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RESEARCH PAPER

Nutri Gard Nano Biopolymer fertilizer as a tool to improve nutrient use efficiency in *Padi Wai* (Sarawak Specialty Rice)

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Key Message: Nutri Gard NPK fertilizer significantly improved nutrient use efficiency, vegetative growth, and grain yield of Sarawak specialty rice compared with conventional compound fertilizer. These benefits were attributed to enhanced soil nutrient retention by nano-polymer components, which protected and reduced nutrient losses through leaching even when applied at a reduced rate.

Abstract

Prolonged dependence on conventional compound fertilizers often results in low nutrient use efficiency (NUE) and increased environmental degradation due to nutrient losses through leaching and volatilization. This study evaluated the growth performance, nutrient use efficiency, and yield response of the Sarawak specialty rice variety *Padi wai* under Nutri Gard fertilizer compared with standard fertilization. The experiment was conducted for 169 days under nursery-scale conditions at Universiti Putra Malaysia Sarawak using a randomized complete block design with five treatments and three replications: soil only (S), standard fertilizer (SF), Nutri Gard at the recommended rate (NG1, 100%), Nutri Gard at a 30% reduced rate (NG2, 70%), and Nutri Gard with elevated potassium (NG3). Plant height was greatest under NG2 (192.3 cm) and NG3 (187.4 cm), exceeding SF (182.1 cm) and NG1 (183.7 cm). Panicle weight improved substantially with Nutri Gard, reaching 421 g (NG1), 405 g (NG2), and 470 g (NG3), compared with 297 g under SF. Grain weight followed a similar pattern, with NG2 producing the highest value (347 g), followed by NG1 (312 g) and NG3 (311 g), all surpassing SF (253 g). NG3 generated the highest grain number (23,446 grains), while SF recorded the lowest (16,628 grains). Nutrient use efficiencies were markedly enhanced by Nutri Gard. NG2 achieved the highest N, P, and K efficiencies (16%, 28%, and 68%, respectively), compared with SF (4%, 13%, and 24%). Total soil N remained higher in NG1 (0.42%), NG2 (0.40%), and NG3 (0.34%) than in SF (0.21%). Available P was 603 ppm (NG1), 624 ppm (NG2), and 521 ppm (NG3), compared with 417 ppm in SF. Overall, the nano-biopolymer-based Nutri Gard fertilizer significantly enhanced nutrient retention, nutrient use efficiency, and paddy growth performance, even at reduced application rates, demonstrating its potential as a sustainable alternative to conventional NPK fertilization. © 2025 The Author(s)

Keywords: Biopolymer fertilizer, Nano fertilizer, Nutrient use efficiency, Rain shield protection nutrients, Sarawak specialty rice, Sustainable fertilization

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Introduction

Despite the widespread use of conventional compound fertilizers in rice cultivation, nutrient use efficiency (NUE) remains low, particularly for nitrogen (N) and potassium (K), due to loss via volatilization, leaching, fixation, and poor synchronization between nutrient release and crop demand. These losses are exacerbated in tropical soils such as those in Sarawak, East Malaysia which are often characterized by high rainfall, variable nutrient retention capacity, and suboptimal fertilizer management practices (Kavitha et al., 2024). Consequently, farmers frequently apply fertilizers at higher than required rates, increasing production costs and environmental risks without proportionate yield gains. Rice (*Oryza sativa* L.) is one of the world's most important staple crops and requires an adequate and balanced supply of nutrients to sustain optimal growth and productivity. Rice growth and development are divided into three distinct phases, namely the vegetative, reproductive, and ripening stages, each characterized by specific physiological processes and nutrient demands (Yuan et al., 2024). Among the essential macronutrients, N plays a pivotal role during the vegetative stage, because it is directly involved in leaf expansion, tiller formation, and chlorophyll synthesis, thereby strongly influencing aboveground growth and development as well as biomass accumulation (Zhu et al., 2025). Adequate N availability during this stage promotes vigorous plant growth, increased tiller numbers, and greater plant height (Padhan et al., 2023). In addition to N, phosphorus (P) is crucial for early root development and energy transfer processes (Wei et al., 2022), while K contributes to plant structural integrity, stress tolerance, and overall physiological resilience (He et al., 2025). Therefore, the balanced application of N, P, and K is essential to ensure optimal growth performance and developmental progression of rice (Paiman et al., 2021).

In rice production systems, compound NPK fertilizers are widely adopted due to their ease of application and ability to supply the three primary macronutrients: N, P, and K simultaneously (Wang et al., 2025). These fertilizers are particularly favored by farmers because they provide rapid nutrient availability, especially during the early vegetative stages of rice growth (Wang et al., 2025). Accordingly, Liu et al. (2023) reported that NPK fertilization remains the dominant nutrient management strategy in rice cultivation. Apart from that, urea is typically applied through broadcasting or split applications according to rice growth stages. The problem with urea application is, under flooded paddy conditions, urea is often associated with substantial N losses via ammonia volatilization, leaching, and denitrification, as demonstrated by Ma et al. (2025). Such losses reduce N bioavailability and significantly impair N use efficiency (Wang et al., 2025). Furthermore, Wu et al. (2025) highlighted that the poor synchronization between nutrient release from conventional fertilizers and crop nutrient demand can lead to uneven rice growth, particularly during the critical tillering stage. Consequently, farmers frequently resort to excessive fertilizer application to compensate for nutrient losses, resulting in increased production costs and potential environmental risks (Wu et al., 2025).

Most of the studies have been focused on major rice varieties under generalized field conditions, with limited empirical evidence evaluating their performance in specialty cultivars grown under Sarawak soil and climatic conditions. *Padi wai*, a specialty paddy cultivar in Sarawak, has received limited scientific evaluation regarding optimized nutrient management strategies tailored to its physiological demand and local soil conditions (Department of Agriculture, Sarawak, 2022). While nano-enabled and biopolymer-coated fertilizers have shown potential to enhance nutrient release control and improve nutrient retention in soil (Bongiwe et al., 2022), their effectiveness in improving NUE and yield performance of *wai* rice under Sarawak conditions remains poorly understood. Therefore, the key knowledge gap lies in the lack of empirical evidence on whether nano-biopolymer fertilizer formulations, such as Nutri Gard, can enhance soil nutrient retention, improve plant NUE, and sustain yield performance of *Padi wai* compared with conventional fertilization systems. In this project, our approach was to use fertilizer formulation with combination of nanotechnology and biopolymers known as Nutri Gard fertilizers in rice cultivation using Sarawak Specialty variety, (*padi wai*) as a test crop. In Nutri Gard fertilizer, nano biopolymers were infused with N, P, and K to protect the major nutrients (N, P, and K) from being leached in waterlogged farming system and from being volatile in dry season farming (Latifah et al., 2021; Kavitha et al., 2024).

Nutri Gard fertilizer is formulated using nano biopolymers crop derived materials that are engineered at the nanoscale to produce advanced biopolymeric systems with tailored physicochemical properties (Yang et al., 2020). Owing to their renewable origin and inherent biodegradability, nano-biopolymers represent a sustainable alternative to synthetic polymers (Kolovou et al., 2023). Among various sources, starch has received considerable attention due to its abundance, low cost, and excellent film-forming ability (Kavitha et al., 2022). By manipulating starch at the nanoscale, its native limitations can be overcome, resulting in enhanced mechanical strength, flexibility, and functional performance (Yang et al., 2020). Furthermore, starch-based nano-biopolymers are designed to undergo natural degradation, thereby minimizing persistent waste accumulation and reducing environmental pollution (Kavitha et al., 2022).

Despite studies specifically addressing the performance and release dynamics of Nutri Gard fertilizers are limited, its proposed mode of action is conceptually comparable to that of controlled-release fertilizers (CRFs) and enhanced-efficiency fertilizers (EEFs), whose agronomic benefits have been extensively documented in recent literature (Wu et al., 2025). According to Zhu et al. (2025), formulated fertilizers with controlled-release properties generally operate through similar mechanisms, primarily by minimizing nutrient losses while enhancing plant nutrient uptake. Controlled-release fertilizers supply nutrients in a temporally regulated manner that better synchronizes nutrient availability with plant demand, thereby improving NUE (Wang et al., 2025). It remains unclear whether nano-biopolymer formulations of Nutri Gard can effectively enhance *Padi wai* growth and development, NUE and sustain yield performance in *Padi wai* while potentially reducing fertilizer application rates. Therefore, this study was conducted to address this knowledge gap by evaluating the effectiveness of Nutri Gard nano-biopolymer fertilizer in improving soil nutrient retention, plant nutrient uptake, and overall nutrient use efficiency in *Padi wai* in comparison to conventional NPK fertilizer. By providing cultivar-specific and region-specific evidence, this work contributes novel insights into sustainable fertilizer management strategies for specialty rice production in tropical environments. This project aimed to determine the effects of Nutri Gard fertilizer application on *Padi wai* growth performance, nutrient use efficiency and soil nutrient availability in comparison with the existed standard fertilization recommended for rice.

