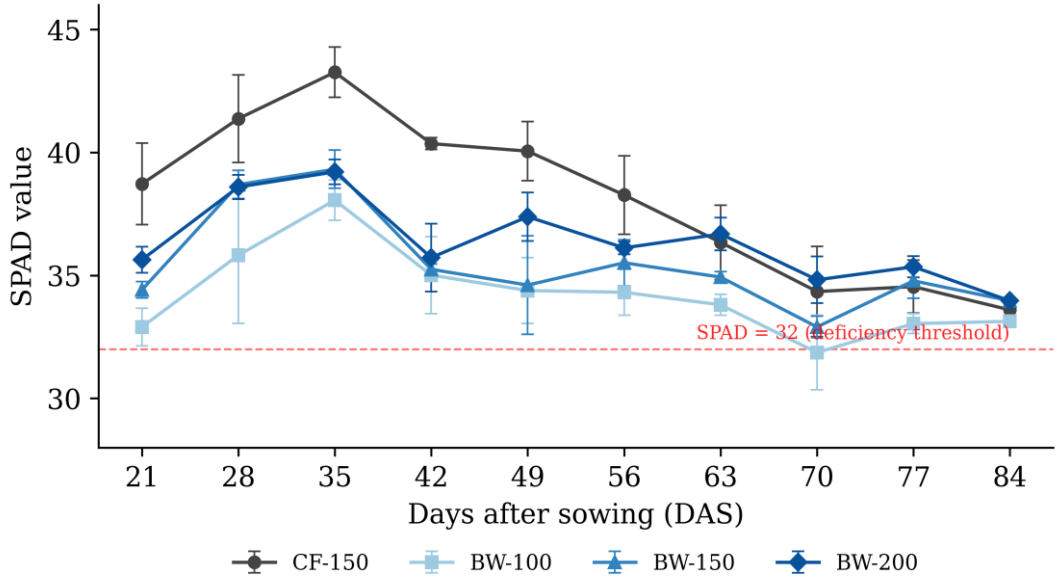

Figure 1. Changes in SPAD value of rice leaves under different NH_4^+-N application rates from biogas wastewater compared with chemical fertilizer (CF-150) during the growing season.

3.3 Growth characteristics

Plant height increased continuously through the growth cycle and differed among treatments (Figure 2). Up to 14 DAS, heights were similar (about 10–28 cm) because plants drew on seed reserves.

From 21 DAS onward, height increased rapidly, and treatments diverged: BW-200 was consistently the tallest, reaching about 79.7 cm by 77 DAS, followed by BW-150 (about 76.3 cm), while CF-150 (about 71.2 cm) and BW-100 (about 69.3 cm) were intermediate and similar. Height tended to increase with the NH_4^+-N rate, confirming that nitrogen — preferentially taken up by rice in the ammonium form — is a key driver of stem and leaf growth [17]. After about 63–77 DAS, height growth slowed and stabilized as plants shifted to the reproductive phase. The wider standard deviations in BW-100 reflect greater variability among replicates at the lower application rate.

