Received: 02 June 2025 | Revised: 04 June 2025 | Accepted: 17 June 2025 | Available online: 25 July 2025
DOI: https://doi.org/10.31102/eam.2025.2.1.34-47

REVIEW ARTICLE

Environmental & Agriculture Management

Legume-grass intercropping in indonesian pastures: A systematic review on soil and forage nutritional improvements

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Abstract
The productivity and quality enhancement of tropical pastures in Indonesia faces critical constraints from soil degradation and low forage nutritional value. This study evaluates the potential of legume cover crop integration to simultaneously improve grass biomass, forage quality, and soil physicochemical properties. Using systematic analysis of 42 peer-reviewed articles (2000-2024) from Scopus, Web of Science, and Google Scholar, we employed Boolean search terms ("leguminous cover crops" AND "forage quality" AND "tropical pastures") followed by multi-stage screening to assess legume-grass systems across Indonesia's agroecosystems. Research findings reveal consistent improvements in both productivity and soil health parameters. Legume integration enhances biomass production by 30-65% and elevates crude protein content by 40-50% compared to conventional grass monocultures. Particularly effective species such as *Leucaena leucocephala* and *Centrosema pubescens* contribute to measurable soil quality enhancements, including increased organic matter content (0.5-1.5%), improved cation exchange capacity (2-5 cmol(+)/kg), and superior water retention capacity (15-20% improvement), while concurrently reducing soil erosion rates. Rhizobia inoculation requirements present technical barriers for some farming communities, while species-specific soil adaptation needs necessitate careful selection of appropriate legume varieties. Economic constraints further complicate adoption among smallholder farmers, particularly in resource-limited settings. This study underscores legume integration as a sustainable intensification strategy for tropical pasture systems. The dual benefits of productivity enhancement and environmental conservation position legume-based systems as a climate-smart agricultural approach for Indonesia's pasturelands.

KEYWORDS
Cover crop; Nutritive; Environmental; Legume; Soil

1. INTRODUCTION

The persistent decline in forage quality within Indonesia's tropical livestock systems remains a major challenge in achieving protein-based food security. Natural pastures, which support 72% of smallholder farmers, provide only 6-8% crude protein far below the 12-14% required for cattle nutrition (Kumara et al., 2022). Reliance on synthetic nitrogen fertilizers and supplemental feed has created a new paradox: soaring production costs, land degradation, and environmental strain. This trend is particularly alarming given projections from the Ministry of Agriculture, which estimates a 12-million-ton forage deficit by 2025 without technological intervention. Recent analyses indicate that legume-based silvopasture systems can enhance marginal land productivity by up to 40% while simultaneously increasing carbon sequestration capacity (Tramacere et al., 2024). This approach aligns with Indonesia's Nationally Determined Contributions (NDCs), which commit to reducing agricultural greenhouse gas emissions by 29% by 2030 (Eko Cahyono et al., 2022). Microclimatic challenges, such as rainfall variability and seasonal droughts, can be mitigated through the deep-rooting systems of legumes, enhancing ecosystem resilience. Despite this immense potential, technology adoption remains critically low, with farmer uptake below 15% according to data from the Indonesian Center for Animal Research and Development (Agussabti et al., 2022). The integration of innovative agricultural practices necessitates fundamental changes to existing systems. For cover cropping specifically, adoption barriers persist throughout the agricultural calendar (Figure 1), requiring comprehensive system-level adjustments to achieve successful implementation.

The integration of leguminous cover crops into tropical pasture systems is a well-documented agroecological strategy to enhance forage biomass and nutritive value. Studies in Indonesia have demonstrated that legume-grass intercropping significantly improves crude protein content and digestibility, with *Stylosanthes guianensis* increasing nitrogen availability by up to 40% in *Brachiaria*-based systems (Hilmiati et al., 2024). Research also highlights that selective breeding and rhizobium inoculation can further optimize nitrogen fixation efficiency, offering scalable solutions for smallholder farms. Thus, legume-based systems present a sustainable alternative to synthetic fertilizers for tropical forage production. Specific legumes like *Leucaena leucocephala* and *Centrosema pubescens* naturally enhance soil fertility and forage quality through symbiotic nitrogen fixation and organic matter accumulation (Dubeux Jr et al., 2024). In these systems, microbial activity in the rhizosphere plays a pivotal role in mineralizing nutrients, making them bioavailable for companion grasses. Livestock grazing trials in East Nusa Tenggara revealed that *Gliricidia sepium*-grass mixtures elevated cattle weight gain by 0.45 kg/day due to improved forage palatability and nutrient density (Nomseo et al., 2022). Field evidence suggests that combining legume diversification with strategic grazing management accelerates biomass recovery and reduces soil erosion. The primary challenge lies in adapting species-specific protocols to diverse agroecological zones and ensuring farmer adoption through tailored extension programs.

