ISSN: 3063-3583

CALCIUM AND PHOSPHORUS DYNAMICS IN *TRICHODERMA*-FERMENTED NAPIER GRASS–BANANA PEEL BLENDS

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Article history:
Received: December 11, 2024
Accepted: March 15, 2025
Published: July 7, 2025

Keywords:
agro-residues, botanical fermentation, feed optimization, mineral balance, nutrient dynamics, ruminant nutrition, sustainable livestock.

ABSTRACT

Optimizing nutrient utilization from forage and residue combinations is crucial for advancing sustainable ruminant feeding systems. This study evaluated the dynamics of calcium (Ca) and phosphorus (P) in a mixture of Napier grass (*Pennisetum purpureum*) and banana peel (*Musa acuminata* × *balbisiana*) fermented by Trichoderma at various addition levels. A completely randomized design with four treatments was applied, and mineral concentrations were determined using standard laboratory procedures. Results showed a consistent increase in Ca content with higher banana peel additions, while P levels decreased, indicating a differential mineral response to fermentation. Relative changes showed an enrichment of Ca up to 24.05% and a decrease in P concentration, reflecting fermentation-mediated transformation of the substrate matrix. The Ca:P ratio increased from 1.39 to 1.96 across treatments, remaining within the acceptable nutritional range but approaching Ca-dominant conditions at higher addition levels. These findings indicate that microbial fermentation not only improves feed utilization but also re-establishes the mineral balance in the forage-residue system. Moderate inclusion levels provide a more balanced mineral profile, highlighting the importance of optimizing feed composition. Overall, integrating agro-industrial residues through fermentation offers a viable strategy to improve nutritional efficiency and support sustainable livestock production.

Keywords:
dinamika nutrisi, fermentasi botani, keseimbangan mineral, nutrisi ruminansia, optimalisasi pakan, peternakan berkelanjutan, limbah pertanian.

ABSTRACT

Optimalisasi pemanfaatan nutrisi dari kombinasi hijauan dan residu sangat penting untuk memajukan sistem pemberian pakan ruminansia yang berkelanjutan. Studi ini mengevaluasi dinamika kalsium (Ca) dan fosfor (P) dalam campuran rumput Taiwan (Pennisetum purpureum) dan kulit pisang (Musa acuminata × balbisiana) yang difermentasi oleh Trichoderma pada berbagai tingkat penambahan. Desain acak lengkap dengan empat perlakuan diterapkan, dan konsentrasi mineral ditentukan menggunakan prosedur laboratorium standar. Hasil menunjukkan peningkatan yang konsisten dalam kandungan Ca dengan penambahan kulit pisang yang lebih tinggi, sementara kadar P menurun, menunjukkan respons mineral yang berbeda terhadap fermentasi. Perubahan relatif menunjukkan pengayaan Ca hingga 24,05% dan penurunan konsentrasi P, yang mencerminkan transformasi matriks substrat yang dimediasi fermentasi. Rasio Ca:P meningkat dari 1,39 menjadi 1,96 di seluruh perlakuan, tetap berada dalam kisaran nutrisi yang dapat diterima tetapi mendekati kondisi dominan Ca pada tingkat penambahan yang lebih tinggi. Temuan ini menunjukkan bahwa fermentasi mikroba tidak hanya meningkatkan pemanfaatan pakan tetapi juga membangun kembali keseimbangan mineral dalam sistem hijauan-residu. Tingkat inklusi moderat memberikan profil mineral yang lebih seimbang, menyoroti pentingnya mengoptimalkan komposisi pakan. Secara keseluruhan, mengintegrasikan residu agroindustri melalui fermentasi menawarkan *strategi yang layak untuk meningkatkan efisiensi nutrisi dan mendukung produksi ternak yang berkelanjutan.*