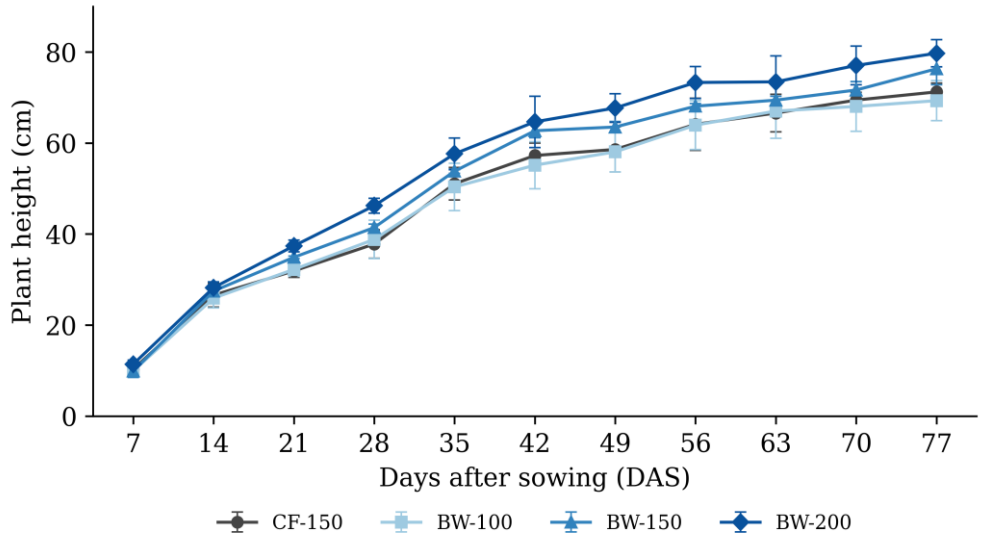

Figure 2. Changes in plant height of rice under different NH_4^+-N application rates from biogas wastewater compared with chemical fertilizer (CF-150) during the growing season.

The number of tillers per square meter increased with the NH_4^+-N rate, from about 414 plants m^{-2} in BW-100 to about 629 plants m^{-2} in BW-200, with CF-150 and BW-150 at intermediate to high values (Figure 3a). Panicle number followed the same trend, with BW-150 and BW-200 producing significantly more panicles per square meter than the lower-dose treatments (Figure 3b). Adequate ammonium supply thus enhanced effective tillering, a primary determinant of panicle number and yield [3]. Panicle length also increased with the NH_4^+-N rate, from about 18.8 cm in BW-100 to about 21.2 cm in BW-200 (Figure 3c); longer panicles are associated with more spikelets per panicle, although excessively long panicles may increase the risk of lodging during grain filling.

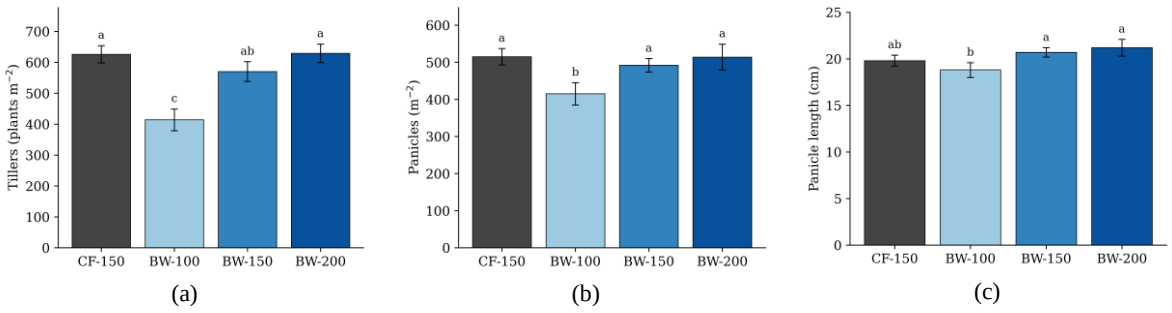

Figure 3. Effect of NH_4^+-N application rate from biogas wastewater on (a) tiller number, (b) panicle number, and (c) panicle length of rice. Bars with the same letter are not significantly different at $p < 0.05$ (Duncan's test).

3.4 Yield components

The total number of grains per panicle differed significantly among treatments, with BW-150 and BW-200 reaching about 98–108 grains per panicle compared with about 75–82 in the lower-dose treatments ($p < 0.05$; Figure 4a). Favorable nitrogen nutrition during panicle initiation and flowering increased the number of effective spikelets, improved pollination, and reduced unfilled grains [3]. The 1,000-grain weight also differed significantly (Figure 4b): BW-100 gave about 21.3 g, whereas BW-150 and BW-200 reached about 25.3–25.6 g; all values remained within the typical 20–25 g range governed mainly by varietal genetics [3]. Dry straw biomass increased with the NH_4^+-N rate, from about 494 g m^{-2} in BW-100 to about 1,061 g m^{-2} in BW-200 (Figure 4c), reflecting enhanced vegetative growth; however, increases in vegetative biomass are not always matched by proportional grain-yield gains because of competition for assimilates between vegetative and reproductive organs [4].