Materials and Methods

Soil sampling, preparation and analysis

Soil for the pot experiment was collected from the Bekenu Series (*Typic Paleudults*) at a depth of 0–20 cm from an uncultivated secondary forest at Universiti Putra Malaysia Sarawak (UPMS), Malaysia (3°12′19.4″ N, 113°04′22.8″ E). The collected soil was air-dried for seven days, crushed, and passed through a 5 mm sieve for pot establishment. A subsample was further sieved to < 2 mm for the determination of selected physicochemical properties before and after the pot experiment. Soil particle-size distribution was determined using the Bouyoucos hydrometer method based on sedimentation principles. This method quantifies sand (2.0–0.05 mm), silt (0.05–0.002 mm), and clay (<0.002 mm) fractions according to Stoke's law. A 50 g air-dried soil sample (passed through a 2 mm sieve) was weighed into a dispersion cup. Distilled water was added, followed by 3 M NaOH (four drops) as a dispersing agent to promote deflocculation of soil particles. The suspension pH was adjusted to approximately 10 to ensure effective dispersion. The mixture was mechanically stirred for 15 minutes to achieve complete dispersion of soil aggregates. The dispersed suspension was quantitatively transferred into a 1 L graduated sedimentation cylinder, and the volume was adjusted to 1,000 mL with distilled water. The cylinder was securely covered and inverted several times to ensure a uniform suspension before placing it on a stable surface to allow sedimentation. A calibrated soil hydrometer was inserted into the suspension, and the first hydrometer reading was taken at 40 seconds to determine the combined silt and clay fraction remaining in suspension. The temperature of the suspension was recorded concurrently, and hydrometer readings were corrected for temperature deviations from the standard calibration temperature of 20 °C. After 2 hours of sedimentation, a second hydrometer reading was taken to determine the clay fraction remaining in suspension. Temperature corrections were applied to all readings. The percentage of sand was calculated by difference, subtracting the corrected silt + clay fraction from the total sample weight, while silt content was obtained by subtracting the clay fraction from the silt + clay fraction. Soil textural class was subsequently determined using the USDA textural triangle (Tan, 2005).

Soil pH was determined in 1 M KCl using a soil-to-solution ratio of 1: 2 following standard procedures (Tan, 2005). Briefly, 10 g of air-dried soil was weighed into a plastic vial, and 20 mL of 1 M KCl solution was added. The suspension was shaken on an orbital shaker at 180 revolutions per minute (rpm) for 15 minutes and then allowed to equilibrate. The pH was measured using a calibrated digital pH meter (SevenEasy, Mettler Toledo). Total organic matter (OM), total carbon (C), and total N were determined using a LECO TruSpec Micro CHNS elemental analyzer (LECO Corporation, New York, USA). Prior to analysis, soil samples were air-dried, finely ground, and sieved to pass through a 250 µm sieve. Approximately 2.2 mg of the prepared soil was weighed and placed into a tin capsule for analysis. The samples were combusted at 1075 °C in the CHNS analyzer. Total C and N concentrations were determined automatically using the instrument's integrated detection system and software. Soil organic matter content was estimated from the measured total C using a conversion factor, assuming that OM contains 58% carbon (i.e., SOM = total C × 1.724) (Tan, 2005).

Measurement of exchangeable ammonium (NH_4^+) and available nitrate (NO_3^-)

Exchangeable ammonium (NH_4^+) and available nitrate (NO_3^-) were determined according to the method of Keeney and Nelson (1982) using potassium chloride (KCl) extraction followed by steam distillation. A 5 g air-dried soil sample was weighed and extracted with 50 mL of 2 M KCl solution. The suspension was shaken mechanically for 1 hour to ensure complete extraction of inorganic nitrogen forms and then filtered through Whatman No. 2 filter paper. The filtrate was collected for subsequent analysis. For the determination of exchangeable NH_4^+, a 20 mL aliquot of the KCl extract was transferred into a distillation tube. Approximately 0.2 g of magnesium oxide (MgO) was added to liberate NH_4^+ as ammonia (NH_3), and the mixture was steam-distilled for 5 minutes. The released NH_3 was captured in 10 mL of boric acid solution containing bromocresol green and methyl red mixed indicator. Following the determination of NH_4^+, NO_3^- in the same extract was reduced to NH_4^+ by adding 0.2 g of Devarda's alloy to the distillation tube. The mixture was distilled for an additional 5 minutes, and the liberated NH_3 was again trapped in boric acid indicator solution. The distillates containing NH_4^+ (from both the original ammonium and reduced nitrate fractions) were titrated with standardized 0.01 M HCl. The concentrations of exchangeable NH_4^+ and available NO_3^- in the soil were calculated based on the volume of acid consumed during titration as given in the following equation:

$$NH_4^+ / NO_3^- (mg/kg) = (V \times M \times 14.01/Vd) \times 100\% \times 10{,}000 \quad (1)$$

Where

V = Volume of 0.01 M HCl used for titration (mL)
M = Molarity of HCl solution
14.01 = Atomic mass of N
Vd = Volume of filtrate used for distillation (mL)

Measurement of soil available phosphorous

Soil available P was determined using the double acid extraction method followed by the molybdenum blue colorimetric method as described by Murphy & Riley (1962). A 5 g air-dried soil sample was weighed into a 250 mL Erlenmeyer flask, and 20 mL of the double acid extracting solution was added. The mixture was shaken mechanically at 180 rpm for 10 minutes to ensure complete extraction of available P. The suspension was then filtered through Whatman No. 2 filter paper, and the clear filtrate (supernatant) was collected for analysis. For colour development, acid molybdate stock solution (Reagent A) and ascorbic acid stock solution (Reagent B) were prepared. Phosphorus standard solutions were prepared to obtain working standards ranging from 0 to 0.6 ppm P. Aliquots of 0, 1, 2, 3, 4, 5, and 6 mL of the standard solution were pipetted into separate 50 mL volumetric flasks, followed by the addition of 8 mL of Reagent B to develop the characteristic molybdenum blue colour. The solutions were then diluted to volume with distilled water and mixed thoroughly. For the soil samples, 4 mL of the filtrate was transferred into a 50 mL volumetric flask, and 8 mL of Reagent B was added. The solution was diluted to the mark with distilled water, mixed well, and allowed to stand for full colour development. Absorbance of both standards and samples was measured at 840 nm using a UV–VIS spectrophotometer (PerkinElmer Lambda 25, USA). A standard calibration curve was constructed from the P standard solutions, and soil available P concentrations were calculated as given in the following equation:

$$P\left(\frac{\text{mg}}{\text{kg}}\right) = (\text{UV reading}) \times \left(50\frac{\text{mL}}{\text{A}}\right) \times \left(\frac{\text{B}}{\text{Wt}}\right) (2)$$

Where

A = Volume of extractant used for blue color development
B = Initial volume of extractant
Wt = Weight of sample used for extraction

Measurement of exchangeable potassium

Exchangeable K^+ were extracted using the neutral 1 M ammonium acetate (NH_4OAc) leaching method. A 10 g of air-dried soil (passed through a 2 mm sieve) was placed in a leaching tube and extracted with 100 mL of 1 M NH_4OAc (pH 7.0). The leaching process was carried out over 5 hours to ensure complete displacement of exchangeable cations by NH_4^+ ions. The leachate was collected and analyzed for exchangeable K^+ concentrations using atomic absorption spectrophotometry (AAS) (PerkinElmer AAnalyst 800, Norwalk, USA) and the cation concentration was calculated using the formula given:

$$\text{Exchangeable K}\left(\frac{\text{mg}}{\text{kg}}\right) = (\text{AAS reading}) \times \left(\frac{\text{A}}{\text{Wt}}\right) \times \text{DF} (3)$$

Where
AAS = Concentration of the extract shown by atomic absorption spectrophotometer
A = Initial volume of extractant
Wt = Weight of sample used for extraction
DF = Dilution factor

Measurement of soil cation exchange capacity

Soil cation exchange capacity (CEC) was determined by saturating the exchange complex with 1 M NH_4OAc (pH 7.0) using the same leaching procedure (Cottenie, 1980), followed by steam distillation as described by Bremner (1965). After saturation, excess NH_4OAc was removed by washing the soil sample with 30 mL of 95% ethanol to eliminate residual electrolyte and further leached with 100 mL of 0.1 M K_2SO_4. The combined leachate was collected in a 100 mL volumetric flask and diluted to volume with distilled water. A 10 mL aliquot was transferred into a distillation flask, and 10 mL of 40% NaOH was added to liberate NH_4^+ as NH_3. The mixture was steam-distilled for 5 minutes, and the evolved NH_3 was trapped in 10 mL of 2% boric acid solution containing bromocresol green and methyl red mixed indicator. The distillate was then titrated with standardized 0.01 M HCl. Soil CEC was calculated based on the amount of displaced NH_4^+ and expressed as $\text{cmol}_{(+)}\ \text{kg}^{-1}$ soil. The CEC was calculated as follows:

$$\text{CEC}\ (\text{cmol}(+))\ \text{kg} - 1 = \text{V} \times \text{M} \times \text{R} \times (1000\ \text{kg} - 1/\text{Wt})/10\ (4)$$

Where

V = Volume of HCl used for titration
M = Molarity of HCL used for titration,
R = Ratio of volume of initial leachate to the volume of leachate used for distillation
Wt = Weight of air-dried sample

Pot experiment

A pot experiment was conducted at the Nursery Unit of Universiti Putra Malaysia Sarawak (UPMS), Malaysia, to evaluate *Padi wai* growth under semi-controlled conditions. The semi-controlled system refers to paddy cultivated in pots rather than under open field conditions, enabling precise regulation of soil conditions, fertilizer application rates, and water management while minimizing environmental variability. The rice cultivar *Padi wai*, a locally important Sarawak variety, was used as the test crop. Prior to sowing, *Padi wai* seeds were surface-cleaned and soaked in distilled water for 24 h, followed by drainage and incubation for an additional 24 h to induce uniform germination. The pregerminated seeds were then sown in seedling trays filled with soil and allowed to establish under nursery conditions. Soil quantity for the pot experiment was determined based on measured bulk density and pot dimensions. Each plastic pot (45 cm top diameter × 38 cm bottom diameter × 51 cm height) was filled with 30 kg of air-dried soil. All pots were filled with soil only and allowed to equilibrate for 24 h prior to transplanting. Rice seedlings were transplanted at the 7-day growth stage, when shoots had reached approximately 8 cm in height (Fig. 1). Four uniform seedlings of *Padi wai* were transplanted into each pot. Throughout the experimental period, the water level in each pot was maintained at approximately 3 cm above the soil surface to simulate flooded (waterlogged) paddy conditions. The experiment was conducted under nursery environmental conditions (Fig. 1).