INTRODUCTION

Sustainable livestock production increasingly depends on the efficient integration of forage resources and agro-industrial by-products within circular agricultural systems (Alimuddin et al., 2024; Chisoro et al., 2023; Oosting et al., 2022). In many tropical regions, forage grasses such as *Pennisetum purpureum* (Napier grass) constitute the primary basal diet for ruminants due to their high biomass productivity and adaptability (Islam et al., 2023; 2024). At the same time, fruit-processing industries generate substantial volumes of banana peel residues, particularly from *Musa acuminata* × *balbisiana*, which remain underutilized and often contribute to localized environmental burdens (Gumisiriza et al., 2017). The strategic incorporation of such residues into ruminant feeding systems represents a practical pathway toward nutrient recycling and resource-use efficiency in integrated farming systems (Adegbeye et al., 2020; Gupta et al., 2012; Wang'ombe, 2023).

Banana peel contains moderate levels of crude protein, fiber, and ash, including essential macro-minerals (Ahmed et al., 2021; Kumari et al., 2023). However, its direct use in ruminant diets is constrained by structural carbohydrates and variable nutrient availability (Putra et al., 2019). Biological treatment through fermentation has been widely applied to enhance feed quality, improve digestibility, and modify nutrient profiles (Asmare, 2020; Cao et al., 2024; Kårlund et al., 2020). Filamentous fungi such as *Trichoderma* are recognized for their cellulolytic activity and rapid aerobic growth, enabling structural degradation of plant cell walls and potential modification of mineral availability during bioconversion processes (Ferreira Filho et al., 2020; Hemati et al., 2022; Lima et al., 2024). Fermentation may influence mineral dynamics not only by concentrating ash fractions through dry matter loss but also by altering mineral-binding complexes within fibrous matrices (Chen et al., 2022).

Calcium (Ca) and phosphorus (P) are essential macro-minerals in ruminant nutrition, playing central roles in skeletal development, metabolic regulation, and energy utilization (Yadav et al., 2024). Adequate dietary Ca and P balance—generally around 0.5% of dry matter with appropriate ratios—is fundamental to maintaining animal health and productive performance (de Carvalho et al., 2011; Lei et al., 2024). While numerous studies have evaluated the effects of fermentation on crude protein and fiber fractions, comparatively fewer investigations have examined how microbial fermentation of forage–residue blends influences Ca and P profiles within integrated feeding strategies. Understanding these mineral dynamics is therefore important for developing nutritionally balanced and environmentally responsive ruminant diets.

Napier grass–banana peel blends provide a relevant model for examining such interactions. The combination links primary forage production with agro-industrial residue valorization, while fermentation using *Trichoderma* offers a biologically driven approach to feed improvement. Evaluating Ca and P responses across graded inclusion levels of banana peel may clarify whether mineral concentrations remain within acceptable nutritional thresholds and how fermentation mediates these changes.

Therefore, this study aimed to evaluate calcium and phosphorus dynamics in *Trichoderma*-fermented Napier grass–banana peel blends under different inclusion levels, and to assess their suitability as alternative components in sustainable ruminant feeding systems.

RESEARCH METHODS

Experimental Site and Materials

The study was conducted from June to July 2014. The fermentation process was carried out at the Faculty of Agriculture, Animal Science, and Fisheries, Universitas Muhammadiyah Parepare, Indonesia, while mineral analyses were performed at the Animal Feed Chemistry Laboratory, Faculty of Animal Science, Universitas Hasanuddin, Makassar.

The primary substrates consisted of fresh Napier grass (*Pennisetum purpureum*) and banana peels from kepok banana (*Musa acuminata* × *balbisiana*). A commercial inoculum of Trichoderma spp. was used as the fermentative agent. All analytical-grade reagents used for calcium (Ca) and phosphorus (P) determination complied with standard laboratory specifications.

Experimental Design and Fermentation Procedure

The experiment employed a completely randomized design (CRD) with four treatments and three replications (12 experimental units). Each treatment consisted of a forage–residue blend supplemented with 1% (w/w) Trichoderma inoculum: 100% Napier grass (control/T0), 90% Napier grass + 10% banana peel (T1), 80% Napier grass + 20% banana peel (T2), 70% Napier grass + 30% banana peel (T3).