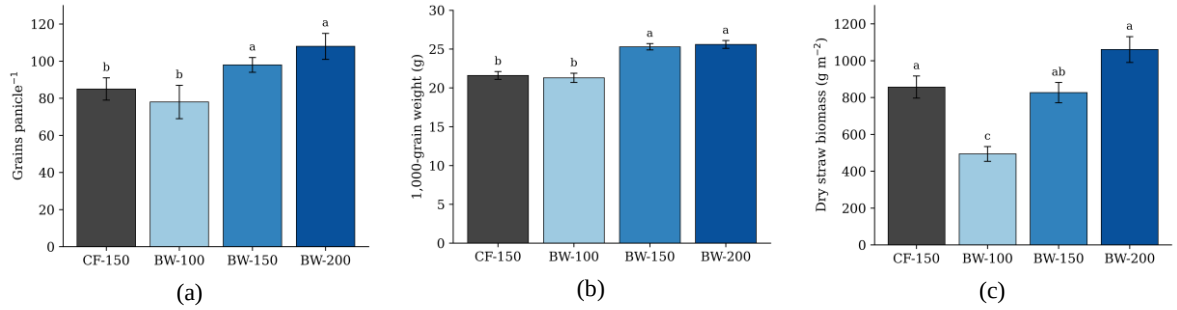

Figure 4. Effect of NH_4^+-N application rate from biogas wastewater on (a) grains per panicle, (b) 1,000-grain weight, and (c) dry straw biomass of rice. Bars with the same letter are not significantly different at $p < 0.05$ (Duncan's test).

3.5 Grain yield

Grain yield (adjusted to 14% moisture) differed significantly among treatments (Figure 5). Crucially, the grain yields of BW-150 and BW-200 were statistically comparable to the chemical-fertilizer reference CF-150 ($p > 0.05$), at 691 ± 63 g m^{-2}, 718 ± 50 g m^{-2}, and 692 ± 50 g m^{-2}, respectively, whereas BW-100 produced a significantly lower grain yield of 473 ± 83 g m^{-2}. The strong grain-yield response between 100 and 150 kg N ha^{-1}, followed by the absence of a significant further increase from 150 to 200 kg N ha^{-1}, indicates that yield approached a plateau at around 150 kg N ha^{-1}. Although BW-200 yielded the highest numerical value, it also showed the greatest variability among replicates, whereas BW-150 combined a high yield with better stability. The soil's relatively high OM and TN contents likely provided a substantial indigenous N supply, which may partly explain why grain yield plateaued at about 150 kg NH_4^+-N ha^{-1}.

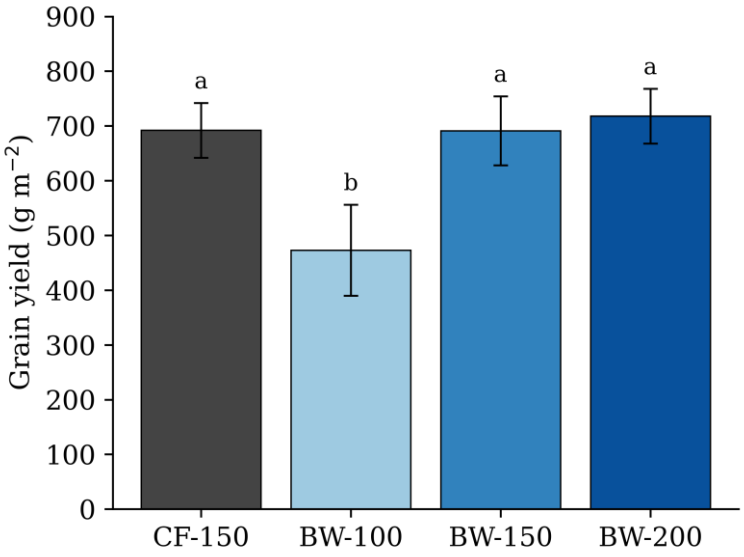

Figure 5. Grain yield (14% moisture) of rice under different NH_4^+-N application rates from biogas wastewater compared with chemical fertilizer (CF-150). Bars with the same letter are not significantly different ($p < 0.05$).