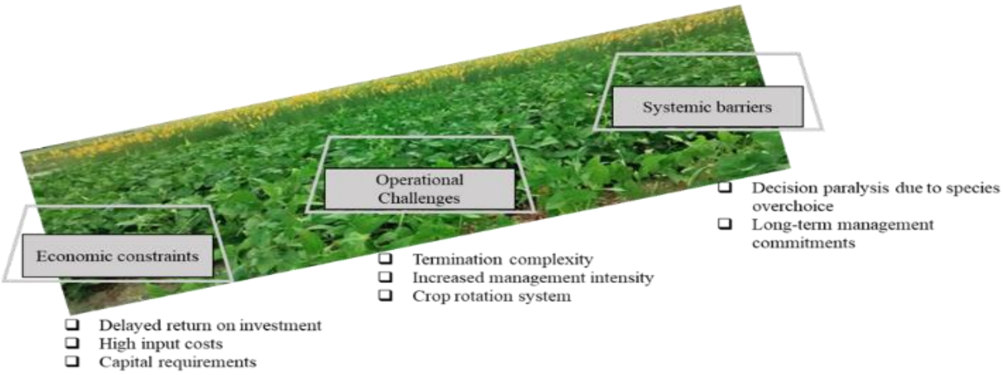

Figure 1. Visual summary of major challenges in agricultural cover crop adoption

Leguminous cover crops are increasingly recognized as vital components in tropical pasture systems, where they are typically integrated during fallow periods or as intercrops to optimize land use. Their successful implementation, however, demands careful consideration of species adaptation to local conditions, precise timing of planting and termination, and synchronization with livestock grazing cycles. This review seeks to systematically examine the role of leguminous cover crops in enhancing biomass production and nutritive value of tropical grass pastures, with particular emphasis on species-performance relationships under diverse Indonesian agroecologies and practical management approaches for smallholder systems. The primary aim of this review is to synthesize existing evidence on how legume-grass systems can simultaneously improve forage quality and soil health in Indonesia's tropical pastures. By analyzing the complex soil-plant-animal interactions, including nitrogen transfer mechanisms and organic matter accumulation processes, this work provides a comprehensive understanding of the synergies that make these systems effective. Furthermore, the review identifies optimal management practices, from species selection to grazing synchronization, that can be adapted to the unique constraints faced by Indonesian smallholder farmers.

2. METHODS

2.1 Literature review methodology

This study systematically evaluates the influence of legume cover crops on biomass production and nutritional quality of grasses in Indonesian tropical grazing systems. The literature search primarily relied on Scopus database, with complementary searches conducted in Web of Science and Google Scholar to identify potentially relevant but less indexed publications. The review focused on publications from 2000 to April 2024 to ensure the findings reflect contemporary agricultural practices. The literature selection process was carried out in stages (Figure 2).

2.2 Search strategy and selection criteria

The search strategy employed Boolean operators (AND, OR) to combine key terms including "leguminous cover crops", "forage legumes", "grass biomass production", "nutritive value", "legume cover crop" and "tropical pastures". This balanced approach aimed to optimize both search breadth and result relevance. The selection process involved rigorous multi-stage screening. Initial screening of 223 records based on titles and abstracts yielded 42 potentially relevant articles. Full-text evaluation applied strict inclusion criteria requiring studies to be conducted in Indonesia or similar tropical regions, with quantitative measurements of grass biomass and nutritional parameters including crude protein content and digestibility. Studies lacking proper control groups or sufficient empirical data were excluded from analysis.