Fresh Napier grass was chopped to approximately 2–3 cm using a mechanical chopper. Banana peels were cleaned and similarly reduced in size to ensure homogeneous mixing. The substrates were blended according to treatment proportions on a fresh-weight basis, and 1% Trichoderma inoculum (w/w) was evenly incorporated. Moisture content was adjusted to approximately 60–65% to support fungal activity under aerobic conditions.

The mixtures were placed in clean polyethylene bags, loosely tied to allow limited air exchange, and incubated at ambient temperature (27–30°C) for four days. After fermentation, samples were oven-dried at 60°C to constant weight, ground to pass a 1-mm sieve, and stored in airtight containers pending chemical analysis.

Mineral Extraction and Determination

Sample Ashing

For mineral extraction, approximately 2 g of dried and ground sample was subjected to dry ashing in a muffle furnace at 550°C for 4–5 h until white ash was obtained. The ash was cooled in a desiccator before acid dissolution.

Calcium (Ca) Determination

Calcium concentration was determined using an acid digestion–permanganometric titration method. The ash residue was dissolved in 5 mL concentrated HCl and gently evaporated to near dryness. The solution was diluted with distilled water and transferred quantitatively into a 100 mL volumetric flask.

An aliquot (20 mL) was pipetted into a beaker, neutralized with NH_4OH (1:1) using methyl red indicator, and re-acidified with diluted HCl (1:3) to achieve a slightly acidic condition. The solution was heated to boiling, and 15 mL of ammonium oxalate was added to precipitate calcium as calcium oxalate. The precipitate was filtered, washed with hot distilled water until acid-free, and transferred into an Erlenmeyer flask containing distilled water and 5 mL concentrated H_2SO_4.

The solution was heated to 70–80°C and titrated with standardized $KMnO_4$ until a persistent pink endpoint was observed. Calcium concentration was calculated based on titrant volume, normality, and sample weight, and expressed as a percentage of dry matter.

Phosphorus (P) Determination

Phosphorus concentration was determined spectrophotometrically using the molybdenum blue method. Ash samples were dissolved in 5 mL concentrated HCl, diluted to 100 mL with distilled water, and homogenized.

A 1 mL aliquot was transferred into a 50 mL volumetric flask, followed by the addition of 3 mL ammonium molybdate solution and 2.5 mL ascorbic acid (vitamin C) reagent. The volume was adjusted with distilled water and mixed thoroughly. After 30 min of color development, absorbance was measured at 570 nm using a UV–Vis spectrophotometer. Phosphorus concentration was calculated from a standard calibration curve and expressed as a percentage of dry matter.

RESULTS AND DISCUSSION

Mineral Composition of Fermented Blends

The concentrations of calcium (Ca) and phosphorus (P) across treatments are presented in Table 1 and visually illustrated in Figure 1. The results indicate that Ca content increased with higher inclusion levels of banana peel, reaching the highest value in T3 (0.98%), while P content showed a declining trend, with the lowest value observed in T2 (0.48%). This contrasting pattern suggests that fermentation-mediated changes in substrate composition influenced mineral distribution within the blends.

The increasing Ca concentration can be associated with higher mineral content of banana peel, and the concentration effect results from dry matter reduction during fermentation. In contrast, the reduction in P levels may reflect microbial utilization, transformation into less soluble forms, or dilution effects within the fermented matrix. Similar findings have been reported in studies on fungal fermentation of agro-residues, where mineral concentration shifts are driven by both substrate composition and microbial metabolism (Sharma & Arora, 2015; Wang et al., 2019; Yafetto et al., 2023).

