International Journal of Agriculture and Biosciences 2026 15(4): 1700-1708.
https://doi.org/10.47278/journal.ijab/2026.079

RESEARCH ARTICLE
eISSN: 2306-3599; pISSN: 2305-6622

PGPR-Driven Enhancement of Forage Traits in Pakchong, Biograss and Dwarf Napiergrass for Sustainable Livestock Feeding

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ABSTRACT

The increasing demand for high-quality forage under land use constraints necessitates sustainable strategies to enhance productivity and nutritional value. This study investigates the effects of Plant Growth-Promoting Rhizobacteria (PGPR) on the morphological traits, yield, fiber composition, and digestibility of three elephant grass varieties: Pakchong (*Pennisetum purpureum* cv. Pakchong), Biograss (*Pennisetum purpureum* cv. Biograss), and Dwarf Napiergrass (*Pennisetum purpureum* cv. Mott). PGPR was applied at varying levels to evaluate its impact on grass morphology and nutritional quality. Results revealed that PGPR significantly improved morphological parameters, including plant height, leaf area, and stem diameter, thereby increasing dry matter (DM) yield. PGPR also reduced fiber fractions, including Acid Detergent Fiber (ADF), Neutral Detergent Fiber (NDF), cellulose, and lignin, which are negatively correlated with forage digestibility. Enhanced digestibility was observed in vitro DM digestibility (IVDMD), in vitro organic matter digestibility (IVOMD), in vitro ADF digestibility (IVADFD), in vitro NDF digestibility (IVNDF), in vitro cellulose digestibility (IVCD), and in vitro lignin digestibility (IVLD), with optimal responses varying across grass types and PGPR levels. With its high biomass potential and adaptability to marginal soils, *Pennisetum purpureum* benefits significantly from PGPR application, making it a strategic resource for livestock feed and bioenergy. In conclusion, PGPR is a growth booster and an environmentally friendly approach to improving forage quality and productivity, particularly in land-limited agricultural systems. Its integration into forage cultivation supports sustainable intensification and contributes to resilient livestock feeding strategies.

Keywords: Dry matter yield, Growth booster, Marginal land, *pennisetum purpureum,* Plant Growth-Promoting Rhizobacteria.

Article History
Article # 26-001
Received: 01-Jan-26
Revised: 13-Feb-26
Accepted: 20-Feb-26
Online First: 28-Mar-26

INTRODUCTION

Forage grasses are a cornerstone of ruminant livestock nutrition, providing essential fiber, energy, and protein for optimal livestock performance. However, the increasing scarcity of arable land due to urbanization and industrial expansion has posed significant challenges to the availability of high-quality forage (Desta, 2022; Wahyudin et al., 2023). In response, sustainable intensification strategies are needed to enhance forage productivity and nutritional value without expanding land use.

Cite this Article as: Utamy RF, Ako A, Baba S, Zulkharnaim Z, Gustina S, Alhamd L, Indrawirawan I, Khasanah AUN, Ramadan Z, Mufliha R, Rahman AA, Mutfaidah A, Figri M and Nurbina AF, 2026. PGPR-driven enhancement of forage traits in pakchong, biograss, and dwarf napiergrass for sustainable livestock feeding. International Journal of Agriculture and Biosciences 15(4): 1700-1708. https://doi.org/10.47278/journal.ijab/2026.079

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One promising approach is the application of Plant Growth-Promoting Rhizobacteria (PGPR), a group of beneficial soil microorganisms that colonize the rhizosphere and stimulate plant growth through various mechanisms. PGPR enhances nutrient uptake, produces phytohormones such as auxins and gibberellins, suppresses soil-borne pathogens, and improves soil health (Vocciante et al., 2022; Sharma et al., 2023). These functions contribute to improved plant morphology, increased biomass and enhanced forage quality, making PGPR a viable alternative to chemical fertilizers (Lacava et al., 2022; Patwardhan et al., 2022; He et al., 2023).

Recent studies have demonstrated that PGPR can maintain forage biomass and quality even when nitrogen fertilizer rates are reduced, indicating their potential to lower chemical inputs while sustaining productivity (Buckley et al., 2019). Moreover, PGPR treatments have been shown to improve fiber composition—such as reductions in acid detergent fiber (ADF) and neutral detergent fiber (NDF)—and increase crude protein (CP) content under varying environmental conditions.

Among tropical forage grasses, Pakchong (*Pennisetum purpureum* cv. Pakchong), Biograss (*Pennisetum purpureum* cv. Biograss), and Dwarf Napiergrass (*Pennisetum purpureum* cv. Mott) are widely cultivated due to their adaptability, rapid growth, and suitability for ruminant feeding. However, these cultivars differ in morphological traits, fiber structure, and digestibility, which influences their nutritional value and efficiency as livestock feed. Understanding the interaction between PGPR and these genotypes is essential to optimize their agronomic and nutritional performance.

This study aims to evaluate the effects of PGPR on the morphological characteristics, fiber composition, and digestibility of Pakchong, Biograss, and Dwarf Napiergrass. By comparing morphological responses to PGPR treatment, the research seeks to identify sustainable strategies to improve forage quality and support resilient livestock production systems.