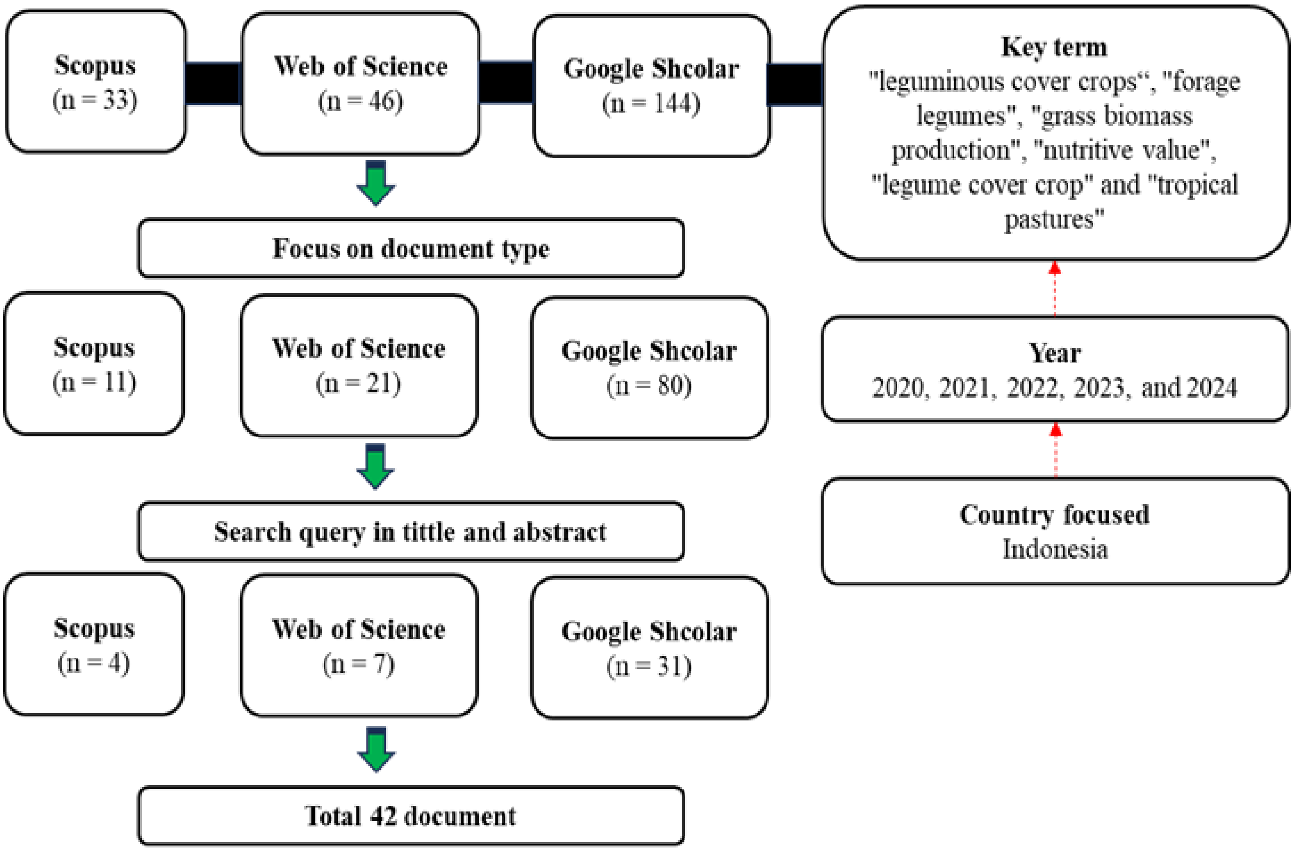

Figure 2. Flow chart data mining in this study

2.3 Data extraction and synthesis

A standardized extraction template systematically captured key variables including study location, legume and grass species, cultivation methods, biomass measurements, and nutritional quality indicators. Soil characteristics and management practices were also documented to enable deeper analysis. To minimize bias, two researchers independently performed data extraction, with any discrepancies resolved through consensus discussion (Pollock et al., 2023). Findings were synthesized through dual approaches. Quantitative data, particularly comparative measurements like crude protein enhancement, underwent meta-analysis using specialized software. Qualitative insights regarding adoption barriers and farmer preferences were analyzed thematically. Each study's quality was assessed based on methodological rigor, data completeness, and relevance to small-scale farming systems in Indonesia.