Table 1. Calcium and Phosphorus Concentrations in Fermented Blends

Treatment	Composition	Calcium (%)	Phosphorus (%)	Ca:P Ratio
T0	100% Napier grass	0.79 ± 0.02	0.57 ± 0.01	1.39
T1	90% TG + 10% BP	0.86 ± 0.03	0.55 ± 0.02	1.56
T2	80% TG + 20% BP	0.81 ± 0.02	0.48 ± 0.02	1.69
T3	70% TG + 30% BP	0.98 ± 0.04	0.50 ± 0.01	1.96

Note: Values expressed on dry matter basis (mean ± SD)

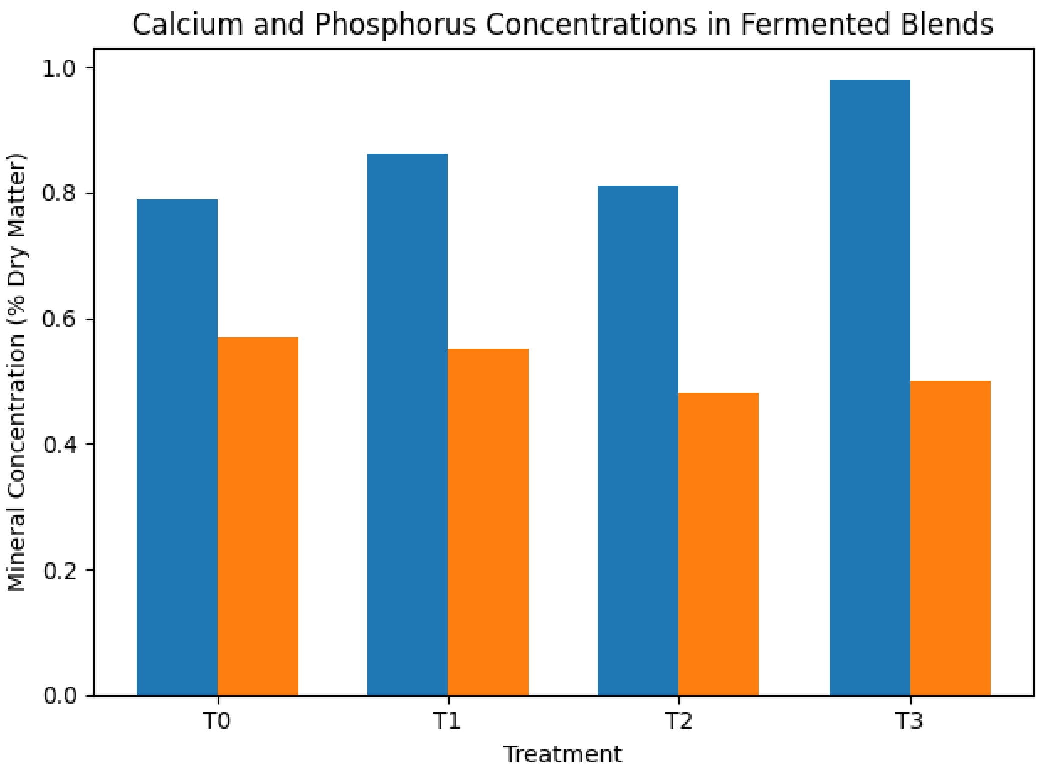

Figure 1. Calcium and Phosphorus Concentrations

Relative Mineral Changes and Fermentation Effects

The relative changes in mineral concentrations compared to the control are summarized in Table 2. Calcium exhibited a consistent increase across treatments, with the highest increment observed in T3 (+24.05%), indicating a strong enrichment effect. Conversely, phosphorus showed a decreasing trend, particularly in T2 (−15.79%), highlighting differential mineral responses to fermentation.

These results suggest that Trichoderma-mediated fermentation selectively alters nutrient availability through enzymatic degradation of lignocellulosic components. The breakdown of structural carbohydrates likely increases the relative concentration of minerals such as Ca, while P dynamics may be influenced by microbial immobilization or conversion into organic-bound forms. Previous studies have demonstrated that filamentous fungi, including Trichoderma, can modify nutrient profiles through enzymatic activity and biomass accumulation, thereby influencing mineral accessibility in fermented feeds (Cui et al., 2021; Lima et al., 2024).