MATERIALS & METHODS

This research was conducted in Tanete Riaja Village, Barru Regency, South Sulawesi. The temperature during the research ranged from 24 to 33˚C, and the humidity ranged from 57 to 90%. Feed quality testing was conducted at the Dairy Nutrition Laboratory of the Faculty of Animal Science, IPB University.

This study used a completely randomized design factorial pattern with two factors. The first factor was the variety of *Pennisetum purpureum* (V), which includes Pakchong, Biograss, and Dwarf napiergrass. The second factor was the level of PGPR: 0 kg/ha (T0), 100 kg/ha (T1), 200 kg/ha (T2), 300 kg/ha (T3), and 400 kg/ha (T4). This dosage is based on the use of commercial fertilizer on elephant grass, which ranges from 100 to 400kg/hectare (Wastiti et al., 2022). There were 15 treatment combinations, each repeated 10 times, for a total of 150 trial units. PGPR was applied to Pennisetum purpureum fields at the specified rates. The PGPR was then mixed with water at a 1:50 ratio. Once mixed, it was ready to be applied to pasture land to restore soil fertility. PGPR was applied 10 days after planting (DAP) (Fig. 1).

The measurement variables include morphological traits (i.e., plant length, plant diameter, tiller number, fresh, and dry weight), fiber content (i.e., ADF, NDF, cellulose and lignin), and digestibility (i.e., IVDMD, IVOMD, IVADFD, IVNDFD, IVADLD, and IVCD). Plant length (cm) was measured from the base of the stem to the tip of the highest leaf (Bódi et al., 2008); diameter measurements were taken using a caliper on the largest part of the plant stem (Mohamed et al., 2013); and tiller number measurements were taken by manually counting all tillers from all plants (Scotford & Miller, 2004); at 45 DAP. Fresh and dry weights of livestock feed were measured; fresh weight (grams) was taken from 1 square meter at a randomly selected position, harvested at 45 DAP. Next, 250g was taken as a sub-sample, dried in an oven at70°C for 4 days to measure dry weight (grams) (Tarawali, 1995).

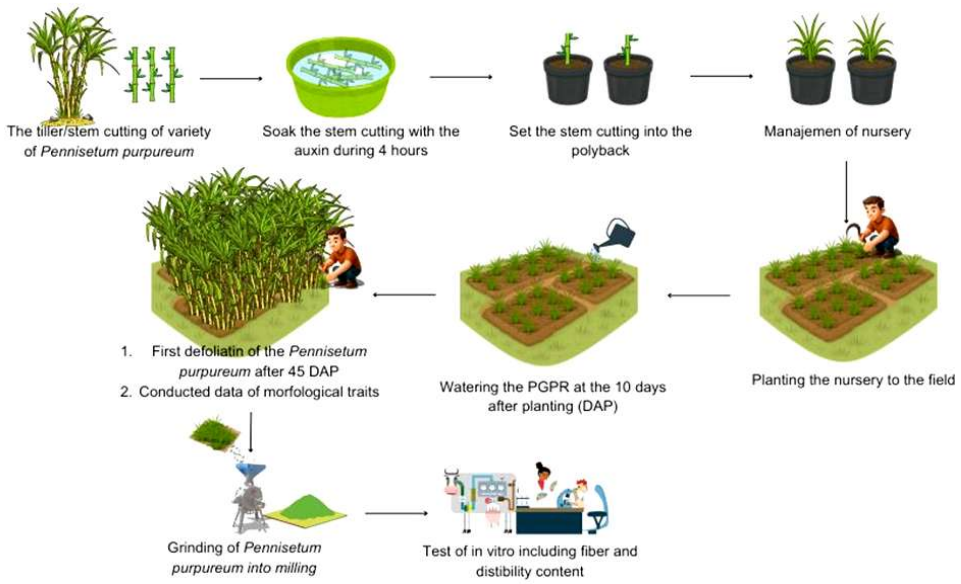

Fig. 1: Procedure of the study.

While ADF, NDF, Cellulose, and ADL values were tested using the Van Soest method. Van Soest analyzes the use of chemical treatments to separate plant cell wall components based on their solubility. NDF analysis was conducted on the sample, which was boiled in a neutral detergent solution (typically cetyltrimethylammonium bromide and sodium sulphate in a pH 7.0 buffer). This dissolves soluble carbohydrates, starches, pectins, and proteins, leaving behind insoluble fiber. ADF analysis was conducted on the sample, which was boiled in an acid detergent solution (cetyltrimethylammonium bromide in 1N sulfuric acid). This dissolves the hemicellulose, leaving the lignocellulose complex intact. NDF analysis was conducted on the sample, which was boiled in an acid detergent solution (cetyltrimethylammonium bromide in 1N sulfuric acid). This dissolves the hemicellulose, leaving the lignocellulose complex intact. Cellulose is calculated as the difference between ADF and ADL (Van Soest et al., 1984).

$$\%IVxD = \text{x Sample (g)} - (\text{x Residual (g)} - \text{x Blank (g)}) \times 100\%$$
$$\%IVxD = \text{x Sample (g)} \times 100\%$$

Feed digestibility testing was carried out in vitro using the Tilley & Terry (1963), with the following equation:

$$\%IVxD = \frac{\text{x Sample (g)} - (\text{x Residual (g)} - \text{x Blank (g)})}{\text{x Sample (g)}} \times 100\%$$

Note: x= ADF, NDF, lignin, etc.

