Circular feed innovation: biotechnological upgrading of rice straw and agro-wastes into high-value silage using fungal enzymes

Nur Aizzah Mazlan[1], *Nor Dini* Rusli[2], *Ahmad Fariz* Nicholas[3], *Hasliza Abu* Hassim[4,8], *Agung* Irawan[5,8], *Anuraga* Jayanegara[6,8], *Zulfi Nur Amrina* Rosyada[7], and *Amirul Faiz* Mohd Azmi[1,8*]

[1]Animal Nutrition and Production Research Group, Department of Veterinary Preclinical Sciences, Faculty of Veterinary Medicine, Universiti Malaysia Kelantan, 16100, Malaysia
[2]Faculty of Agro-Based Industry, Universiti Malaysia Kelantan, 16100, Malaysia
[3]Faculty of Veterinary Medicine, Universiti Sultan Zainal Abidin, 22200, Malaysia
[4]Institute of Tropical Agriculture and Food Security, Universiti Putra Malaysia, Malaysia
[5]Vocational School, Universitas Sebelas Maret, Indonesia
[6]Faculty of Animal Science, IPB University, 16680, Indonesia
[7]Division of Animal Husbandry, Department of Veterinary Science, Faculty of Veterinary Medicine, Universitas Airlangga, Surabaya, East Java 60115, Indonesia
[8]Animal Feed and Nutrition Modelling Research Group (AFENUE), IPB University, 16680, Indonesia

Abstract. Agricultural production in Southeast Asia generates large quantities of lignocellulosic biomass, particularly rice straw and oil palm residues, which are frequently underutilized or disposed of through open burning practices. Biotechnological conversion of these residues into silage offers a sustainable strategy to improve feed availability while reducing environmental impacts. This study reviews the potential of upgrading agricultural waste into high-value ruminant feed through microbial fermentation combined with fungal enzyme supplementation. Fungal fibrolytic enzymes enhance lignocellulosic degradation, increase fermentable carbohydrate availability, and improve silage fermentation quality. Enzyme-treated rice straw silage consistently demonstrates improved pH reduction, fiber degradation, crude protein retention, digestibility, and aerobic stability. Feeding studies have indicated enhance feed intake, rumen fermentation efficiency, and animal performance when enzyme-treated silage partially replaces conventional forages. Environmentally, valorization of agricultural residues reduces greenhouse gas emissions and supports circular bioeconomy frameworks. Overall, fungal enzyme-assisted ensiling represents a promising and sustainable feeding strategy for ruminant production systems.

* Corresponding author: amirul.ma@umk.edu.my

1 Introduction

Rice cultivation generates substantial lignocellulosic residues, with approximately 1.0–1.5 kg of rice straw produced per kilogram of harvested grain [1]. In many Southeast Asian countries, including Malaysia, rice straw is commonly disposed of through open burning or natural field decomposition, contributing to environmental pollution and greenhouse gas emissions [2 ,3]. Such practices reduce environmental quality and result in nutrient losses from agricultural systems.

Rice straw has considerable potential as an alternative ruminant roughage due to its abundance and low cost. However, its utilization is constrained by high lignocellulosic content and low fermentable carbohydrate concentration, which reduce digestibility and feeding efficiency [4, 5]. These limitations restrict its integration into intensive livestock production systems.

Ensiling is a well-established forage preservation method that stabilizes biomass through anaerobic fermentation dominated by lactic acid bacteria [6]. Nevertheless, rice straw silage often exhibits poor fermentation characteristics due to insufficient soluble carbohydrates and high buffering capacity [7]. Therefore, innovative biological treatments are required to enhance fermentation efficiency and nutritive value.

Fungal enzyme supplementation has emerged as a promising strategy to improve lignocellulosic biomass utilization. Cellulases, hemicellulases, and ligninolytic enzymes degrade plant fiber structures and increase fermentable substrate availability for silage microorganisms [8, 9]. This approach supports circular feed innovation by converting agricultural residues into functional feed resources while improving environmental sustainability.

The conceptual framework of fungal enzyme-assisted ensiling for upgrading rice straw into value-added ruminant feed is illustrated in Figure 1. The figure summarizes the environmental challenges associated with rice straw disposal, the enzymatic degradation of lignocellulosic structures during ensiling, and the resulting improvements in fermentation efficiency and digestibility. This integrated approach demonstrates the potential of fungal enzyme supplementation to enhance feed quality while promoting sustainable agricultural waste management.