Table 2. Relative Change in Mineral Concentrations Compared to Control

Treatment	Δ Calcium (%)	Δ Phosphorus (%)	Interpretation
T1	+8.86	-3.51	Ca enrichment begins
T2	+2.53	-15.79	P dilution effect
T3	+24.05	-12.28	Strong Ca concentration

Nutritional Implications for Ruminant Feeding Systems

The nutritional adequacy of the fermented blends is presented in Table 3, which contextualizes mineral concentrations relative to ruminant dietary requirements. All treatments maintained Ca levels within or above recommended thresholds, while P levels remained generally adequate, although a slight decline was observed in higher inclusion treatments. Importantly, the Ca:P ratio increased progressively from 1.39 (T0) to 1.96 (T3), as shown in Figure 2, indicating a shift toward Ca-dominant mineral balance.

This shift has important implications for ruminant nutrition. While Ca enrichment can support skeletal development and metabolic functions, excessive Ca relative to P may reduce phosphorus bioavailability and impair nutrient utilization efficiency. Optimal Ca:P ratios in ruminant diets typically range between 1:1 and 2:1, suggesting that all treatments remain within acceptable limits, although higher banana peel inclusion approaches the upper threshold. Similar observations have been reported in studies evaluating alternative feed resources, where mineral imbalances can emerge when agro-industrial residues are incorporated without proper formulation (Egbu et al., 2024).

Table 3. Mineral Adequacy Relative to Ruminant Nutritional Requirements

Treatment	Ca Status	P Status	Nutritional Balance
T0	Adequate	Adequate	Balanced
T1	Adequate	Adequate	Optimal
T2	Adequate	Marginal	Moderate imbalance
T3	High	Adequate	Ca-dominant