Data Analysis

An analysis of data using SPSS one-way analysis of variance (ANOVA) was conducted, followed by the Duncan Multiple Range Test (DMRT) to identify any significant differences within the parameters.

RESULTS & DISCUSSION

Morphological Responses of a Variety of Pennisetum purpureum to PGPR Application

The morphological characteristics of forage crops are critical indicators of their growth performance and biomass potential. In this study, the application of PGPR significantly influenced the morphological traits of various *Pennisetum purpureum varieties*. Key parameters observed included tiller number, diameter, plant length, and dry matter yield.

The application of PGPR significantly influenced the morphological traits of the three *Pennisetum purpureum* cultivars— Pakchong, Biograss, and Dwarf Napiergrass. Key parameters observed included plant height, tiller number, and stem diameter. These traits are critical indicators of vegetative vigor and biomass potential in forage grasses. Across all cultivars, PGPR treatments (particularly T2 and T3) resulted in marked improvements in plant length and tiller number compared to the control (T0). Biograss exhibited the most pronounced response, with an average increase of up to 35% in tiller number under PGPR treatment (Table 1). This suggests a strong compatibility between the Biograss types and the PGPR used, consistent with findings by Utamy et al. (2025), who emphasized the role of genotype-microbe interactions in optimizing growth responses.

Tiller number also increased significantly in PGPR-treated plots, particularly in Biograss and Dwarf Napiergrass (Table 1). The increase in tiller number production is likely associated with enhanced nitrogen availability and hormonal stimulation, particularly auxins and cytokinins, which promote cell division and leaf expansion (He et al., 2019; Adedeji et al., 2020). PGPR

Table 1: Morphological Responses of a Variety of *Pennisetum purpureum* to PGPR

Parameters	Level PGPR	Variety of *Pennisetum purpureum*			Average	*p*-value		
		Dwarf Napiergrass	Biograss	Pakchong		PGPR	V	P*V
Tiller number (plant/m2)	T0	6.66±1.86	4.00±0.72	6.00±1.30	5.55±1.54	0.42	0.00	0.73
	T1	6.41±1.79	3.33±0.27	4.08±1.13	4.61±1.76			
	T2	8.41±2.48	3.88±1.03	4.16±0.88	5.49±2.62			
	T3	8.16±3.09	4.25±1.06	5.66±1.67	6.02±2.56			
	T4	8.00±5.03	5.50±0.79	4.50±2 .15	6.00±3.27			
	Average	7.53±2.81^{b}	4.19±1.04^{a}	4.88±1.56^{a}				
Diameter (cm)	T0	19.62±4.96	19.62±6.13	18.96±2.63	19.40±4.35	0.31	0.15	0.74
	T1	20.50±5.70	17.60±2.35	20.30±4.26	19.46±4.15			
	T2	18.14±4.95	16.03±2.34	19.56±3.09	17.91±3.61			
	T3	23.29±6.91	20.26±3.05	19.49±2.09	21.01±4.43			
	T4	21.31±2.67	17.94±3.71	24.02±3.17	21.09±3.90			
	Average	20.57±4.96	18.29±3.70	20.47±3.36				
Plant length (cm)	T0	50.54±3.73	56.70±7.79	67.78±5.52	58.34±9.17^{a}	0.00	0.00	0.42
	T1	50.48±2.55	57.36±6.89	71.45±2.31	59.76±9.96^{a}			
	T2	50.60±2.63	63.086±9.58	68.90±5.25	60.86±9.90^{a}			
	T3	61.91±14.40	76.05±2.59	78.19±5.41	72.05±11.10^{b}			
	T4	54.09±9.66	65.45±1.88	82.54±8.50	67.36±13.97^{b}			
	Average	53.52±8.50^{a}	63.73±9.21^{b}	73.77±7.75^{c}				
Dry matter yield (ton/ha)	T0	1.50±0.00^{a}	5.10±2.70^{bc}	5.20±0.00^{cd}	3.90±1.80^{a}	0.04	0.00	0.00
	T1	1.50±0.00^{a}	5.60±3.00^{fg}	4.80±0.30^{b}	4.00±1.80^{ab}			
	T2	1.50±0.00^{a}	5.80±3.50^{g}	5.10±0.00^{bc}	4.10±1.90^{ab}			
	T3	1.40±0.00^{a}	5.60±4.20^{fg}	5.50±0.10^{def}	4.20±2.00^{b}			
	T4	1.60±0.00^{a}	5.40±0.20^{cde}	5.60±0.00^{fg}	4.20±1.90^{b}			
	Average	1.50±0.00^{a}	5.50±0.30^{c}	5.20±0.30^{b}				

T0= level of PGPR 0kg/ha, T1= 100kg/ha, T2= 200kg/ha, T3= 300kg/ha, T4= 400kg/ha, PGPR= Plant Growth-Promoting Rhizobacteria, V=Variety of Pennisetum purpureum, P*V= Interaction of level of Plant Growth-Promoting Rhizobacteria and Variety of Pennisetum purpureum.

strains, such as Bacillus spp. and Pseudomonas spp., are known to produce phytohormones that improve canopy development and photosynthetic capacity.