Fig. 1 Pot trial set up for assessing the effectiveness of Nutri Gard fertilizers over conventional fertilizers in *Padi wai* cultivation

Fertilizer application rates

Nutri Gard fertilizers and conventional NPK fertilizers used in this study were supplied by Hextar Fert Sdn. Bhd. and Macrotech Solutions Sdn. Bhd. Fertilizer application rates were established based on the standard nutrient recommendation for lowland rice cultivation in Malaysia, equivalent to 151 kg ha^{-1} N, 97.8 kg ha^{-1} P_2O_5, 130 kg ha^{-1} K_2O, and 7.6 kg ha^{-1} MgO (Muda Agricultural Development Authority, 2014). All fertilization treatments were applied according to the experimental design summarized in Table 1. The fertilizer rate for treatment NG1 was established at 100% of the standard recommended nutrient rate for rice cultivation. Treatment NG2 received a reduced fertilizer input, corresponding to 70% of the recommended rate (i.e., a 30% reduction relative to NG1), to evaluate the potential for improved nutrient use efficiency under lower nutrient supply. In contrast, treatment NG3 was formulated with nutrient inputs exceeding the standard recommendation, particularly with respect to K. The elevated K rate was based on the working hypothesis that increased K availability would enhance grain filling and yield performance of *Padi wai* considering the well documented role of K in carbohydrate translocation, enzyme activation, and grain development. For pot-scale application, field-recommended rates were proportionally converted to a per-hill basis to reflect the nutrient requirement of individual rice plants under controlled conditions. The conversion from hectare-based recommendations to per hill rates was calculated based on plant population density and scaled to ensure consistency with agronomic field practices while maintaining experimental precision. Fertilizers were applied according to a time specific schedule aligned with key crop growth stages, as detailed in Table 1. Soil only (S) without addition of fertilizers was used to calculate nutrient efficiency, which involves the amount of fertilizer taken up and used by plant versus the amount of fertilizer lost (Dobermann, 2005) (Table 1).

Table 1 Fertilizer regimes tested in pot experiment for *Padi wai* growth and development

Code	Fertilizers Composition (gram)
S	Control (soil only)
SF	0.55 g Urea + 0.79 ERP + 0.24 g MOP: 1st application
	0.55 g Urea + 0.79 ERP + 0.24 g MOP + 0.06 g Epsomite + ZnCu: 2nd application
NG1	2.05 g Nutri Gard (12.5 N/10.5 P/ 7 K): 1st application
	(12.5 N/10.5 P/ 7 K /0.8 MgO): 2nd to 6th application
NG2	1.44 g Nutri Gard (12.5 N/10.5 P/ 7 K): 1st application
	(12.5 N/10.5 P/ 7 K /0.8 MgO): 2nd to 6th application
NG3	2.45 g Nutri Gard (12.5 N/10.5 P/ 7 K/0.8 MgO): 1st application
	2.55 g Nutri Gard (12.5 N/10.5 P/ 17.5 K/ 1 MgO): 2nd to 6th application

Note: Fertilizer application: 1st (15 DAT), 2nd (35 DAT), 3rd (50 DAT), 4th (70 DAT), 5th (90 DAT) and 6th (133 DAT); Days of transplanting (DAT)

Fertilizer application schedules

For the standard fertilization (SF) treatment, the first fertilizer application was carried out at 15 days after transplanting (DAT), equivalent to 0.55 g urea (46% N), 0.79 g Egyptian rock phosphate (ERP), and 0.24 g muriate of potash (MOP) per hill (Table 1). Subsequent applications were performed at 35 DAT, 50 DAT, 70 DAT, 90 DAT, and 133 DAT. During the second to fifth applications, 0.06 g of Epsomite enriched with Zn and Cu (Epsomite + ZnCu) was included per hill to supply secondary and micronutrients for SF. Similarly, the fertilization schedules for NG1, NG2, and NG3 consisted of six split applications at 15 DAT, 35 DAT, 50 DAT, 70 DAT, 90 DAT, and 133 DAT. For NG1 and NG2, 0.8 g MgO was incorporated from the second to the sixth application to ensure adequate magnesium supply throughout the vegetative and reproductive growth stages. In contrast, NG3 received a higher MgO rate (1.0 g per hill) over the same application intervals, consistent with its enhanced nutrient formulation (Table 1).

Monitoring of *Padi wai* growth and development

The growth and development of *Padi wai* were monitored over a 169-day cultivation period, encompassing the vegetative, reproductive, and maturity stages. Plant height was measured at regular intervals from transplanting until physiological maturity particularly after fertilization using a standard measuring tape and mean values per treatment were calculated. In addition, phenological stages such as tillering, panicle initiation, flowering, grain filling, and maturity were recorded to evaluate crop development under different fertilization regimes. General plant vigor and tiller production were also assessed periodically. Routine field observations were conducted to monitor the occurrence and severity of pest and disease incidence throughout the growing period. Visual assessments were carried out to detect symptoms associated with common rice pests and diseases, and any signs of infestation or infection were documented. There were no serious pest or disease outbreaks observed during the experimental period, and crop growth proceeded without significant biotic constraints. The rice crop successfully reached maturity and was harvested at 169 DAT, corresponding to 36 days after the final fertilizer application at 133 DAT (Fig. 2). This ensured that grain filling and physiological maturity were completed prior to harvest.

Harvesting of the *Padi wai*

At harvest (169 DAT), *Padi wai* aboveground biomass was collected by cutting the tillers at 1.5 cm above the soil surface using a sharp stainless-steel knife. Root systems were carefully removed from each pot, manually separated from the soil, and thoroughly washed under running tap water followed by rinsing with distilled water to remove adhering soil particles. Both aboveground and belowground plant samples were oven-dried at 60 °C until a constant weight was achieved, following the method described by Selvarajh and Ch'ng (2021). The dried shoot and root samples were then finely ground using a laboratory blender. Total nutrient concentration in the plant tissues was determined using the standard procedures (Tan, 2005). Nutrients uptake by rice plants and nutrients use efficiency were subsequently calculated according to the equations proposed by Dobermann (2005) as summarized below:

$$\text{Nutrient use efficiency (\%)} = \frac{(\text{Uptake with fertilizer} - \text{Uptake without fertilizer})}{(\text{Total amount of fertilizers that was applied})} \times 100 \quad (5)$$