These results demonstrate that the NH_4^+-N in pig manure-based BW can supply rice as effectively as mineral nitrogen fertilizer, provided the NH_4^+-N application rate is adequate. At about 150 kg NH_4^+-N ha^{-1}, BW fully matched the grain yield obtained with chemical fertilizer, while a lower rate (100 kg N ha^{-1}) was insufficient and a higher rate (200 kg N ha^{-1}) offered no significant yield benefit and increased variability. However, this comparison was equivalent in NH_4^+-N rather than in total N. On a TKN basis, BW-150 supplied about 186 kg N ha^{-1}, i.e., approximately 24% more N than CF-150, together with about 100 kg PO_4^{3-}-P ha^{-1} and 163 kg TOC ha^{-1}. Part of the yield parity may therefore be attributable to the mineralization of organic N and to the additional P and C supplied by BW, and the partial factor productivity of BW expressed per unit of total N was lower than that of urea. Nevertheless, BW-150 only matched, and did not exceed, the grain yield of CF-150 despite its larger total-N input, and the further increase in TKN input in BW-200 (248 kg N ha^{-1}) produced no significant additional yield. This suggests that the organic N fraction of BW contributed little to grain yield within a single season and that the readily available NH_4^+-N fraction mainly drove the grain-yield response. This is consistent with previous reports that biogas effluent can substitute, partly or wholly, for mineral nitrogen in rice and other crops [14, 17, 18, 13, 26, 34], and it refines those reports by showing that dosing on the basis of NH_4^+-N concentration, rather than total nitrogen or wastewater volume, is an effective and practical management approach for flooded rice. This result also aligns with microcosm experiments in Can Tho, where the nitrogen dose from cattle biogas effluent was calculated from its NH_4^+-N concentration, and grain yield increased with the crop's leaf color (SPAD) status [21]. This study showed that rice grain production approached a nitrogen saturation threshold of near 150 kg NH_4^+-N ha^{-1}. The additional nitrogen supplied by BW-200 was preferentially allocated to vegetative tissues rather than to reproductive sinks, so that agronomic nitrogen-use efficiency declined while grain yield did not increase further. Comparable yield plateaus and declining agronomic efficiency at high nitrogen rates have been widely reported for rice [23, 24, 25, 28], supporting the interpretation that BW-200 supplied nitrogen in excess of crop demand.

From a practical standpoint, NH_4^+-N-based dosing allows farmers to estimate the appropriate biogas-wastewater volume using simple ammonium test kits, avoiding both under- and over-application. This reduces the volume of effluent discharged into the environment, lowers chemical fertilizer costs, and supports the sustainable, biosafe recycling of livestock waste within a circular agriculture framework. However, the present work was a net-house pot study over a single season; the

persistence of these benefits and potential trade-offs, such as greenhouse-gas emissions associated with repeated BW application, warrant evaluation under field conditions across multiple seasons and varieties. Future trials should also include a total-N-equivalent BW treatment and a P-balanced chemical reference to separate the effects of NH_4^+-N from the organic N, P, and C contained in BW.