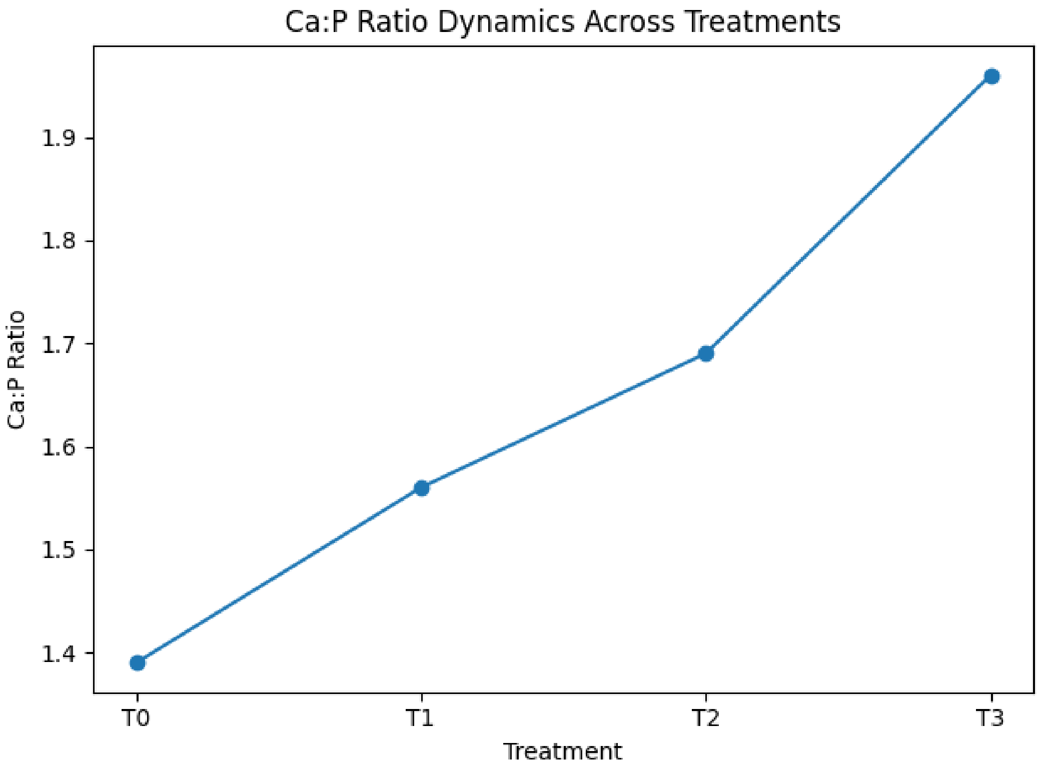

Figure 2. Ca:P Ratio Dynamics

System-Level Interpretation in Integrated Feeding Systems

From a systems perspective, the integration of Napier grass and banana peel through microbial fermentation represents a practical strategy for resource valorization within sustainable livestock production. The observed mineral dynamics reflect not only compositional changes but also functional interactions between substrate characteristics and microbial processes. As illustrated in Figure 1, the divergence between Ca and P trends underscores the need to evaluate feed resources beyond single nutrient metrics.

The increasing Ca:P ratio (Figure 2) further highlights how fermentation can reshape nutritional balance within forage–residue systems. Rather than being viewed solely as a processing step, fermentation acts as a bioconversion mechanism that influences feed quality, nutrient availability, and overall system efficiency. This aligns with broader concepts of circular agriculture, where waste streams such as banana peels are reintegrated into productive use, reducing environmental burdens while enhancing feed resource diversity.

Implications for Sustainable Livestock Production

The findings of this study demonstrate that Trichoderma-mediated fermentation can improve the functional value of forage–residue blends by enhancing Ca concentration while maintaining acceptable P levels. However, the observed mineral shifts emphasize the importance of balancing inclusion levels to avoid potential nutritional imbalances.

In the context of sustainable livestock systems, the use of locally available agro-industrial residues offers significant advantages, including reduced feed costs, improved resource efficiency, and lower environmental impact. International frameworks on sustainable agriculture, such as those promoted by the Food and Agriculture Organization, highlight the importance of integrating crop and livestock systems to enhance resilience and sustainability.

Overall, the results indicate that moderate inclusion levels of banana peel (e.g., T1–T2) provide a more balanced mineral profile, while higher inclusion levels (T3) may require dietary adjustment. These findings reinforce the need for system-oriented feed formulation approaches that consider not only nutrient composition but also interactions among feed components, microbial processes, and animal requirements.

CONCLUSION

This study demonstrates that Trichoderma-mediated fermentation of Napier grass–banana peel blends significantly alters calcium (Ca) and phosphorus (P) dynamics, resulting in a consistent increase in Ca concentration and a relative decline in P levels across treatments. These shifts indicate that fermentation functions not only as a preservation technique but also as a bioconversion process that restructures mineral composition within forage–residue systems. The observed responses reflect interactions between substrate characteristics and microbial activity, highlighting the importance of understanding nutrient transformations in biologically processed feeds.

From a nutritional perspective, all treatments maintained mineral concentrations within acceptable ranges for ruminant feeding; however, the progressive increase in Ca:P ratio suggests a transition toward Ca-dominant balance at higher levels of banana peel inclusion. Moderate inclusion levels provided a more balanced mineral profile, while higher inclusion levels approached the upper threshold of recommended Ca:P ratios. These findings emphasize that optimizing feed formulation requires careful consideration of both individual mineral concentrations and their interactions to ensure efficient nutrient utilization and animal performance.

Overall, integrating forage crops and agro-industrial residues through microbial fermentation pathways for enhancing resource efficiency in sustainable livestock systems. By improving the functional value of locally available feed resources, this approach supports dependency on conventional inputs while contributing to circular nutrient flows. The results underscore the need for system-oriented strategies that align biological processing, feed composition, and nutritional requirements to advance resilient and sustainable ruminant production systems.

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