Stem diameter, although less variable than other traits, increased modestly in PGPR-treated plants (Table 1), indicating improved structural support and nutrient transport efficiency. These morphological enhancements collectively contribute to greater DM yield accumulation and forage quality. The observed improvements in vegetative growth are consistent with previous studies demonstrating PGPR's role in enhancing root architecture, nutrient uptake, and stress tolerance (Grover et al., 2021; Basu et al., 2021). Enhanced root systems likely facilitated better access to soil nutrients and water, supporting above- ground growth. Overall, the morphological responses observed in this study support the potential of PGPR as a sustainable bio- input to improve the growth performance of tropical forage grasses, particularly under conditions of limited land and reduced chemical inputs.

DM Yield Enhancement in Pakchong, Biograss and Dwarf Napiergrass under PGPR Treatment

The application of PGPR significantly enhanced DM yield across all cultivars, with the most notable increase observed in Biograss under treatment T2, reaching 5.80 ton/ha (Fig. 2). This result indicates that PGPR not only improves vegetative growth but also contributes directly to forage productivity. The increase in DM yield is attributed to improved nutrient uptake, enhanced root development, and hormonal stimulation facilitated by PGPR.

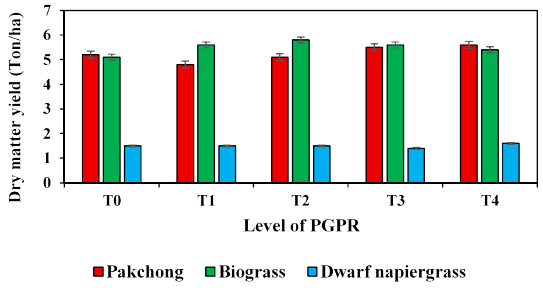

Fig. 2: DM yield of the variety of *Pennisetum purpureum* under PGPR treatment. T0= level of PGPR 0 kg/ha, T1= 100 kg/ha, T2= 200 kg/ha, T3= 300 kg/ha, T4= 400 kg/ha.

Statistical analysis revealed significant differences ($P<0.05$) in DM yield among the three cultivars. Biograss recorded the highest biomass yield at 5.50 ton/ha, followed by Pakchong (5.20ton/ha) and dwarf napiergrass 1.5ton/ha (Table 1). The superior performance of Biograss is likely due to its rapid growth rate, high regenerative capacity, and strong adaptability to environmental conditions. These findings are consistent with previous studies by Husni et al. (2021) and Nulik et al. (2023), which identified Biograss as a promising cultivar for forage production in land-constrained livestock systems.

Additionally, Biograss is easy to propagate using cuttings, tillers, or clump divisions, making it suitable for smallholder farmers.

Plant Growth-Promoting Rhizobacteria treatments T3 and T4 also showed significant effects ($P<0.05$) on DM yield, with the highest yield reaching 4.20tons/ha (Table 1). This confirms the biological effectiveness of PGPR in enhancing nutrient absorption, hormonal stimulation, and vegetative growth. Li et al. (2016) and Kenneth et al. (2019) reported similar findings in hybrid Pennisetum, where PGPR promoted growth through hormone production, phosphate solubilization, and pathogen suppression. Vocciante et al. (2022) further emphasized that PGPR consistently improves tiller number and diameter, thus increasing DM yield.

The increase in DM yield has important implications for forage availability in ruminant livestock systems, particularly under land-use constraints. Higher DM yield can help address feed shortages, especially for small-scale farmers. Andrade et al. (2023) highlighted that PGPR colonize root surfaces and promote plant growth through multiple mechanisms, including enhanced nutrient availability, hormone synthesis, root development, and disease resistance. Grover et al. (2021), Hasan et al. (2024), and Bhat et al. (2019) also confirmed that PGPR inoculation positively affects both root and shoot growth, with root systems playing a key role in water and nutrient uptake, nutrient cycling, soil structure, and carbon storage.

PGPR promotes DM yield by stimulating key growth factors, including tiller number, plant length, root biomass and dry matter (DM) yield. Abbasi & Mohammadi, (2023) and Chen et al. (2023) reported that PGPR can assist plants in nutrient uptake, positively affect root and shoot length and tiller number, and ultimately significantly increase biomass yield.

PGPR-Induced Changes in Fiber Composition and Forage Quality

The findings of this study demonstrate that grass variety, PGPR level, and their interaction exert a highly significant influence ($P<0.001$) on the contents of ADF, NDF, cellulose, and lignin (Table 2). Elevated fiber levels in forage are generally associated with reduced feed quality, as higher concentrations of ADF, NDF, cellulose, and lignin tend to impair digestibility (Putri et al., 2021). Consequently, reducing the fiber content of forage remains a critical objective for producing high-quality livestock feed.