3.6 Potential advantages and challenges of using biogas wastewater in rice cultivation

The findings of this study highlight a considerable potential for using pig manure-based biogas wastewater as a partial or complete substitute for chemical nitrogen fertilizer in rice cultivation. In the Mekong Delta, where household- and farm-scale biogas digesters are widespread, large and continuous volumes of nutrient-rich effluent are generated year-round. Because rice is cultivated intensively over two to three crops per year, it represents an ideal sink for this effluent: its high and continuous nitrogen demand, its preference for the ammonium form that dominates BW, and the flooded condition of paddy fields together allow the nutrients in BW to be recovered productively rather than lost to the environment [3, 13, 17]. Coupling biogas digesters with rice fields therefore turns a polluting waste stream into a local, low-cost nutrient resource and closes the nutrient loop within the farming system.

Several advantages support field-scale adoption. First, BW supplies nitrogen primarily as readily available NH_4^+-N, along with phosphorus, potassium, and organic carbon, thereby reducing or replacing mineral fertilizer inputs, lowering production costs, and improving soil organic matter over time [8, 12, 36]. Second, dosing BW according to its measured NH_4^+-N concentration—the approach validated here—is simple and field-applicable: farmers can use inexpensive ammonium test kits to estimate the required volume, improving nutrient-use efficiency and avoiding the over-application that occurs when dosing by total nitrogen or volume. Third, diverting effluent to the field reduces direct discharge into canals and ponds, mitigating eutrophication and water pollution and improving rural sanitation [9, 10]. Finally, the practice contributes to climate-resilient, circular agriculture by recycling livestock waste and reducing dependence on energy-intensive synthetic fertilizers.

Nevertheless, several challenges remain before widespread field use. The nutrient composition of BW is variable, depending on feedstock, digester loading, retention time, and washing water, so each batch ideally needs to be characterized before application [33]; the high NH_4^+-N and organic-carbon loads also mean that excessive or poorly timed application can cause ammonia toxicity, luxuriant vegetative growth, lodging, and even short-term oxygen depletion in the floodwater [10, 11]. Practical handling is a further constraint: transporting, storing, and uniformly applying large volumes of liquid is labor-intensive at field scale, and ammonia volatilization during application can reduce nitrogen-use efficiency unless the effluent is applied in the late afternoon and incorporated with irrigation water. Biosafety is another concern because anaerobic digestion reduces but does not eliminate pathogens, and repeated application may gradually accumulate heavy metals or antibiotic residues from animal feed [13, 30].

A particularly important trade-off concerns greenhouse gas emissions. Because biogas effluent contains labile organic carbon — the substrate for methanogenesis — its application to continuously flooded paddies can raise methane (CH_4) emissions relative to mineral fertilizer; a field study under triple-cropping in the Mekong Delta reported a mean CH_4 increase of about 19% with cattle biogas effluent, with the magnitude governed by the carbon-to-nitrogen ratio and labile-carbon content of the effluent [22]. Encouragingly, the same study showed that combining effluent application with multiple drainage, alternate wetting and drying (AWD), or midseason drainage followed by intermittent irrigation, reduced CH_4 emission by about 27–30% and offset the increase caused by the effluent, while nitrous oxide (N_2O) emission was actually lower under effluent than under urea, and grain yield was maintained [22]. Addressing the challenges above will therefore require batch-specific nutrient testing, standardized dosing and application guidelines, appropriate water management (such as AWD or midseason drainage to curb CH_4), and multi-season field trials across different soils and rice varieties to confirm agronomic stability, environmental safety, and economic feasibility.