3. POTENTIAL LEGUMINOUS COVER CROP ON SOIL PROPERTIES

Leguminous cover crops have emerged as a cornerstone of sustainable tropical pasture systems in Indonesia, primarily due to their multifaceted capacity to enhance soil ecological functions. Species such as *Centrosema pubescens*, *Leucaena leucocephala*, and *Stylosanthes guianensis* dominate Indonesian agroecosystems, demonstrating remarkable adaptability to acidic soils and variable rainfall patterns (Maftukhah et al., 2023). The agronomic value of these legumes extends beyond nitrogen fixation, encompassing critical improvements in soil physical, chemical, and biological properties that underpin grassland productivity.

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The integration of legume and non-legume cover crops in agricultural systems demonstrates distinct mechanisms in soil organic carbon (SOC) sequestration (Figure 3). First, legume cover crops enhance soil nutrient availability and organic substrates through biological nitrogen fixation, stimulating microbial activity and biochemical transformations. This enhancement not only modifies SOC physical fractions (e.g., macroaggregates) but also alters chemical composition (lower C:N ratio), thereby reinforcing microbial in vivo pathways for long-term SOC accumulation. Second, non-legume cover crops tend to create microbial stoichiometric imbalances (higher C:N ratio), impairing microbial carbon cycling efficiency and reducing SOC retention via in vivo pathways. Third, the effectiveness of SOC sequestration is highly site-specific, where climatic (precipitation, temperature) and edaphic factors (soil texture, pH) interact with cover crop types. For instance, in arid regions, legumes may dominate in enhancing SOC through physical stabilization, while in humid areas, non-legumes could potentially mitigate SOC loss via chemical protection. These findings underscore the importance of location-specific approaches in selecting cover crop species for carbon sequestration optimization.

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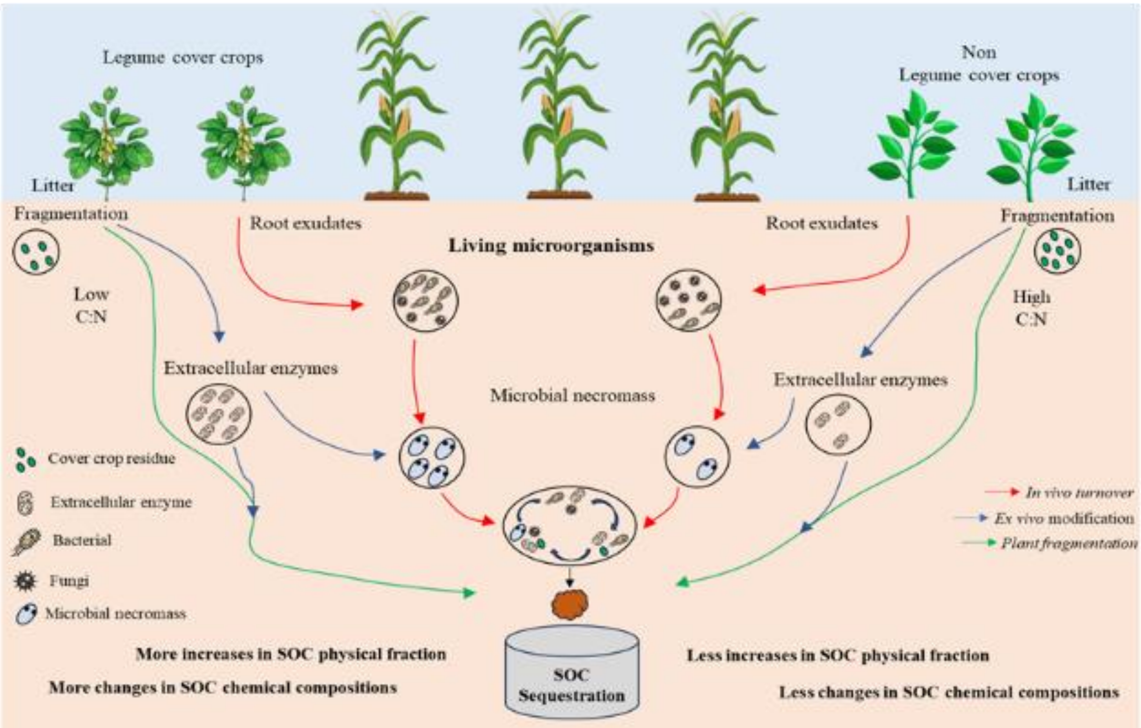