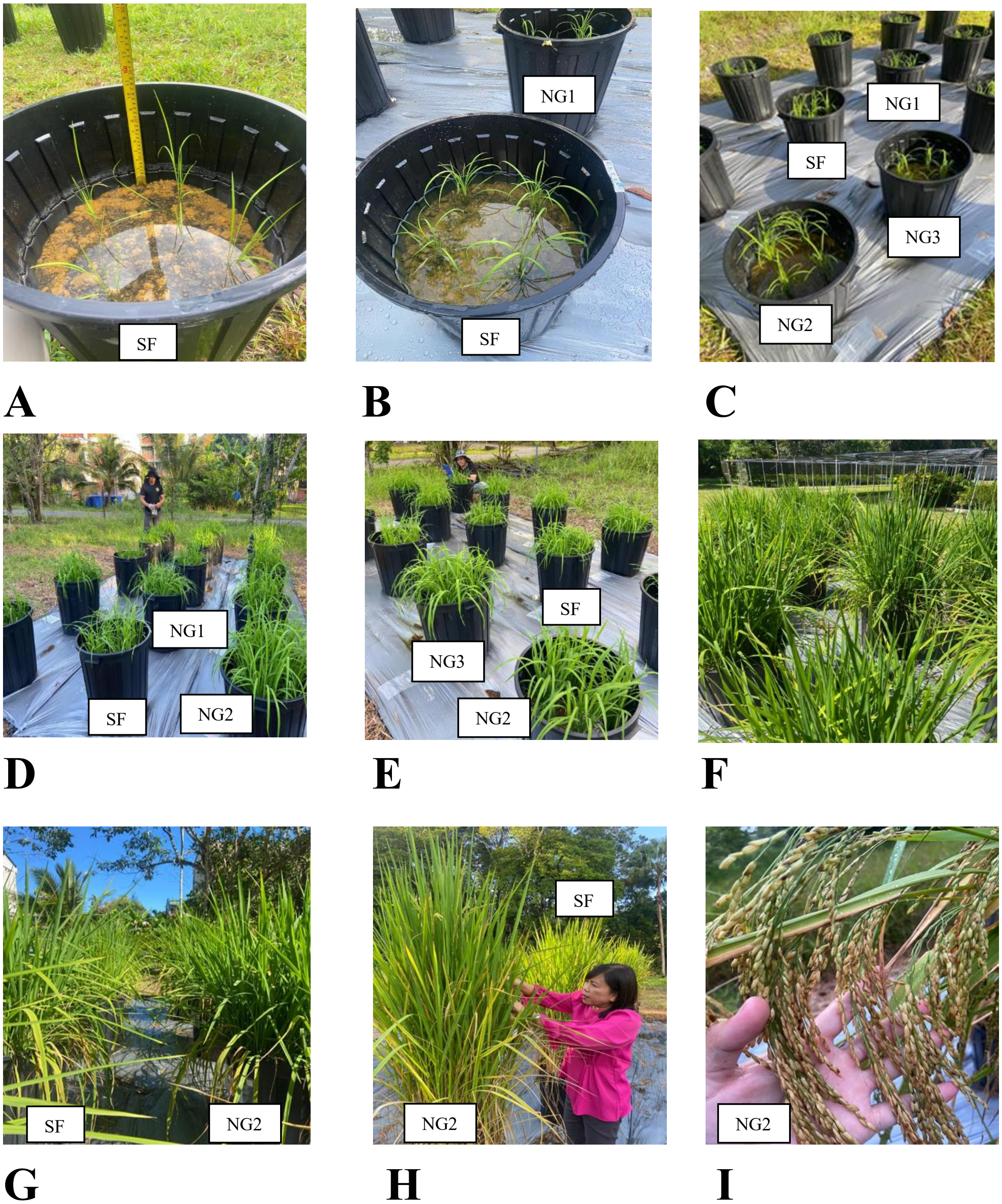

Fig. 2 *Padi wai* growth and development following applications of Nutri Gard fertilizers and conventional fertilizers (A) *Padi wai* seedlings at 7 days after sowing (SF) (B) *Padi wai* seedlings at 13 days after sowing, prior to the first application of standard fertilizer (SF) (C) First fertilization of *padi wai* performed at 15 days after transplanting (DAT) (D) Padi wai growth and developed at 30 DAT prior to second fertilization which was done on 35 DAT (E) Padi wai was monitored for pests and diseases occurring after second fertilization (F) Third fertilization done on 50 DAT (G) Fourth fertilization done on 70 DAT (H) Monitoring of *padi wai during* the flowering stage, showing panicle emergence and anthesis (I) Grain filling stage of Padi wai fertilized with Nutri Gard at 70% of the recommended rate (NG2)

Post-harvest soil nutrient retention analysis

The soil samples from pots were collected immediately upon plant harvesting. The soil was air-dried, crushed, and sieved to pass through a 2 mm sieve. Afterwards, the soil samples were analyzed for total N, available P, and exchangeable K using the method described by Tan (2005).

Experimental design

The pot experiment was arranged in a randomized complete block design (RCBD) with three replications per treatment. Pots were oriented in a North–South direction to ensure uniform sunlight exposure for all rice plants, thereby promoting consistent photosynthetic activity and growth while minimizing shading and inter-plant light competition. This orientation also facilitated standardized monitoring and treatment applications.

Statistical analysis

Data was analyzed using analysis of variance (ANOVA) to evaluate the effects of treatments. When significant differences were detected, treatment means were compared using Duncan's New Multiple Range Test (DNMRT) at a significant level of $p \leq 0.05$. All statistical analyses were performed using the Statistical Analysis System (SAS) software, version 9.4 (SAS Institute, Cary, NC, USA).

Results

Selected initial physico-chemical analyses of Bekenu Series soil

The soil texture of Bekenu Series was identified as sandy loam, containing 47.4% sand, 29.6% silt, and 23.0% clay (Table 2). The soil was acidic, with pH values of 4.01 (Table 2). Soil OM content was low with the amount of 6.43% and total C of 3.74%. Nitrogen availability was notably low, with total N at 0.24%, exchangeable NH_4^+ at 0.014 mg kg^{-1}, and available NO_3^- at 0.004 mg kg^{-1}, indicating a N-limiting condition for crop growth. Available P and exchangeable K were also limited, measured at 0.755 mg kg^{-1} and 17.32 mg kg^{-1}, respectively, reflecting the inherently low nutrients of Bekenu soils. The soil CEC was relatively low at 4.67 cmol$_{(+)}$ kg^{-1}, consistent with its sandy loam texture and indicative of limited nutrient retention capacity. Collectively, these chemical characteristics suggest that Bekenu Series soil presents constraints for nutrient availability, necessitating targeted fertilization for optimal paddy production.

Table 2 Selected initial chemical properties of Bekenu Series soil used for pot study

Properties	Mean values (± SE)
Soil texture	Sandy loam
pH	4.01 ± 0.02
Total carbon (%)	3.74 ± 0.74
Total organic matter (%)	6.43 ± 1.21
Total nitrogen (%)	0.24 ± 0.04
Exchangeable ammonium (mg kg^{-1})	0.014 ± 0.002
Available nitrate (mg kg^{-1})	0.004 ± 0.001
Available phosphorus (mg kg^{-1})	0.755 ± 0.085
Available potassium (mg kg^{-1})	17.32 ± 1.32
Cation exchange capacity (cmol$_{(+)}$ kg^{1})	4.67 ± 0.96

SE = Standard error

Growth performance and grain yield of *Padi wai*

At 169 days after planting (DAP), *Padi wai* fertilized with Nutri Gard at 70% of the recommended rate (NG2) and Nutri Gard with higher K content (NG3) showed significantly greater plant height at harvest, reaching 192 cm and 187 cm, respectively, compared with plants receiving the standard fertilizer (SF) and Nutri Gard at the full recommended rate (NG1), which recorded paddy heights of 182 cm and 183 cm, respectively (Fig. 3). Panicle weight of *Padi wai* was significantly increased under all Nutri Gard–fertilized treatments compared with the standard fertilizer (SF) (Fig. 4). Values of *Padi wai* panicle weight reached 421 g in NG1, 405 g in NG2, and 470 g in NG3, representing substantial improvements over the 297 g recorded in SF (Fig.4). A similar trend was observed for grain weight of *Padi wai* (Fig. 5). Paddy plants treated with Nutri Gard produced higher grain weights of 312 g (NG1), 347 g (NG2), and 311 g (NG3), compared with 253 g under SF. Notably, NG2 achieved the highest grain weight despite the reduced application rate, indicating improved nutrient utilization efficiency under the nano-biopolymer formulation. NG3 with high K recorded higher number of grain (23,446 grains) among all fertilization, followed by NG2 (18,062 grains), NG1 (17,195 grains), and SF (16,628 grains) (Fig. 6).

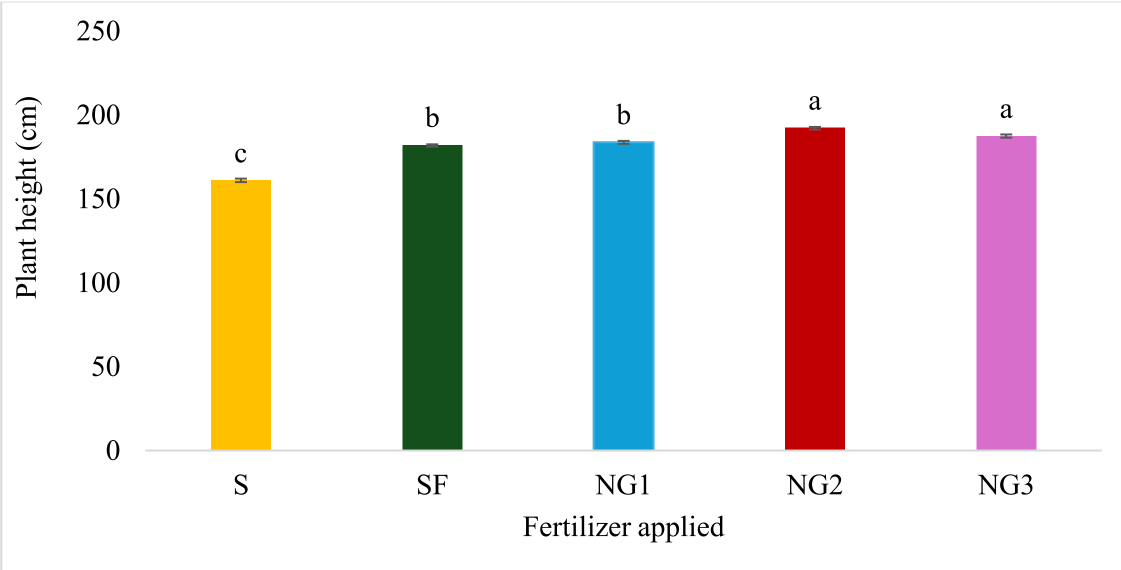

Fig. 3 *Padi wai* height at 169 days after planting following application of different fertilization. Means with different letter(s) indicate significant differences between treatments according to Tukey's Test at $P \leq 0.05$. Bars represent the mean values ± standard error of triplicates. S is soil only, SF is standard fertilizer, NG1 is Nutri Gard fertilizer applied at 100%, NG2 is Nutri Gard applied at 70%, NG3 is Nutri Gard with high K content.