In the broader context of nutrient recovery and circular agriculture, these results align with a growing body of evidence that anaerobic digestion by-products can partially or fully replace synthetic fertilizers across diverse crops and soils. In the Mekong Delta, biogas effluent reformulated into solid or liquid organic fertilizers allowed the recommended NPK dose for maize and mung bean to be cut by about 25% without a yield penalty [37], while biogas-slurry topdressing sustained maize yield by delaying leaf senescence and up-regulating stress-tolerance mechanisms [35], and biogas-plant organic fertilizer improved nutrient uptake and growth in wheat [34]. Reviews of biogas slurry applied to sorghum on sandy soils similarly emphasize gains in soil fertility and nutrient availability [32]. What distinguishes the present study is that it moves beyond total-N- or volume-based dosing toward a simple NH_4^+-N-based guideline, directly matching the ammonium-dominated nitrogen chemistry of biogas wastewater to the preferential ammonium uptake of flooded rice, and identifies roughly 150 kg NH_4^+-N ha^{-1} as the practical substitution threshold [26]. Beyond nitrogen supply, biogas effluent carries a microbial and biochemical dimension: bioslurry contains beneficial microorganisms and labile organic matter that can enhance soil biological activity and fertility when properly managed [38], and downstream processing — separation and valorization of digestate into standardized organic-fertilizer products, or conversion of biogas sludge into slow-release granular fertilizers — offers practical routes to stabilize its variable composition and improve nutrient-use efficiency and storability [27, 33]. Realizing these benefits at field scale will nonetheless require harmonized quality standards and clear regulatory criteria for digestate-based fertilizers, so that ammonium-rich effluents can be integrated safely and consistently into rice-based cropping systems.

4. CONCLUSIONS

Pig manure-based biogas wastewater is a nutrient-rich effluent in which ammonium is the dominant nitrogen form (NH_4^+-N ≈ 325 mg L^{-1}). When applied to rice, biogas wastewater supported growth, chlorophyll status, yield components, and grain yield as effectively as conventional chemical nitrogen fertilizer applied at the same N rate. Grain yields under biogas wastewater at NH_4^+-N rates of 150 and 200 kg N ha^{-1} (691 and 718 g m^{-2}) were statistically comparable to the chemical-fertilizer reference at 150 kg N ha^{-1} (692 g m^{-2}), whereas 100 kg N ha^{-1} was insufficient (473 g m^{-2}). Plant height and grain number per panicle increased with the NH_4^+-N rate, and yield plateaued at about 150 kg N ha^{-1}, combining high productivity with good stability.

The study concludes that pig manure-based BE can achieve grain yield comparable to chemical nitrogen fertilizer in rice cultivation when applied at an NH_4^+-N rate of approximately 150 kg N ha^{-1}. Because BW also supplies organic N, P, and organic carbon, this substitution should be understood on an NH_4^+-N-equivalent rather than a total-N-equivalent basis. The key contribution is an NH_4^+-N-based fertilization approach that enables farmers to estimate the appropriate application volume with simple ammonium test kits, thereby reducing excessive wastewater use, lowering production costs, limiting direct effluent discharge, and promoting the sustainable and biosafe recycling of livestock waste in rice production systems. To safeguard environmental benefits, this fertilization approach should be combined with water-saving practices such as AWD or midseason drainage, which have been shown to offset the methane increase associated with effluent application without yield loss [22]. Further field-scale studies across multiple seasons, soils, and varieties are recommended to confirm these benefits and to assess potential environmental trade-offs.

Acknowledgement

The authors sincerely thank Ngo Nguyen Quoc Huy and Tran Chi Kha, students in the Environmental Science program at the College of Environment and Natural Resources, Can Tho University, for conducting the experiments and collecting the data used in this study. The authors also acknowledge the Department of Environmental Sciences, Can Tho University, for providing the net-house and laboratory facilities.