Figure 3. Mechanisms of SOC sequestration in cover crop systems, comparing leguminous and non-leguminous species (C:N = carbon/nitrogen ratio)

3.1 Soil physical properties

The introduction of leguminous cover crops in Indonesian tropical pastures induces transformative changes in soil physical properties, particularly in bulk density, hydraulic conductivity, and aggregate stability critical factors for sustainable grassland management. Research across Indonesia's major agroecological zones reveals that deep-rooted legumes like *Leucaena leucocephala* reduce bulk density by 12–18% in compacted soils (Esrarf, 2020), while fine-rooted Stylosanthes guianensis enhances topsoil porosity by 25–30% through biopore formation. These structural modifications are attributed to two synergistic mechanisms: (1) root penetration physically disrupts soil compaction layers, and (2) root exudates stimulate microbial production of glomalin, a glycoprotein that binds soil particles into stable aggregates (Priori et al., 2020). Water dynamics show particularly marked improvements. In Sumbawa's semi-arid pastures, *Centrosema pubescens* intercropping increased water infiltration rates by 40% compared to grass monocultures, while reducing surface runoff during monsoon rains by 35% (Maesaroh & Demirbağ, 2020). This is facilitated by the dual action of legume canopies intercepting rainfall energy and root networks creating macropores. Notably, soil moisture retention in East Kalimantan's degraded pastures improved by 15–20% after 24 months of *Flemingia macrophylla* integration, allowing extended grazing periods during dry seasons (Ria et al., 2021). Organic matter contributions from legume litterfall (typically 3.5–5.2 Mg ha^{-1} $year^{-1}$ in Indonesian systems) play a pivotal role in moderating soil temperature fluctuations a key concern in tropical pastures where surface temperatures often exceed 45°C. Field measurements in South Sulawesi demonstrated that *Calopogonium caeruleum* mulch layers reduced peak soil temperatures by 4–6°C, protecting microbial communities and reducing evaporation losses (Neswati et al., 2022).

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3.2 Soil chemical properties

Leguminous cover crops profoundly influence soil chemical properties in Indonesian pasture systems through multiple interconnected mechanisms. These nitrogen-fixing plants significantly enhance soil fertility by improving organic matter content, nutrient availability, and cation exchange capacity while modulating soil pH to optimal levels for plant growth (Wei et al., 2024). The decomposition of legume biomass from species such as *Leucaena leucocephala* and *Centrosema pubescens* contributes substantially to soil organic matter pools. Research across Indonesian agroecosystems demonstrates consistent increases in soil organic carbon ranging from 0.5% to 1.3% within two years of establishment (Tahuk et al., 2023). This organic matter enrichment serves as the foundation for improved soil chemical properties, particularly in nutrient-depleted soils. A key benefit emerges through enhanced nitrogen availability, with legume-based systems providing 40-75 kg of plant-available nitrogen per hectare each growing season. This nitrogen contribution occurs through gradual mineralization of legume residues, offering a more sustainable alternative to synthetic fertilizers. The nitrogen enrichment is complemented by improved phosphorus availability, as legume root exudates help solubilize phosphorus in Indonesia's typically phosphorus-fixing soils (Pantigoso et al., 2023). The cation exchange capacity of soils receives notable improvement through legume incorporation, particularly in degraded Ultisols. Studies document increases of 2-5 cmol (+) kg^{-1} in soil CEC, significantly enhancing the soil's ability to retain essential cations like potassium, calcium, and magnesium (Yang et al., 2024). This improvement proves especially valuable in high-rainfall environments where nutrient leaching represents a major challenge. Leguminous cover crops exhibit unique pH-modulating effects in tropical pasture systems (Shoudho et al., 2024). Unlike some temperate cover crops that may acidify soils, tropical legumes tend to stabilize or slightly increase soil pH through their nitrogen fixation processes. Field observations reveal pH increases of 0.3-0.8 units in acid soils, creating more favorable conditions for nutrient availability and microbial activity.