Different grass varieties exhibit distinct fiber profiles. Notably, Dwarf napiergrass consistently has lower fiber concentrations than other cultivars (Table 3). This can be attributed to its genetic characteristics, particularly the production of softer stems with reduced fiber accumulation in stem tissues (Widjajanto et al., 2022). Beyond genetic factors, soil fertility also plays a pivotal role in determining fiber content. PGPR contributes significantly to soil fertility restoration, which in turn affects plant growth dynamics. In nutrient-rich soils, rapid vegetative growth is often accompanied by reduced fiber synthesis, whereas under nutrient-deficient conditions, plant growth is suppressed and fiber accumulation tends to increase (Serrano et al., 2024).

The application of PGPR as a growth booster has been shown to enhance crop productivity while simultaneously reducing crude fiber, ADF, NDF and lignin levels. Utamy et al. (2025) reported that PGPR treatment of hydroponically

Table 2: The Fiber Composition of the Different Varieties of *Pennisetum purpureum* Under PGPR Treatment

Parameters %	PGPR Level	Variety of *Pennisetum purpureum*			Average	*p*-value		
		Biograss	Dwarf Napiergrass	Pakchong		PGPR	V	P*V
Lignin	T0	2.89±0.09^{c}	6.45±0.05^{j}	6.16±0.05^{i}	5.17±1.71^{d}	0.00	0.00	0.00
	T1	3.13±0.01^{fg}	3.37±0.07^{h}	3.18±0.04^{g}	3.23±0.11^{c}			
	T2	3.01±0.03^{e}	3.42±0.03^{h}	3.09±0.02^{f}	3.17±0.18^{b}			
	T3	2.79±0.01^{b}	2.92±0.05^{c}	3.20±0.03^{g}	2.97±0.18^{a}			
	T4	2.92±0.04^{d}	2.59±0.03^{a}	3.38±0.02^{h}	2.96±0.34^{a}			
	Average	2.95±0.12^{a}	3.75±1.43^{b}	3.80±1.22^{c}				
Cellulose	T0	23.67±0.04^{i}	20.01±0.09^{a}	20.45±0.08^{c}	21.38±1.72^{a}	0.00	0.00	000
	T1	22.49±0.07^{f}	20.13±0.04^{b}	23.20±0.01^{h}	21.94±1.39^{c}			
	T2	22.92±0.03^{g}	20.41±0.02^{c}	23.59±0.08^{i}	22.30±1.44^{e}			
	T3	23.10±0.09^{h}	20.69±0.12^{d}	22.81±0.05^{g}	22.20±1.14^{d}			
	T4	22.85±0.07^{g}	20.69±0.02^{d}	22.07±0.08^{e}	21.87±0.94^{b}			
	Average	23.00±0.40^{c}	20.39±0.29^{a}	22.42±1.14^{b}				
NDF	T0	51.07±0.02^{f}	47.40±0.14^{d}	51.80±0.03^{h}	50.09±2.04^{e}	0.00	0.00	0.00
	T1	50.32±0.34^{e}	46.54±0.24^{a}	51.40±0.02^{g}	49.42±2.21^{a}			
	T2	51.03±0.08^{f}	46.57±0.23^{ab}	51.10±0.01^{f}	49.56±2.24^{b}			
	T3	50.93±0.03^{f}	46.90±0.03^{c}	51.71±0.02^{h}	49.85±2.23^{d}			
	T4	50.51±0.14^{e}	46.79±0.04^{bc}	51.81±0.03^{h}	49.70±2.26^{c}			
	Average	50.77±0.34^{b}	46.84±0.34^{a}	51.56±0.28^{c}				
ADF	T0	26.88±0.04^{gh}	24.50±0.07^{ab}	27.11±0.02^{i}	26.16±1.25^{c}	0.00	0.00	0.00
	T1	26.18±0.04^{d}	24.47±0.08^{ab}	27.46±0.08^{i}	26.03±1.29^{ab}			
	T2	26.56±0.07^{ef}	24.59±0.11^{bc}	27.03±0.04^{k}	26.30±1.38^{d}			
	T3	26.42±0.06^{e}	24.72±0.21^{c}	27.03±0.10^{hi}	26.06±1.04^{b}			
	T4	26.64±0.09^{f}	24.34±0.19^{a}	26.85±0.09^{g}	25.94±1.20^{a}			
	Average	26.53±0.24^{b}	24.52±0.17^{a}	27.24±0.34^{c}				

T0= level of PGPR 0kg/ha, T1= 100kg/ha, T2= 200kg/ha, T3= 300kg/ha, T4= 400kg/ha, PGPR= Plant Growth-Promoting Rhizobacteria, V=Variety of Pennisetum purpureum, P*V= Interaction of level of Plant Growth-Promoting Rhizobacteria and Variety of Pennisetum purpureum; ADF= Acid Detergent Fiber, NDF= Neutral Detergent Fiber.