References

[1] Timmer, C. P. (2010). The changing role of rice in Asia's food security. ADB Sustainable Development Working Paper Series, No. 15. Asian Development Bank, Manila.
[2] Grierson, C. S., Barnes, S. R., Chase, M. W., Clarke, M., Grierson, D., Edwards, K. J., Millar, A. (2011). One hundred important questions facing plant science research. New Phytologist, 192(1), 6–12.
[3] Nguyen, N. D. (2008). Textbook of Rice Plant. Ho Chi Minh City: Vietnam National University Publishing House.
[4] Dobermann, A., & Fairhurst, T. (2000). Rice: Nutrient Disorders and Nutrient Management. Philippines: International Rice Research Institute and Potash & Phosphate Institute.
[5] Yoshida, S. (1981). Fundamentals of Rice Crop Science. Los Baños, Philippines: International Rice Research Institute.
[6] Nguyen, V. B. (2013). Improving Fertilizer-Use Efficiency in Vietnam. Hanoi: Agricultural Publishing House.
[7] Holm-Nielsen, J. B., Al Seadi, T., & Oleskowicz-Popiel, P. (2009). The future of anaerobic digestion and biogas utilization. Bioresource Technology, 100(22), 5478–5484.
[8] 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.
[9] Appels, L., Baeyens, J., Degrève, J., & Dewil, R. (2008). Principles and potential of the anaerobic digestion of waste-activated sludge. Progress in Energy and Combustion Science, 34(6), 755–781.
[10] Khalid, A., Arshad, M., Anjum, M., Mahmood, T., & Dawson, L. (2011). The anaerobic digestion of solid organic waste. Waste Management, 31(8), 1737–1744.
[11] Bui, T. N., Nguyen, T. N. N., & Bui, H. T. (2014). Biogas production potential of water lettuce and water hyacinth in biogas digesters. Journal of Agriculture and Rural Development, 2, 17–25.
[12] Nguyen, Q. K. (2009). Biogas Technology: A Comprehensive Guide to Construction, Operation, Maintenance and Use of Biogas and Effluent. Hanoi: Labour and Social Affairs Publishing House.
[13] Vo, T. K. Q., Nguyen, V. C. N., & Dang, B. T. (2015). Biogas effluent as a potential fertilizer for sustainable agriculture in Vietnam. Journal of Sustainable Agriculture, 39(4), 1–10.
[14] Nguyen, P. T., Nguyen, T. L. A., Tran, T. T. V., & Bui, T. N. (2017). Use of biogas effluent for growing maize (*Zea mays* L.). Can Tho University Journal of Science, 53a, 53–64.
[15] Pham, V. N., Bui, T. N., & Izumi, T. (2015). Use of biogas effluent with pig manure and water lettuce (*Pistia stratiotes*) for growing chilli (Capsicum frutescens L.). Can Tho University Journal of Science, Special Issue on Environment and Climate Change, 35–40.
[16] Bui, T. N., Izumi, T., & Nguyen, C. T. (2015). Use of biogas effluent for growing marigold (*Tagetes patula* L.). Journal of Agriculture and Rural Development, 1, 55–60.
[17] Huynh, C. K., Nguyen, H. C., Nguyen, X. L., Tran, S. N., & Hosen, Y. (2019). Use of cattle manure-based biogas effluent to irrigate rice grown on alluvial soil. Can Tho University Journal of Science, 55(1), 142–148.
[18] Huynh, K. C., Minamikawa, K., Nguyen, N. V. C., Nguyen, C. H., & Nguyen, C. V. (2022). Effects of cattle biogas effluent application and irrigation regimes on rice growth and yield: A mesocosm experiment. Japan Agricultural Research Quarterly, 56(4), 341–348.
[19] Turner, F. T., & Jund, M. F. (1994). Assessing the nitrogen requirements of rice crops with a chlorophyll meter. Australian Journal of Experimental Agriculture, 34(7), 1001–1005.
[20] Takebe, M., Yoneyama, T., Inada, K., & Murakami, T. (1990). Spectral reflectance ratio of rice canopy for estimating crop nitrogen status. Plant and Soil, 122, 295–297.
[21] Minamikawa, K., Huynh, C. K., Hosen, Y., Tran, S. N., & Nguyen, H. C. (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.
[22] Minamikawa, K., Huynh, K. C., Uno, K., Tran, N. S., & Nguyen, C. 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 & Environment, 319, 107568.
[23] He, X., Zhu, H., Shi, A., & Wang, X. (2024). Optimizing nitrogen fertilizer management enhances rice yield, dry matter, and nitrogen use efficiency. Agronomy, 14(5), 919.
[24] Zhu, H., Wen, T., Sun, M., Ali, I., Sheteiwy, M. S., Wahab, A., Wang, X. (2023). Enhancing rice yield and nitrogen utilization efficiency through optimal planting density and reduced nitrogen rates. Agronomy, 13(5), 1387.
[25] Ladha, J. K., Pathak, H., Krupnik, T. J., Six, J., & van Kessel, C. (2005). Efficiency of fertilizer nitrogen in cereal production: Retrospects and prospects. Advances in Agronomy, 87, 85–156.
[26] Huynh, C. K., Le, T. N. N., Tran, S. N., Nguyen, Q. K., & Huynh, V. T. (2026). Use of ammonium-N-based biogas effluent application for sustainable rice production and improved nutrient recycling. Journal of Ecological Engineering, 27(9), 344–352.
[27] Vo, N. X. Q., Tran, T. P. O., Lam, P. T. H., & Trinh, T. B. H. (2024). Reuse of biogas sludge for the slow-release fertilizer production to improve fertilizer use efficiency and soil fertility. Bioresource Technology Reports, 26, 101877.
[28] Zhou, J., Pan, W., Tang, S., Ma, Q., Mi, W., Wu, L., & Liu, X. (2025). Optimizing nitrogen fertilization rate to achieve high yield and high soil quality in paddy ecosystems with straw incorporation. Journal of Environmental Management, 375, 124158.