Fig. 1. Conceptual framework of fungal enzyme-assisted ensiling for upgrading rice straw into high-value ruminant feed. Graphic illustration generated using NotebookLM Pro based on the reviewed scientific sources.

2 Methods

This paper was prepared as a narrative review focusing on fungal enzyme-assisted ensiling of rice straw and agro-residues for ruminant feeding. Relevant peer-reviewed journal articles, conference proceedings, and technical reports were identified through academic databases including Scopus, Web of Science, and Google Scholar.

Keywords used in the literature search included “rice straw silage”, “fungal enzymes”, “lignocellulosic degradation”, “silage fermentation”, “ruminant digestibility”, and “agricultural waste valorization”. Publications from 2000 to 2025 were prioritized to ensure inclusion of recent advances in silage biotechnology and enzyme applications.

Studies were selected based on relevance to (i) lignocellulosic characteristics of rice straw, (ii) fungal enzyme mechanisms during ensiling, (iii) effects on fermentation quality and nutrient composition, and (iv) impacts on ruminant intake, digestibility, and environmental sustainability. Data trends and reported improvement ranges were synthesized and summarized descriptively to highlight comparative outcomes between untreated and enzyme-treated silage systems. The conceptual infographic presented in this manuscript was generated using NotebookLM Pro to visually synthesize the reviewed scientific evidence.

3 Result and discussion

3.1 Lignocellulosic characteristics of rice straw and agro-wastes

Rice straw consists primarily of cellulose, hemicellulose, and lignin, forming a complex structural matrix resistant to microbial degradation [5]. Lignin acts as a physical barrier that limits enzyme accessibility to carbohydrate fractions, thereby reducing ruminal digestibility and nutrient availability [10].

Similar structural limitations occur in oil palm residues, which typically contain high neutral detergent fiber and lignin concentrations, reducing feeding value [11]. Lignin–carbohydrate complexes slow ruminal degradation and restrict microbial colonization, limiting effective nutrient utilization in ruminant diets.

Traditional chemical pretreatments can improve digestibility but may cause organic matter losses and environmental concerns [3]. Biological pretreatment using ligninolytic fungi offers a sustainable alternative by selectively degrading lignin while preserving carbohydrate fractions essential for microbial fermentation [8]. However, integration of fungal pretreatment into practical silage systems requires further investigation under tropical production conditions.

3.2 Fungal enzymes in silage biotechnology

3.2.1 Enzyme types and activity

Fungal enzyme complexes used in silage improvement include cellulases, xylanases, β-glucosidases, and ligninolytic enzymes such as laccases. These enzymes synergistically degrade structural polysaccharides and lignin, enhancing the release of fermentable sugars [9]. Commercial fibrolytic enzyme preparations typically improve soluble sugar concentrations and promote early fiber hydrolysis during ensiling.

3.2.2 Mechanisms during ensiling

During ensiling, fungal enzymes convert structural carbohydrates into soluble sugars, enhancing lactic acid bacterial activity and accelerating fermentation [8]. Enzyme supplementation frequently reduces silage pH below 4.2 within 5–7 days compared with 10–14 days in untreated silage, resulting in improved preservation quality [6]. Rapid acidification suppresses spoilage microorganisms and reduces proteolysis, thereby improving nitrogen retention and silage nutritive value. These improvements in fermentation dynamics and nutrient composition are reflected in the comparative data presented in Table 1.

Table 1. Comparative effects of fungal enzyme supplementation on fermentation characteristics and Nutritional Quality of Rice Straw Silage.