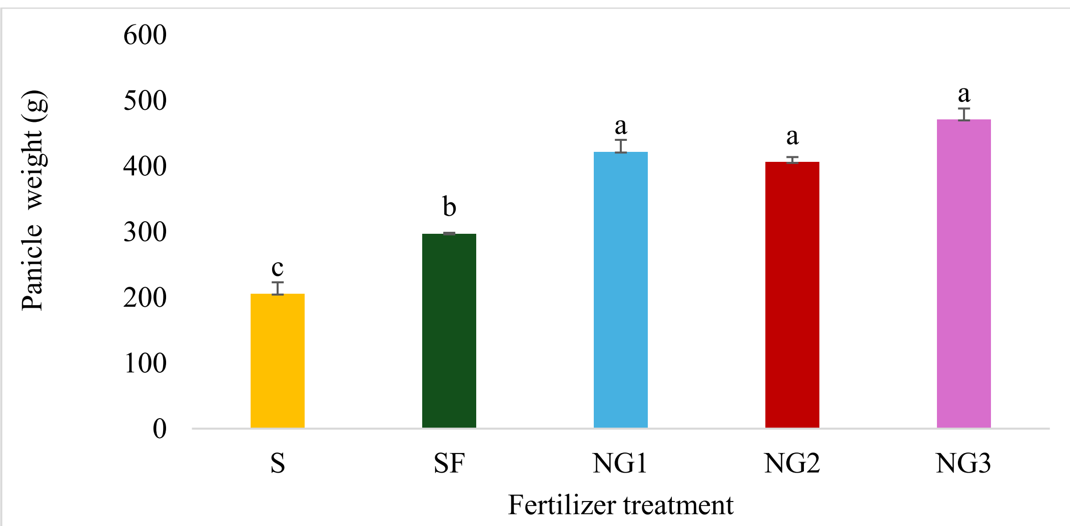

Fig. 4 Panicle weight of *Padi wai* at 169 days after planting following application of different fertilization. Means with different letter(s) indicate significant differences between treatments according to Tukey's Test at $P \leq 0.05$. Bars represent the mean values ± standard error of triplicates. S is soil only, SF is standard fertilizer, NG1 is Nutri Gard fertilizer applied at 100%, NG2 is Nutri Gard applied at 70%, NG3 is Nutri Gard with high K content.

Nitrogen, phosphorus, and potassium use efficiency of *Padi wai*

All Nutri Gard fertilized treatments significantly enhanced N use efficiency compared with the standard fertilizer (SF) (Fig. 7). The highest N use efficiency was observed in NG3 with N use efficiency of 18%, followed closely by NG2 (16%) and NG1 (10%), whereas SF recorded only 4% N use efficiency (Fig. 7). For P, Nutri Gard applied at 100% (NG1) and 70% (NG2) significantly improved P use efficiency to 19% and 28%, respectively, compared with 13% under SF (Fig. 6). The high-K formulation (NG3) did not enhance P use efficiency, as no significant difference was detected between NG3 and SF (Fig. 8). All Nutri Gard–fertilized treatments significantly enhanced K use efficiency compared with the standard fertilizer (SF) (Fig. 9). The highest K use efficiency was recorded in NG2 (68%), followed by NG1 (46%) and NG3 (35%), whereas SF achieved only 24% (Fig. 9).

Post-harvest soil total nitrogen, phosphorus, and potassium

Following harvest at 169 days after *Padi wai* planting, soils treated with Nutri Gard formulations (NG1-NG3) retained substantially higher total N compared with the standard fertilizer (SF) treatment. Total N concentrations were 0.42%, 0.40%, and 0.34% in NG1, NG2, and NG3, respectively, whereas SF recorded only 0.21% (Fig. 10). Similarly, available P levels remained elevated in soils receiving Nutri Gard treatments, with concentrations of 603 ppm (NG1), 624 ppm (NG2), and 521 ppm (NG3), all exceeding the 497ppm observed under SF (Fig. 11). In contrast, post-harvest exchangeable K showed a more moderate response. Soil K concentrations were slightly higher in NG1 (24 ppm) and NG3 (27 ppm) compared with SF (23 ppm), while NG2 (70% application rate) resulted in comparable K levels to SF (Fig. 10). These findings suggest that although reduced-rate application (NG2) maintained soil N and P effectively, NG2 did not enhance residual K retention relative to the conventional fertilization treatment (Fig. 12).

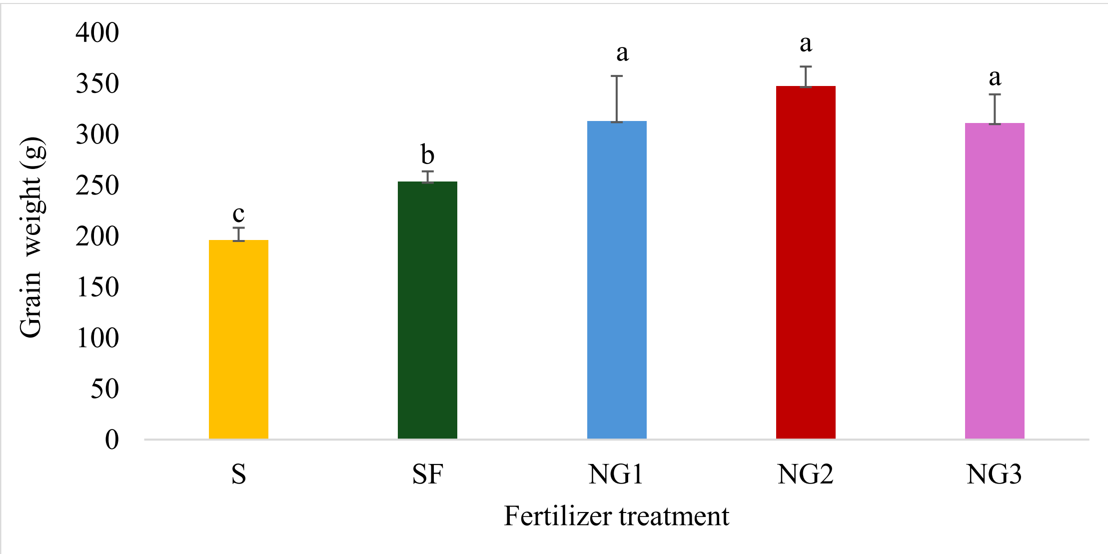

Fig. 5 Grain weight of *Padi wai* at 169 days after planting following application of different fertilization. Means with different letter(s) indicate significant differences between treatments according to Tukey's Test at P ≤ 0.05. Bars represent the mean values ± standard error of triplicates. S is soil only, SF is standard fertilizer, NG1 is Nutri Gard fertilizer applied at 100%, NG2 is Nutri Gard applied at 70%, NG3 is Nutri Gard with high K content.

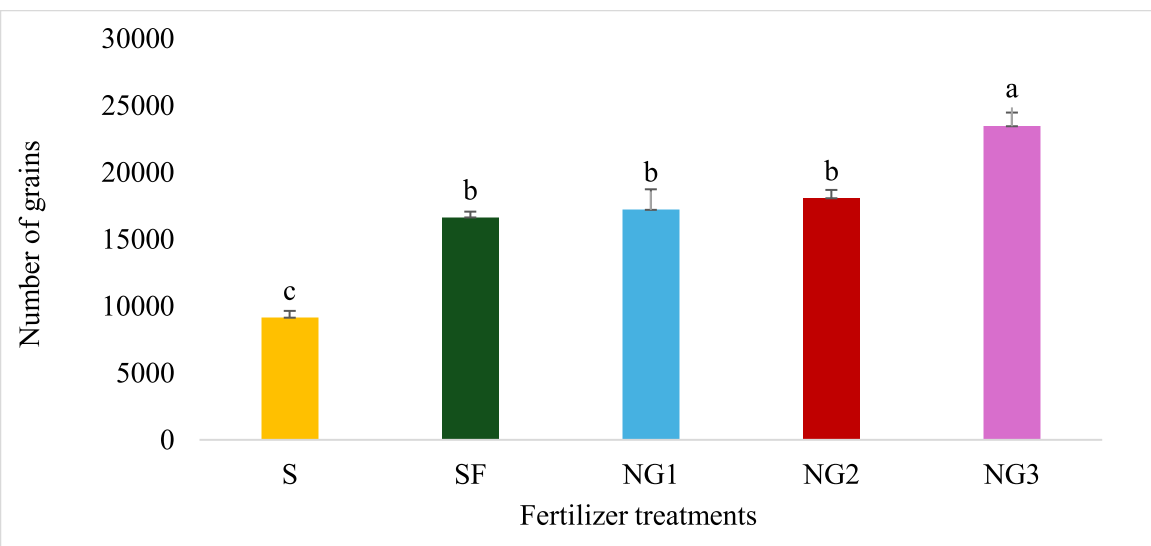

Fig. 6 Number of grains of *Padi wai* at 169 days after planting following application of different fertilization. Means with different letter(s) indicate significant differences between treatments according to Tukey's Test at P ≤ 0.05. Bars represent the mean values ± standard error of triplicates. S is soil only, SF is standard fertilizer, NG1 is Nutri Gard fertilizer applied at 100%, NG2 is Nutri Gard applied at 70%, NG3 is Nutri Gard with high K content

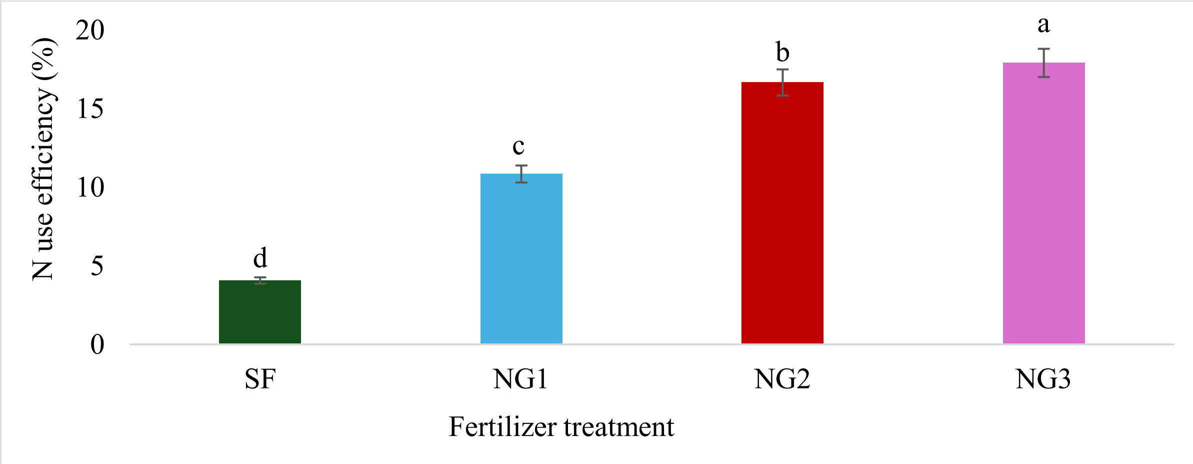

Fig. 7 Nitrogen use efficiency following application of different fertilization. Means with different letter(s) indicate significant differences between treatments according to Tukey's Test at $P \leq 0.05$. Bars represent the mean values ± standard error of triplicates. S is soil only, SF is standard fertilizer, NG1 is Nutri Gard fertilizer applied at 100%, NG2 is Nutri Gard applied at 70%, NG3 is Nutri Gard with high K content.