4. EFFECTS OF LEGUME COVER CROPS ON SUBSEQUENT CROP BIOMASS YIELD

The integration of leguminous cover crops into tropical pasture systems has demonstrated significant potential for enhancing subsequent grass biomass production through multiple synergistic pathways. Research conducted across Indonesia's diverse agroecological zones reveals consistent improvements in forage productivity when legumes are incorporated as cover crops or intercrops (Ngawit, 2023). Field trials in East Java documented substantial biomass increases in Pennisetum purpureum when grown in association with Leucaena leucocephala, with dry matter yields rising by 3.8 to 5.2 metric tons per hectare annually compared to grass monocultures. The mechanisms driving these biomass enhancements are multifaceted, with nitrogen fixation playing a central role. Studies from Lampung province provide compelling evidence of nitrogen transfer from legume to grass components, particularly in systems incorporating Stylosanthes guianensis (Epifanio et al., 2020). The decomposition characteristics of legume residues contribute significantly to this process, as their favorable carbon-to-nitrogen ratios (typically 15:1 to 20:1) facilitate rapid nutrient release during critical growth periods. This temporal synchronization between nutrient availability and grass demand proves especially valuable in smallholder systems where access to synthetic fertilizers remains limited.

Optimal biomass responses depend on careful consideration of several key factors. Species selection emerges as particularly important, with different legumes demonstrating adaptation to specific environmental constraints. Deep-rooted species show superior performance in drought-prone regions, while others excel in areas with periodic waterlogging (Alemu et al., 2020). Planting density represents another critical consideration, with research indicating that maintaining legume proportions between 30% and 40% of the stand typically yields the best results without suppressing grass components. Management practices significantly influence the magnitude of biomass response. Rotational grazing systems incorporating adequate recovery periods appear particularly effective at maximizing the benefits of legume-grass associations (Gultekin et al., 2021). Recent work in Sumbawa has highlighted how strategic defoliation timing can optimize nutrient transfer from legume to grass components, with systems incorporating regular cutting or grazing showing particularly strong performance.

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Table 1 summarizes recent research findings regarding the impact of various leguminous cover crop species on biomass production across different crops and growing environments. The consistent biomass improvements observed across multiple locations and management regimes suggest substantial potential for legume integration to enhance forage production (Bacchi et al., 2021). However, successful implementation requires careful attention to local conditions and management objectives, as the optimal approach may vary considerably between different production contexts. Current research efforts continue to refine recommendations for species selection and management practices, with particular focus on developing systems that balance biomass production with other important considerations such as forage quality and system sustainability.

Table 1. Recent Evidence on Legume Cover Crop Impacts on Following Crop Biomass Output

Legume cover	Subsequent crop	Location	Soil type	Yield increase (%)	Reference
Mucuna pruriens	Maize	USA	Ultisol	38 and 42	(Guterres et al., 2022)
Centrosema pubescens	Pepper	Indonesia	Latosol	28	(Kurniawati et al., 2024)
Crotalaria juncea	Mungbean	Indonesia	Andosol	22	(Winarto, 2022)
Leucaena leucocephala	Coffe	Mexico	Andosol	31	(López-Hernández et al., 2024)
Vigna unguiculata	Wheat	Indonesia	Grumusol	19	(Arif et al., 2021)

5. ENHANCING GRASS FORAGE QUALITY THROUGH LEGUMINOUS COVER CROP INTERCROPPING

The integration of leguminous cover crops with tropical grasses significantly improves forage nutritional quality while reducing dependence on synthetic nitrogen inputs. Legume-grass intercropping systems consistently enhance crude protein content, digestibility, and mineral availability in forage. Field trials in East Java revealed that *Centrosema pubescens* intercropping increased the crude protein content of *Brachiaria decumbens* from 7.2% to 12.8%, meeting the nutritional requirements for growing cattle (Fitriansa et al., 2022).