Table 3: The Digestibility of the Different Varieties of *Pennisetum purpureum* under PGPR Treatment

Parameters	PGPR Level	Variety of *Pennisetum purpureum*			Average	*p*-value		
		Biograss	Dwarf Napiergrass	Pakchong		PGPR	V	P*V
IVLD	T0	18.34±0.44^{bc}	18.16±0.45^{bc}	21.47±0.05^{g}	19.47±1.53^{a}	0.00	0.00	0.00
	T1	24.33±0.20^{i}	19.30±0.45^{cd}	22.26±0.47^{gh}	21.96±2.21^{b}			
	T2	22,67±0,80^{h}	20.14±0.84^{de}	17.078±0.06^{a}	19.96±2.49^{ab}			
	T3	18.55±0,31^{bc}	20.81±0.68^{ef}	18.12±0.34^{b}	19.16±1.32^{ab}			
	T4	21.12±0.56f^{f}	22.89±0,76^{h}	18.21±0.72	20.74±2.12^{ab}			
	Average	21.00±2.44^{c}	20.35±1.62^{b}	19.42±2.14^{a}				
IVCD	T0	53.05±0.89^{c}	52.91±0.12^{c}	56.32±0.25^{e}	54.09±1.73^{a}	0.00	0.00	0.00
	T1	61.71±0.33^{hi}	54.73±0.48^{d}	62.35±0.46^{i}	59.59±3.68^{b}			
	T2	61.19±1.04^{h}	57.33±0.36^{f}	51.76±0.26^{b}	56.76±4.14^{ab}			
	T3	50.78±0.59^{ef}	56.96±0.30^{ef}	56.29±0.22^{e}	54.68±2.95^{a}			
	T4	56.33±0.65^{e}	59.13±0.48^{g}	50.86±0.55^{a}	55.44±3.67^{a}			
	Average	56.61±4.52^{c}	56.21±2.26^{b}	55.25±4.24^{a}				
IVNDFD	T0	59.80±0.73^{bc}	60.72±0.17^{c}	66.38±1.62^{g}	62.30±3.21^{a}	0.00	0.00	0.00
	T1	71.76±0.59^{i}	60.57±0.53^{c}	69.91±0.88^{h}	67.41±5.22^{b}			
	T2	67.69±0.87^{g}	62.92±0.92^{d}	60.88±1.56^{c}	63.83±3.18^{a}			
	T3	58.90±0.46^{b}	63.00±0.66^{d}	65.19±0.26^{ef}	62.36±2.79^{a}			
	T4	64.81±1.15^{e}	67.63±0.44^{g}	57.13±0.67^{a}	63.19±4.75^{a}			
	Average	64.59±5.03^{c}	62.97±2.68^{a}	63.90±4.70^{b}				
IVADFD	T0	56.85±0.76^{cd}	57.85±0.29^{de}	61.54±0.86^{f}	58.75±2.21^{a}	0.00	0.00	0.00
	T1	68.34±1.00^{h}	58.68±0.59^{e}	66.02±0.59^{g}	64.34±4.41^{b}			
	T2	65.43±0.89^{g}	60.84±0.88^{f}	56.32±0.71^{bc}	60.86±4.00^{ab}			
	T3	55.55±0.39^{b}	60.52±0.79^{f}	61.10±0.78^{f}	59.05±2.70^{a}			
	T4	61.19±0.63^{f}	65.04±0.21g	53.01±0.01^{a}	59.74±5.33^{a}			
	Average	61.47±5.09^{c}	60.58±2.62^{a}	59.60±4.69^{a}				
IVOMD	T0	64.14±0.57^{bc}	71.55±1.24^{f}	65.48±1.38^{cd}	67.06±3.55^{a}	0.00	0.00	0.00
	T1	74.04±0.63^{gh}	74.86±0.96^{hi}	72.41±1.29^{g}	73.77±1.38^{b}			
	T2	71.40±0.65^{f}	75.29±1.55^{j}	65.54±0.37^{cd}	70.74±4.33^{ab}			
	T3	63.03±0.26^{ab}	73.16±0.80^{gh}	68.76±1.41^{e}	68.32±4.47^{ab}			
	T4	67.08±1.12^{de}	74.70±1.16^{hi}	61.78±1.08^{a}	67.85±5.73^{ab}			
	Average	67.94±4.39^{b}	73.91±1.78^{c}	66.79±3.83^{a}				
IVDMD	T0	67.50±0.60^{bc}	71.66±0.94^{d}	68.63±1.27^{c}	69.26±2.04^{a}	0.00	0.00	0.00
	T1	76.07±0.63^{f}	73.61±1.00^{e}	74.43±1.02^{ef}	74.70±1.33^{b}			
	T2	73.92±0.64^{e}	74.49±0.90^{ef}	68.12±0.53^{bc}	72.78±3.11^{b}			
	T3	66.76±0.28^{ab}	74.90±0.57^{ef}	71.67±0.91^{d}	71.11±3.59^{ab}			
	T4	70.38±0.95^{d}	75.98±1.84^{f}	65.38±1.04^{a}	70.58±4.73^{ab}			
	Average	70.92±0.95^{b}	74.13±1.78^{c}	69.64±3.33^{a}				