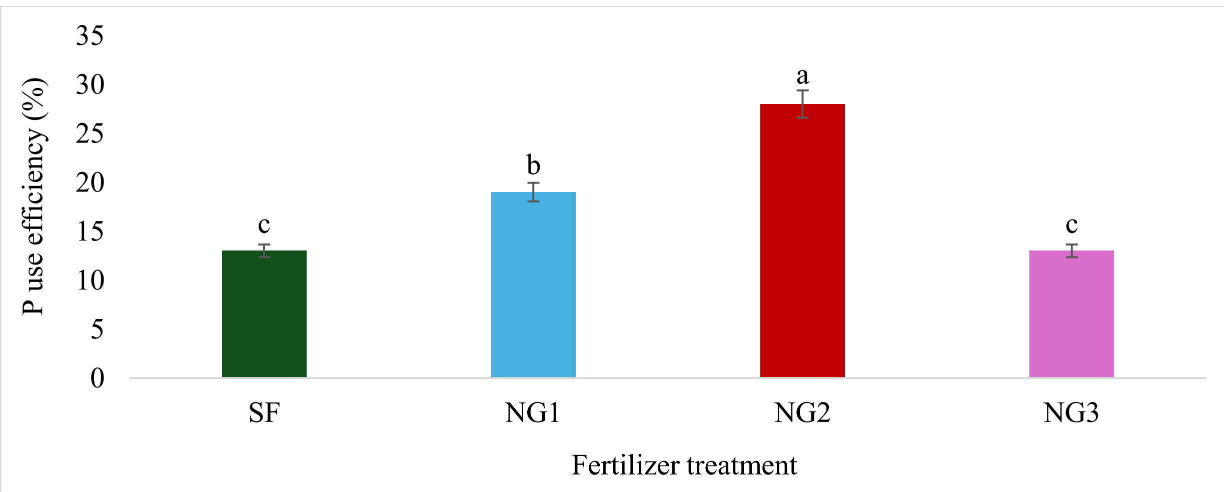

Fig. 8 Phosphorus use efficiency following application of different fertilization. Means with different letter(s) indicate significant differences between treatments according to Tukey's Test at $P \leq 0.05$. Bars represent the mean values ± standard error of triplicates. S is soil only, SF is standard fertilizer, NG1 is Nutri Gard fertilizer applied at 100%, NG2 is Nutri Gard applied at 70%, NG3 is Nutri Gard with high K content.

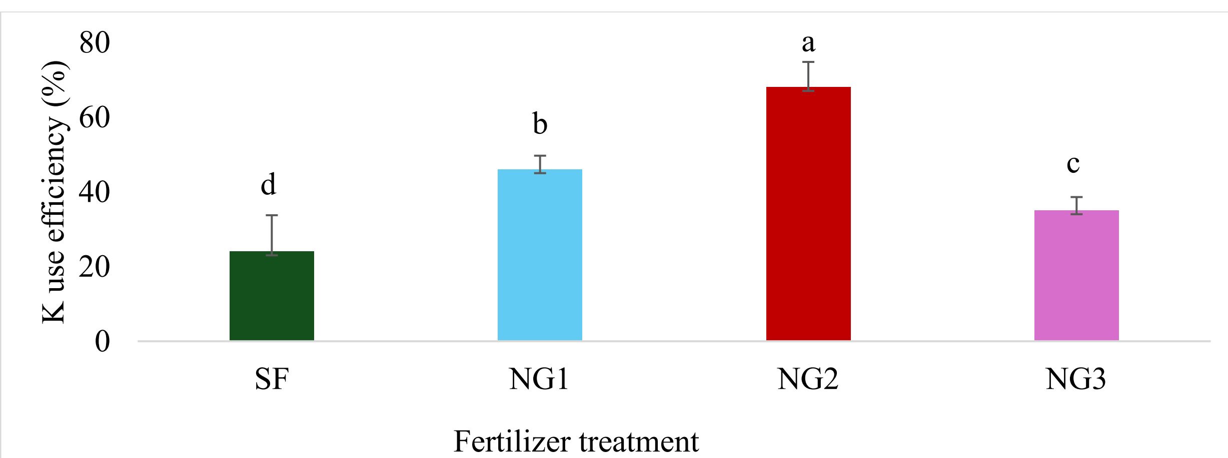

Fig. 9 Potassium use efficiency following application of different fertilization. Means with different letter(s) indicate significant differences between treatments according to Tukey's Test at $P \leq 0.05$. Bars represent the mean values ± standard error of triplicates. S is soil only, SF is standard fertilizer, NG1 is Nutri Gard fertilizer applied at 100%, NG2 is Nutri Gard applied at 70%, NG3 is Nutri Gard with high K content.

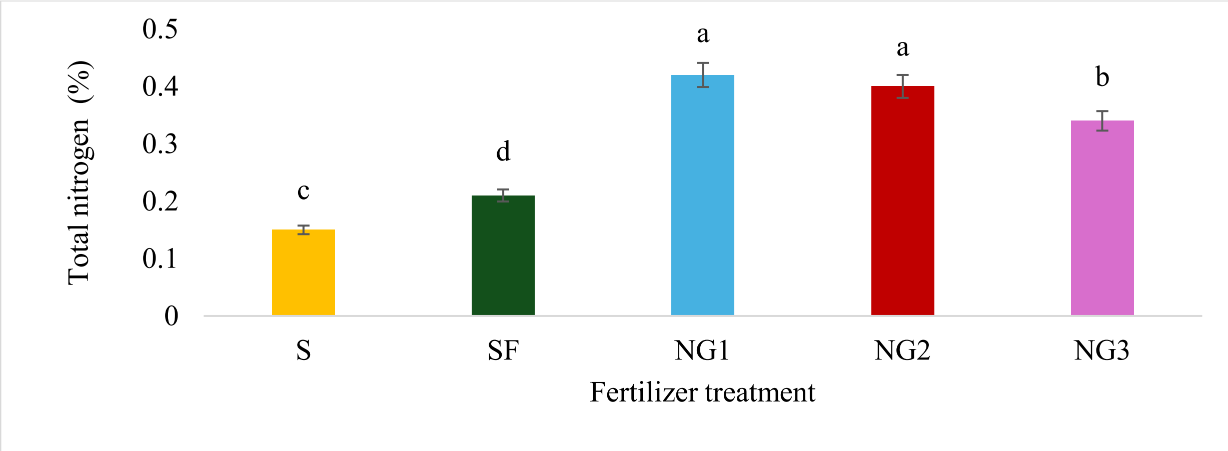

Fig. 10 Total nitrogen retained in soil following application of different fertilization. Means with different letter(s) indicate significant differences between treatments according to Tukey's Test at $P \leq 0.05$. Bars represent the mean values ± standard error of triplicates. S is soil only, SF is standard fertilizer, NG1 is Nutri Gard fertilizer applied at 100%, NG2 is Nutri Gard applied at 70%, NG3 is Nutri Gard with high K content.

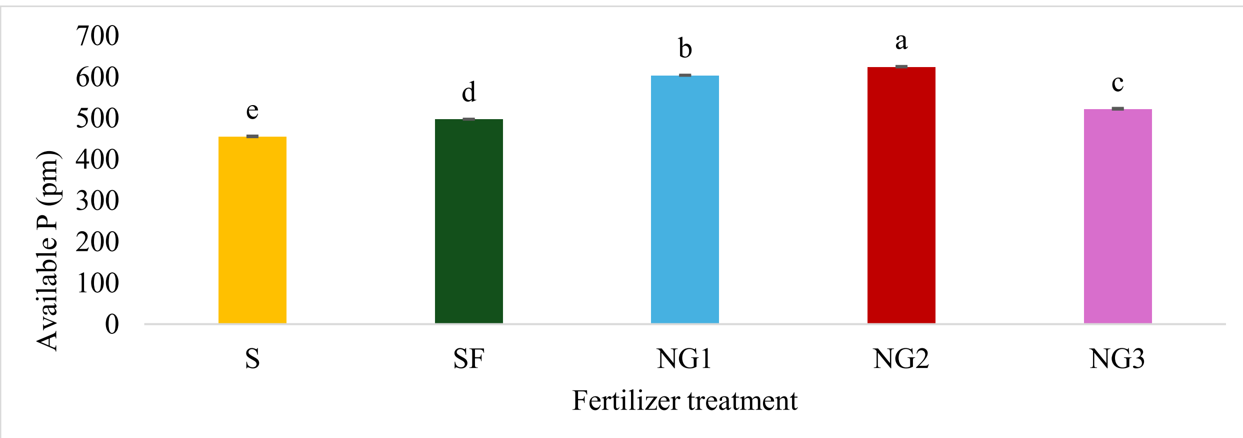

Fig. 11 Available phosphorus remained in soil following application of different fertilization. Means with different letter(s) indicate significant differences between treatments according to Tukey's Test at $P \leq 0.05$. Bars represent the mean values ± standard error of triplicates. S is soil only, SF is standard fertilizer, NG1 is Nutri Gard fertilizer applied at 100%, NG2 is Nutri Gard applied at 70%, NG3 is Nutri Gard with high K content.