[29] Kamuruzzaman, M., Rees, R. M., Islam, M. T., Drewer, J., Sutton, M., Bhatia, A., Bealey, W. J., & Hasan, M. M. (2024). Improving nitrogen fertilizer management for yield and N use efficiency in wetland rice cultivation in Bangladesh. Agronomy, 14(12), 2758.

[30] German Biogas Association (Fachverband Biogas e.V.), & Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. (2016). Biogas Safety First! Guidelines for the Safe Use of Biogas Technology (BIOGAS Know-how 2). Freising, Germany.

[31] General Statistics Office of Vietnam. (2020). Statistical Yearbook of Vietnam 2019. Hanoi: Statistical Publishing House.

[32] Mgxaji, Y., Mutengwa, C. S., Mukumba, P., & Dzvene, A. R. (2025). Biogas slurry as a sustainable organic fertilizer for sorghum production in sandy soils: A review of feedstock sources, application methods, and agronomic impacts. Agronomy, 15(7), 1683.

[33] Romio, C., Ward, A. J., & Møller, H. B. (2024). Characterization and valorization of biogas digestate and derived organic fertilizer products from separation processes. Frontiers in Sustainable Food Systems, 8, 1415508.

[34] Erenoğlu, E. B., & Hacırüstemoğlu, K. D. (2022). Biogas facility-based organic fertilizer enhances nutrient uptake and growth of wheat (Triticum aestivum). Applied Ecology and Environmental Research, 20(6), 5343–5360.

[35] Liang, X., Wang, C., Wang, H., Yao, Z., Qiu, X., Wang, J., & He, W. (2023). Biogas slurry topdressing as replacement of chemical fertilizers reduces leaf senescence of maize by up-regulating tolerance mechanisms. Journal of Environmental Management, 344, 118433.

[36] German Biogas Association (Fachverband Biogas e.V.), & Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. (2018). Digestate as Fertilizer (BIOGAS Know-how 4). Freising, Germany.

[37] Nghia, N. K., Thy, C. T. A., Xa, L. T., & Luan, D. T. (2022). Recycling of biogas wastewater to organic fertilizers and influence of organic fertilizers on maize, mung bean growth and yield under the field conditions. Applied Environmental Biotechnology, 7(1), 16–27.

[38] Kamath, V., Apte, M., Dawda, H., Gore, S., Sahasrabuddhe, P., Behara, P., Bhosale, S., Gupta, S., Jadhav, N., Mulla, A., & Panchal, A. (2026). Biogas effluent as a sustainable biofertilizer: Biochemical, microbiological and agronomic insights. J-BNB: A Multidisciplinary Journal, 14, 37–44.