T0= level of PGPR 0kg/ha, T1= 100kg/ha, T2= 200kg/ha, T3= 300kg/ha, T4= 400kg/ha, PGPR= Plant Growth-Promoting Rhizobacteria, V=Variety of Pennisetum purpureum, P*V= Interaction of level of Plant Growth-Promoting Rhizobacteria and Variety of Pennisetum purpureum, IVDMD= in vitro DM digestibility, IVOMD= in vitro organic matter digestibility, IVADFD= in vitro ADF digestibility, IVNDF= in vitro NDF digestibility, IVCD= in vitro cellulose digestibility, and IVLD= in vitro lignin digestibility.

grown corn forage not only reduced fiber content but also improved nutritional parameters, including crude protein and digestibility. PGPR exerts its effects through multiple mechanisms, including enhancing soil fertility and stimulating plant growth via phytohormone production, particularly indole-3-acetic acid (IAA), a key auxin involved in regulating plant development. Additionally, PGPR accelerates metabolic processes, promotes the synthesis of phytochemicals and phenolic compounds, and mitigates oxidative stress, all of which contribute to reduced fiber accumulation in plant tissues.

As shown in Table 2, the application of PGPR at level T4 resulted in the lowest fiber content in Biograss and Dwarf napiergrass, while the Pakchong variety exhibited its lowest fiber levels at PGPR level T3. These variations suggest that each grass species responds differently to PGPR treatment and soil conditions. Certain varieties are more adaptable to nutrient-rich environments, whereas others perform optimally under low-fertility conditions (Mokgakane et al., 2021). Understanding these varietal responses is essential for optimizing forage quality and tailoring PGPR applications to specific agronomic contexts.

Improvement in Forage Digestibility through PGPR-Mediated Growth Promotion

The digestibility of forage determines the quality of feed for livestock, thereby increasing productivity. Forage digestibility refers to the extent to which livestock can absorb nutrients from forage, such as organic matter digestibility or dry matter digestibility. In addition, fiber digestibility is also very important in determining the quality of forage feed. The digestibility of forage fed with PGPR in this study is shown in Table 3.

The variability of in vitro ADF and NDF digestibility (IVADFD and IVNDFD) across grass varieties is strongly influenced by PGPR application (Table 3). Although elevated ADF and NDF values are typically associated with reduced forage quality, their impact on ruminant nutrition remains acceptable if concentrations remain within physiological norms. Utamy et al. (2024) reported that high PGPR levels may increase ADF and NDF levels, yet fiber concentrations remain within tolerable limits for ruminant digestion. Kumar et al. (2022) further emphasized that PGPR, when integrated with nutrient management practices, can reduce ash content, thereby improving overall digestibility.

A strong positive correlation between ADF and NDF has been consistently observed in forage crops (Utamy et al., 2024; Arora et al., 2024), underscoring their importance as indicators of fiber quality. Higher ADF values are negatively correlated with digestibility, while elevated NDF levels are associated with reduced forage intake (Ball et al., 2015; Siska et al., 2025). Souza et al. (2021) noted that increased NDF concentrations in tropical grasses often coincide with higher lignin content, which adversely affects IVDMD. Lignin, along with phenolic acid linkages, contributes to the indigestible fraction of NDF in forage crops. Moreover, as forage plants mature, ADF and NDF levels tend to rise due to increased stem-to-leaf ratios, resulting in higher concentrations of structural carbohydrates and lignin (Luna et al., 2015; Ernawatia et al., 2023).

The interaction between grass variety and PGPR level also significantly influenced cellulose digestibility and lignin digestibility ($P<0.01$). The highest IVLD was recorded in F1 (Pakchong) at PGPR level T1 (200L/ha), while the lowest was observed in F3 (Dwarf Napiergrass) at level T4 (500L/ha). Conversely, the highest IVCD was found in F3 at PGPR level T1, and the lowest in F1 at level T3 ($P<0.01$) (Table 3). These results suggest that PGPR application can modulate the digestibility of specific fiber components, depending on the grass genotype and level.

Cellulose digestibility is closely linked to ADF and NDF values, as cellulose is a major constituent of both fractions. Lignin, which serves as a protective barrier around cellulose, plays a critical role in limiting its digestibility. Ansah et al. (2021) described cellulose and hemicellulose as carbohydrate fractions derived from ADF and NDF, while Silva et al. (2024) emphasized their role in determining fiber quantity and quality. Hu et al. (2008) identified lignin as an antioxidant compound that shields cellulose from microbial degradation. A negative correlation between NDF and lignin has been observed, where increased lignin deposition in fibrous tissues—especially in older plants—reduces digestibility (Luna et al., 2015; Ernawatia et al., 2023).

Cellulose digestibility is also influenced by the type and amount of available fiber substrates. High ruminal microbial activity facilitates rapid cellulose breakdown (Qori'ah et al., 2016). However, lignin, particularly in xylem and sclerenchyma tissues, can significantly reduce digestibility. Mauri et al. (2019) highlighted that increased proportions of these tissues are associated with higher lignin deposition in cell walls, further reducing forage digestibility.

These findings underscore the importance of PGPR in enhancing forage quality by modulating fiber composition and digestibility. By optimizing PGPR level and selecting appropriate grass varieties, it is possible to improve nutrient availability, reduce indigestible fiber fractions, and support sustainable livestock nutrition.