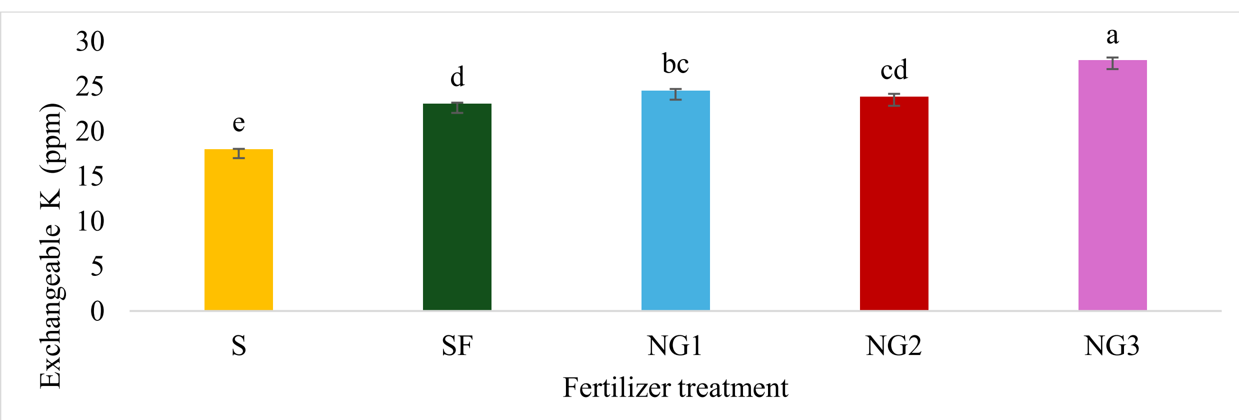

Fig. 12 Exchangeable potassium retained in soil following application of different fertilization. Means with different letter(s) indicate significant differences between treatments according to Tukey's Test at $P \leq 0.05$. Bars represent the mean values ± standard error of triplicates. S is soil only, SF is standard fertilizer, NG1 is Nutri Gard fertilizer applied at 100%, NG2 is Nutri Gard applied at 70%, NG3 is Nutri Gard with high K content.

Discussion

Initial characterization of Bekenu Series soil

The texture of Bekenu Series soil used in a pot study was sandy loam soils which characterized by a predominance of sand particles (47.4% sand) with moderate amounts of silt (29.6% silt) and clay (23.0% clay) (Table 2). According to Li et al. (2021), the sandy loam soil texture significantly constrains water and nutrient retention capacity, thereby impeding the sustainability of year-round agricultural production. From a soil fertility and nutrient retention perspective, sandy loam often presents inherent constraints that can classify it as low fertile as indicated by acidic nature (4.01), low OM content (6.43%) and poor C content (3.74%) (Table 2). The acidic nature of Bekenu Series is a typical of highly weathered tropical soils that are strongly leached, nutrient-depleted, and dominated by sesquioxides (Shamshuddin & Anda, 2012). Low OM content of the Bekenu Series soil used in this study limits nutrient storage and biological nutrient cycling. In addition, low total N (0.24%), exchangeable NH_4^+ (0.014 mg kg^{-1}), and available NO_3^- (0.004 mg kg^{-1}), available P (0.755 mg kg^{-1}), and exchangeable K (17.32 mg kg^{-1}) levels (Table 2), resulting in very low fertility status and corresponding low N, P, and K availability for *Padi wai* growth and development. As a result, farming systems in such soil become highly dependent on fertilizer applications. Sandy loam soils typically have low CEC values as reflected in this study with 4.67 $cmol_{(+)}$ kg^1) CEC (Table 1) due to limited clay and organic matter content, which results in fewer negatively charged sites to bind nutrient ions. As a result, applied nutrients are more prone to leaching beyond the root zone, especially under heavy rainfall or irrigation. This low nutrient-holding capacity directly reduces the soil effective fertility especially using conventional fertilization. Due to low soil productivity, the area under rice cultivation in Malaysia has decreased from 700,000 ha in 2018 to 647,900 ha in 2021 (Department of Statistics Malaysia, 2021).

Despite of low soil productivity such as the Bekenu Series, the Sarawak government has set a strategic goal to achieve rice self-sufficiency by year 2030, focusing on 14,000 hectares of paddy granaries through modern, high-tech, and commercialized farming systems (Department of Agriculture, Sarawak, 2022). Central to this initiative are the implementation of the large-scale smart paddy field programs, extensive mechanization supported by a RM60 million budget for 2025, and the local production of fertilizers and seeds to reduce dependence on imports. These integrated approaches aim to enhance productivity, optimize resource use, and ensure sustainable rice production in the state (Department of Agriculture, Sarawak, 2022). To address low soil productivity, the federal government implements a fertilizer subsidy programme that provides two types of fertilizers per hectare per season such as 12 bags of compound fertilizer and four bags of urea. The subsidy is allocated for a maximum of 10 hectares per farmer per season to support improved nutrient management and enhance rice production efficiency (World Bank Group and Ministry of Economic Affairs, 2019). Although fertilizer subsidy programmes are designed to support farmers and enhance rice yields, fixed input allocations such as standardized quantities per hectare may unintentionally encourage over application when fertilizer use is not aligned with site specific soil nutrient status or crop demand. In such cases, farmers may apply the full subsidized amount regardless of actual field requirements, leading to nutrient imbalances, reduced nutrient use efficiency, and increased losses through leaching, runoff, and volatilization. According to Hou et al. (2022), China accounts for nearly 30% of global fertilizer consumption, a disproportionately high share given that it contains only about 9% of the world's arable land. Although the extensive use of chemical fertilizers has significantly strengthened national food security, excessive application has increasingly resulted in declining marginal productivity and reduced agronomic efficiency (Wu & Ge, 2019). Thus, it is important to adopt smart fertilizers such as Nutri Gard in rice production to enhance nutrient use efficiency while minimizing environmental losses. The effectiveness of the smart Nutri Gard fertilizer in enhancing *Padi wai* growth performance and nutrient use efficiency is elaborated in the following section. Particular emphasis is placed on its capacity to synchronize nutrient release with crop demand, thereby improving *Padi wai* vegetative growth, reproductive development, and yield formation. In addition, the analysis evaluates its influence on N, P, and K use efficiencies relative to conventional fertilization. By integrating growth, yield, and nutrient recovery parameters, this section elucidates the agronomic and environmental advantages of optimized smart fertilizer application in sustainable paddy production systems.

Growth and development performance and grain yield of *Padi wai*

When applied at optimized rates based on crop requirements and soil conditions, Nutri Gard improves the growth of *Padi wai* as summarized in Fig. 3-6. The higher *Padi wai* height in all Nutri Gard fertilized treatments particularly in NG2 (70% application rate) than *Padi wai* height in SF (Fig. 3) suggests that reducing the application rate of Nutri Gard (NG2) or optimizing its nutrient composition can enhance vegetative growth, particularly plant height, relative to conventional fertilizer practices (Fig. 3). In addition, the greater values of panicle and grain weights as affected by Nutri Gard fertilized treatments indicate that Nutri Gard primarily enhanced post-anthesis processes rather than sink formation. The increased panicle weight (Fig. 4) and grain weight (Fig. 5) suggests improved grain filling efficiency, seemingly attributed to the nano-biopolymer matrix infused within the fertilizer formulation (NG1-NG3). According to Karunakaran and Ramakrishna (2023), nano-biofertilizers applied at relatively low rates compared with conventional fertilizers; however, their potential to enhance crop productivity, promote biofortification, and strengthen tolerance to both abiotic and biotic stresses is considerable. These attributes underscore their strategic importance in advancing sustainable agricultural systems (Karunakaran & Ramakrishna, 2023).

Nutri Gard fertilizer used in this study is developed using nano biopolymers derived from crop-based materials, engineered at the nanoscale to create advanced biopolymeric systems with precisely tailored physicochemical properties (Yang et al., 2020). The effectiveness of nano bio polymer fertilizer such as Nutri Gard in enhancing *Padi wai* growth is possible as reported in recent research indicates that nanoscale materials, owing to their unique physicochemical properties, are readily absorbed by plant roots and foliage and are more efficiently assimilated within plant tissues. This enhanced uptake and utilization not only improves crop performance but also supports the development of more efficient, smart, and sustainable agricultural systems (Kalia et al., 2019; Shao et al., 2022). In a study of Akhtar et al. (2022), the effectiveness of nano fertilizers is related to the mode of action such as once applied, nano fertilizers are absorbed by crop plants in the rhizosphere through endocytosis, plasmodesmata, or with the help of carrier proteins. The nutrients are then transported through symplastic and apoplastic pathways (Akhtar et al., 2022). Whereas Tarafdar (2020) stated that the application of nano fertilizers ensures slow availability, resolves the issue of low fertilizer use efficiency, and allows the release of active ingredients to meet plant nutrient demands. As a result, the nano-biopolymer in Nutri Gard may have facilitated sustained nutrient availability during the critical grain-filling stage, thereby enhancing assimilate translocation and nutrient uptake efficiency. In addition, Nutri Gard appears to improve *Padi wai* yield by optimizing nutrient delivery to developing grains rather than increasing grain number per panicle as evidence by slight insignificant different in number of grains among SF, NG1, and NG2 (Fig. 6). The effectiveness of Nutri Gard fertilizer in improving *Padi wai* yield is consistent with the research on smart fertilizer technologies. For example, Sutardi et al. (2025) reported that smart fertilizers with ameliorant-based NPK coatings significantly improved rice yield and quality. The similarity lies in the use of advanced formulation strategies such as ameliorants or nano biopolymers that enhance nutrient retention in the soil and optimize temporal nutrient release patterns. These strategies have consistently been shown to increase soil nutrient use efficiency, reduce environmental nutrient losses, and translate into measurable yield improvements under paddy cultivation. In related study of rice production, Poudel et al. (2023) reported a substantial increase in grain yield of approximately 48.9%, accompanied by significant enhancements in multiple quality parameters. Poudel et al. (2023) demonstrated comparable improvements, highlighting the effectiveness of the applied treatments using nano fertilizers.