Parameter	Untreated Rice Straw Silage	Fungal Enzyme-Treated Silage	Improvement Range (%)	Primary Fungal Enzyme Involved
Soluble sugar (g kg^{-1} DM)	30 – 50	45 – 80	20 – 60 ↑	Cellulase, ß-glucosidase
Silage pH (Day 5–7)	4.6 – 5.2	3.8 – 4.2	Faster acidification	Cellulase, Xylanase
Stable fermentation time (days)	10 – 14	5 – 7	40 – 50 ↓	Cellulase complex
Lactic acid (g kg^{-1} DM)	25 – 40	45 – 70	30 – 75 ↑	Cellulase, Hemicellulase
Ammonia-N (% total N)	10 – 18	6 – 10	30 – 50 ↓	Indirect effect via rapid acidification
Neutral detergent fiber (%)	70 – 75	62 – 68	8 – 15 ↓	Cellulase, Xylanase
Acid detergent fiber (%)	45 – 50	38 – 44	10 – 15 ↓	Cellulase
In vitro digestibility (%)	40 – 48	50 – 62	20 – 30 ↑	Cellulase, Xylanase
Cellulose degradation (%)	5 – 10	15 – 25	100 – 150 ↑	Cellulase
Lignin reduction (%)	0 – 3	8 – 18	Significant	Laccase, Lignin peroxidase
Estimated commercial enzyme cost (USD kg^{-1} DM) *	0	0.004 – 0.03	Marginal increase +0.4 – 3.0% ↑	Commercial fibrolytic enzyme blend

Note: ↑ Increase; ↓ Reduction
*Estimated based on commercial fibrolytic enzyme price range USD 8-15 kg^{-1} and inclusion rate 0.5-2.0 g kg^{-1} DM

3.3 Effects on silage fermentation quality

Fungal enzyme supplementation significantly improves fermentation end-product formation. Enzyme-treated rice straw silage often contains higher lactic acid concentrations, reflecting improved carbohydrate fermentation efficiency [7]. Fiber fractions are reduced through enzymatic hydrolysis, enhancing digestibility and feeding value.

Enzyme treatment also improves nitrogen preservation by reducing proteolysis during fermentation, resulting in higher crude protein concentrations. Additionally, enzyme-treated silage exhibits improved aerobic stability due to reduced residual sugars and lower yeast populations, which delays spoilage during feed-out.

3.4 Impacts on ruminant intake, digestibility, and performance

Improved fermentation quality enhances feed utilization in ruminants. Enzyme-treated rice straw silage increases digestibility by approximately 20–30%, reflecting improved ruminal microbial colonization and fiber degradation [12].

Higher digestibility is commonly associated with increased voluntary feed intake. Feeding trials indicate that replacing 30–50% of conventional forage with enzyme-treated rice straw silage improves dry matter intake and nutrient utilization [13]. Enhanced ruminal fermentation results in increased volatile fatty acid production, improving metabolizable energy supply and animal growth performance.

3.5 Environmental and sustainability implications

Utilization of rice straw for silage reduces open burning and associated greenhouse gas emissions. Conversion of straw into feed can reduce CO_2-equivalent emissions while improving resource efficiency [14]. Improved feed digestibility also contributes to reduced enteric methane emissions per unit of animal product due to enhanced ruminant fermentation efficiency and greater volatile fatty acid production relative to methane output.

From an economic perspective, integrating agricultural residues into feed production reduces reliance on imported forages and supports feed self-sufficiency. This strategy supports circular bioeconomy principles by converting waste biomass into valuable feed resources.

However, the economic feasibility of fungal enzyme supplementation depend on commercial enzyme cost, application rate and scale of production. Typical fibrolytic enzyme inclusion ranges from 0.5-2.0 g kg^{-1} dry matter. Assuming a commercial enzyme price of MYR 31.00 – 58.00 (USD 8.00 -15.00) per kg, the estimated additional cost ranges between MYR 20.00 – 140.00 (USD 0.004-0.03) per kg silage dry matter. This incremental cost may be offset by improved digestibility (20-30%), higher feed intake efficiency, reduced feeding period and lower methane intensity per unit of production. Cost-benefit analysis under farm-scale conditions in therefore essential to determine economic viability, particularly for smallholder systems.

3.6 Challenges and future directions

Despite demonstrated benefits, several limitations remain. Enzyme performance varies with substrate composition, environmental conditions, and ensiling management. Economic cost of enzyme production may limit adoption in smallholder systems. Future research should focus on optimizing multi-enzyme formulations, evaluating long-term feeding effects, and conducting life-cycle assessments to quantify environmental benefits [15].

4 Conclusions

Fungal enzyme-assisted ensiling of rice straw and agro-wastes improves fermentation quality, digestibility, and ruminant performance while reducing environmental impacts. This technology supports circular feed innovation by transforming agricultural residues into nutritionally valuable feed resources. Continued optimization and field-scale evaluation are essential to support sustainable livestock production systems.

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