Implications of PGPR Application for Sustainable Forage under Land Use Constraints

Land serves as a fundamental resource for sustaining life, supporting biodiversity, and enabling agricultural productivity. However, increasing population pressure, poor land governance, and the accelerating impacts of climate change have placed significant stress on land resources (Kondong et al., 2025). As agricultural land continues to shrink due to urban expansion and industrial development, a growing imbalance between limited land availability and rising food and feed demand threatens long- term food security (Han et al., 2021).

To address these challenges, sustainable intensification strategies are essential—focusing on increasing productivity per unit area through the adoption of modern agricultural technologies, improved cultivars, and environmentally friendly inputs such as organic fertilizers (Hamzens et al., 2025). In this context, forage production must also be

prioritized, as it is integral to integrated farming systems and supports livestock-based livelihoods.

Pennisetum purpureum is one of the most abundant yet underutilized biomass resources. Its vigorous growth and adaptability to marginal soils make it an ideal candidate for forage production without competing with food crops for fertile land. However, the coarse stems of elephant grass are often overlooked due to their lower digestibility and nutritional value (Ikpeseni et al., 2024). Conventional approaches to improving forage yield often rely on chemical fertilizers, which can degrade soil health and contribute to environmental pollution by accumulating heavy metals. In contrast, organic inputs such as PGPR offer a more sustainable alternative by enhancing soil structure and microbial activity (Ren et al., 2025).

PGPR, as a natural growth booster, plays a pivotal role in improving plant health, nutrient uptake, and soil fertility. These rhizobacteria colonize plant roots and facilitate key processes, including nitrogen fixation, phosphate solubilization, and phytohormone production (Tawakkal et al., 2025). Their application reduces dependence on synthetic inputs and aligns with the principles of climate-smart, eco-friendly agriculture. PGPR also enhances plant resilience to abiotic and biotic stresses, contributing to long-term soil health and productivity (Benjamen, 2025).

The findings of this study confirm that PGPR application significantly improves biomass yield, forage quality, and digestibility across different elephant grass varieties. These improvements are particularly valuable in land-constrained systems, where maximizing output per hectare is critical. By increasing nutrient efficiency and promoting faster vegetative growth, PGPR enable/s more intensive forage production without expanding agricultural land. This aligns with the goals of sustainable land management and supports the resilience of smallholder farmers, especially in regions facing feed shortages (Burkart & Mwendia, 2024; Joseph et al., 2025).

Furthermore, the enhanced DM yield of *Pennisetum purpureum* under PGPR treatment offers strategic advantages not only for livestock feed but also as a potential bioenergy source (Nascimento et al., 2025). This dual-purpose utility reinforces the role of PGPR in integrated agricultural systems that balance productivity, environmental stewardship, and resource efficiency.

Conclusion

This study demonstrates the significant potential of PGPR to enhance morphological traits, yield, fiber composition, digestibility, and sustainability in forage grass production, particularly in three varieties: Pakchong, Biograss, and Dwarf Napiergrass. The application of PGPR across different levels and grass types resulted in notable improvements in plant length, diameter, and DM yield, indicating its effectiveness as a natural growth booster. PGPR also played a critical role in modifying fiber composition, reducing levels of ADF, NDF, cellulose, and lignin, which are known to negatively affect forage digestibility. These changes improved DM and organic matter digestibility, as well as the digestibility of fiber fractions, including IVADFD, IVNDFD, IVCD, and IVLD. The interaction between PGPR level and grass variety revealed that optimal responses vary across genotypes, emphasizing the need for tailored application strategies. Furthermore, the application of PGPR aligns with sustainable land management practices, especially in areas with limited arable land and increasing pressure on natural resources. By improving soil fertility, reducing dependence on chemical fertilizers, and supporting ecological balance, PGPR offers a viable solution to intensify forage production without compromising environmental integrity. Its role in enhancing DM yield also supports feed security and provides strategic value for bioenergy development. In conclusion, PGPR is a promising natural growth booster that supports the dual goals of agricultural productivity and sustainability. Its integration into forage grass cultivation systems can contribute to resilient livestock feeding strategies, improved land-use efficiency, and long-term soil health—making it a key component of future-oriented, climate-smart agricultural practices.

DECLARATIONS

Funding: This research was supported by the RIIM LPDP Grant and BRIN, grant number (184/IV/KS/11/2023).

Acknowledgement: The authors would like to thank the Dean of the Faculty of Animal Science, the Dairy Laboratory at Hasanuddin University, and PT. Hasanuddin Agrivisa Internusa for their support in this research through the facilities provided.

Conflict of Interest: The authors declare that they have no conflicts of interest related to this study.

Data Availability: Data will be available upon request

Ethics Statement: No animal trials were conducted in this study, as the research focused solely on laboratory-based analyses.

Author's Contribution: RFU and AA: Conceptualization, Formal analysis, Methodology, Writing – review and editing. SB, ZZ, SG, and LA: Data curation, Formal analysis, and Writing. II, AUNK, ZR, RM, and AAR: Investigation, Formal analysis, and writing. AM, MF, and AFN: Writing – original draft.

Generative AI Statement: The authors declare that no Gen AI/DeepSeek was used in the writing/creation of this manuscript.

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