Nutrient use efficiency of *Padi Wai*

Based on the recorded nutrient use efficiencies as previously described in Fig. 7-9, Nutri Gard treatments markedly outperformed the standard fertilizer (SF). In NG1, N, P, and K use efficiencies were 10%, 19%, and 46%, respectively, while NG2 (70% application rate) achieved even higher efficiencies of 16%, 28%, and 68% (Fig. 7–9). In contrast, SF exhibited substantially lower efficiencies, with only 4% for N, 13% for P, and 24% for K. These results indicate that the nano-biopolymer infused Nutri Gard fertilizer enhances nutrient utilization by mitigating rapid nutrient hydrolysis and minimizing soil nutrient losses. The biopolymer matrix seemingly functions as a protective barrier that modulates nutrient release kinetics, thereby improving synchronization between nutrient availability and crop demand while reducing leaching losses. Notably, NG2 achieved the highest N, P, and K use efficiencies despite being applied at a reduced rate, demonstrating that optimized nano-biopolymer formulation can enhance nutrient recovery efficiency while lowering fertilizer input. This finding underscores the potential of Nutri Gard as a resource-efficient and environmentally sustainable fertilization strategy for paddy cultivation. The findings of this study were in line with the study of Zulfiqar et al. (2019) who reported improvement in nutrient use efficiency associated with a significant feature of nano fertilizers that facilitate a controlled and gradual release of nutrients. The authors highlighted the size of nanoparticles plays a vital role in their increased and effective uptake by plants (Zulfiqar et al., 2019). Based on this finding, it is worth to note that for optimal plant response, it is essential to provide plants with the appropriate types and forms of nutrients. Nano fertilizers possess crucial attributes, with the expansive surface area of the nanoparticles playing a pivotal role in effectively retaining a surplus of nutrients (Bongiwe et al., 2022). Moreover, they facilitate a controlled and gradual nutrient release that aligns with the requirements of the plants. The plants are highly selective in their nutrient uptake, so the use of an appropriate nano formulation is necessary.

Padi wai grown in Nutri Gard at 100% and 70% rates (N1 and N2) help to synchronize N, P, and K availability in soil (Fig. 8-10), thus improve N, P, and K efficiency as corroborated by the higher N, P, and K use efficiency than standard fertilizer (Fig. 7-9). These findings suggest that Nutri Gard with innovative fertilizer formulations offer practical agronomic benefits for rice production systems. A study by Poudel et al. (2023) demonstrated that applying 100% nitrogen–potassium (NK) combined with 75% of the recommended dose of nano-phosphorus (P), supplemented with two foliar applications of nano-P, achieved a 25% reduction in phosphorus requirements compared with conventional diammonium phosphate (DAP) application. Similarly, Deo et al. (2022) reported that a regime consisting of 50% P, 100% N-K, root dipping, and two foliar sprays of nano-DAP at 20–25 and 45–50 days after transplanting enhanced nutrient use efficiencies and overall crop production.

Mejias et al. (2021) demonstrated that foliar application of nano-nitrogen (N) and nano-phosphorus (P) enables more precise management of these nutrients and reducing N losses to the environment and minimizing P immobilization in the soil. According to Hong et al. (2021), the use of nano fertilizers not only has the potential to improve crop productivity but also enhances soil fertility. Moreover, this innovative approach can lower environmental pollution and create a more favourable environment for soil microbial activity (Hatami et al., 2016).

The NG3, which contains a comparatively higher K concentration, exhibited lower P and K use efficiency, despite increased fertilizer input. The excessive K supply seemingly induced luxury consumption, where paddy plants absorbed K beyond their physiological requirement without translating this uptake into proportional P and K use efficiency. Such imbalanced nutrient uptake may also interfere with the absorption of other essential nutrients, particularly N thereby reducing overall fertilizer efficiency. Furthermore, the higher application rate associated with NG3 increased nutrient availability beyond the crop's effective utilization capacity, resulting in diminishing returns and lower P and K use efficiency compared with NG1 and NG2. This suggests that simply increasing nutrient concentration, especially K, does not necessarily enhance paddy productivity and may instead compromise nutrient synchronization with crop demand. In contrast, NG2, applied at 70% of the standard recommended rate, demonstrated promising effects on paddy growth performance, nutrient use efficiency and paddy yield. This finding highlights the improved nutrient use efficiency achieved through optimized nutrient balance and controlled-release characteristics of the formulation. The ability of NG2 to maintain or enhance yield at a reduced application rate suggests more effective nutrient retention and gradual nutrient release, enabling better alignment with the paddy growth cycle. Overall, these results emphasize that optimized nutrient ratios and application rates are more critical for maximizing fertilizer use efficiency than higher nutrient inputs. NG2 represents a more efficient and sustainable fertilization strategy, achieving superior yield performance while reducing fertilizer input by 30%, thereby offering both agronomic and environmental advantages over NG1 and NG3.

Nutri Gard fertilizer was more effective than conventional compound fertilizer in retaining soil total N, and P but not K (Fig. 12) throughout the cropping period. Soils treated with Nutri Gard consistently showed higher residual nutrient levels, suggesting reduced N losses through leaching and volatilization, which are commonly associated with conventional fertilizer applications (Latifah et al., 2021). Conventional fertilizer application methods are still not efficient enough and result in a significant amount of fertilizer being lost in the environment without benefiting the plants. Nanomaterials are more efficient than traditional fertilizers, but they must be applied in low quantities to avoid harmful effects on the environment. This enhanced nutrient retention is attributed to the nano-biopolymer matrix in Nutri Gard that regulates nutrient release and improves N and P and soil interactions. Importantly, the improved availability of soil N and P under Nutri Gard treatments corroborated the higher nutrient use efficiency observed in paddy, particularly in NG2 where Nutri Gard was applied at a 30% reduced rate. Despite lower fertilizer input, NG2 maintained sufficient N and P availability in the soil to support plant uptake, indicating more efficient synchronization between nutrient release and crop demand. This finding demonstrates that reduced-rate Nutri Gard application can optimize N and P utilization, minimize excessive nitrate and phosphate, and enhance fertilizer efficiency compared to conventional fertilization practices, thereby supporting more sustainable paddy production systems. In a study of using controlled released fertilizer, Wang et al. (2025) demonstrated that the application of controlled-release fertilizer promoted more balanced paddy growth and greater biomass accumulation by maintaining adequate N availability during the vegetative and early reproductive stages, a finding that is consistent with and supports the enhanced growth performance observed in the present study.

Enhanced nutrient retention within the soil matrix as affected by Nutri Gard fertilized treatments with total N of 0.42% remained in NG1, 0.40% remained in NG2, and 0.34% remained in NG3 compared to 0.21% total N in SF. Whereas for P, SF indicated lower amount with 417 ppm available P compared to 521 ppm in NG3, 603 ppm in NG1, and 624 ppm in NG2. Exchangeable K were higher in NG3 (27 ppm) and in NG1 (25 ppm) than SF (23 ppm). The higher nutrients retention in Nutri Gard fertilized treatments resulted in improved nutrient availability throughout the crop growth period, leading to superior paddy growth performance in paddy fertilized with Nutri Gard relative to conventional fertilizers (Fig. 10 and 11). These findings highlight Nutri Gard's potential as an efficient and environmentally sustainable fertilizer strategy for rice cultivation. In line with the findings of the present study, Zhu et al. (2025) reported that specialty fertilizers with controlled- and slow-release properties enhance nutrient uptake by minimizing nutrient losses, thereby improving overall fertilizer use efficiency and plant performance.

Conclusion

Based on the significant effects on paddy height, panicle weight, and grain weight, Nutri Gard can be effectively applied at a 30% reduced application rate (70% of the recommended dosage) without compromising crop performance compared to conventional fertilizer. The optimized lower input did not only enhanced growth and yield attributes but also improved nutrient use efficiency, thereby demonstrating Nutri Gard fertilizer capacity to reduce fertilizer inputs and associated production costs while sustaining or enhancing rice productivity. This efficiency-driven reduction suggests that Nutri Gard fertilizer has a potential as a cost-effective and resource-efficient fertilizer strategy for sustainable rice cultivation. Post-harvest soil nutrients retention suggest that

Nutri Gard effectively protects fertilizer nutrients from rapid hydrolysis and premature losses in the soil environment. The infusion of nano-biopolymer matrices within the fertilizer formulation provides a protective mechanism that regulates nutrient release, thereby minimizing leaching and enhancing nutrient retention in the soil system. As a results of improved nutrient availability and sustained release dynamics, Nutri Gard (NG2) significantly enhanced paddy growth performance compared with conventional fertilizer formulation (SF).

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Availability of data and materials: All data generated or analyzed during this study are included in this published article and its supplementary materials.

Declarations

i. Ethics approval and consent to participate: This study did not involve human participants, human data, or animal studies; therefore, ethical approval was not required.

ii. Competing interests: The authors declare that there is no conflict of interest regarding the publication of this manuscript.

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