The nutritional enhancement primarily stems from two mechanisms: nitrogen transfer from legumes to companion grasses and improved mineral cycling. Studies using 15N isotopic tracing demonstrated that 25-35% of nitrogen fixed by *Leucaena leucocephala* becomes available to associated grasses within one growing season (Bageel et al., 2020). This nitrogen enrichment occurs through root exudation, leaf litter decomposition, and animal-mediated transfer via urine and dung in grazed systems. The lower carbon-to-nitrogen ratio (18:1) of legume biomass compared to tropical grasses (40:1) accelerates decomposition and nutrient release, particularly during peak grass growth periods. The forage quality improvements translate directly to livestock performance. Smallholder farms in Sumba implementing *Gliricidia sepium* grass systems reported 23% higher daily weight gain in Bali cattle compared to grass-only pastures (Marsetyo & Sulendre, 2022). Similarly, dairy cooperatives in West Java observed 15% greater milk yields when feeding Leucaena supplemented forage (Kamid et al., 2024). Current research focuses on developing dual purpose legumes that combine high nitrogen fixation with anti-methanogenic properties to simultaneously improve forage quality and reduce greenhouse gas emissions (Króliczewska et al., 2023). These advancements position legume-grass systems as a cornerstone of sustainable intensification in Indonesia's livestock sector.

6. PERFORMANCE OF LEGUMINOUS COVER CROP SPECIES IN INDONESIA AGROECOSYSTEMS

Cover crops have been successfully integrated into various agricultural systems across Indonesia, including smallholder farms, agroforestry, and commercial plantations. Among the most widely adopted species are *Centrosema pubescens*, *Leucaena leucocephala*, and *Stylosanthes guianensis*, which have demonstrated adaptability to diverse soil and climatic conditions. Research in East Java revealed that *Leucaena leucocephala* intercropping in maize systems improved soil nitrogen content by 35–50 kg ha^{-1}, leading to a 20–25% increase in maize yields compared to monoculture systems (Harsono et al., 2020).

In sugarcane plantations, *Calopogonium mucunoides* and *Pueraria javanica* have been shown to improve soil structure and reduce erosion while increasing sugarcane yields by 15–20% (Widiyani et al., 2022). These findings align with earlier studies in Lampung, where *Centrosema pubescens* was found to enhance water retention in degraded soils, supporting more resilient crop production during dry seasons (Wisnubroto et al., 2023). Despite these benefits, the effectiveness of leguminous cover crops varies depending on agroecological conditions. For instance, *Leucaena performs* exceptionally well in alkaline soils of East Java but struggles in highly acidic peatlands of Sumatra (Nufus et al., 2022). Similarly, Stylosanthes thrives in well-drained upland areas but is less effective in waterlogged lowlands (Amankwaa-Yeboah et al., 2023). To optimize adoption, site-specific recommendations are essential. These findings underscore the potential of leguminous cover crops to enhance soil health and crop productivity in Indonesia, provided species selection and management are adapted to local conditions.

7. IMPLICATION FOR PRACTICE AND POLICY

The integration of legume-grass systems in Indonesian tropical pastures offers transformative potential for both smallholder farmers and national agricultural development. For farmers, adopting locally adapted legume species such as *Leucaena leucocephala* and *Stylosanthes guianensis* can significantly improve forage quality while reducing reliance on synthetic fertilizers, provided they receive training in low-cost rhizobia inoculation techniques and rotational grazing management. These practices not only enhance livestock productivity but also build climate resilience by improving soil water retention and organic matter content, particularly crucial in drought-prone regions like East Nusa Tenggara. At the policy level, strategic interventions are needed to scale these benefits across Indonesia's diverse agroecological zones. Government support through seed subsidies, expanded extension services, and research into drought-tolerant legume varieties could accelerate adoption, while aligning with national climate commitments under the NDCs. By fostering public-private partnerships to strengthen legume seed markets and integrating forage improvement programs with existing land restoration initiatives, Indonesia can simultaneously address food security, soil degradation, and emission reduction goals. The success of small-scale models, such as the *Gliricidia*-based systems in Sumba that boosted cattle weight gain by 23%, demonstrates the viability of this approach when supported by coordinated policies and farmer-centric innovation.

8. LIMITATION

Despite their numerous benefits, several constraints hinder the widespread adoption of leguminous cover crops in Indonesian agricultural systems. The effectiveness of biological nitrogen fixation is significantly influenced by environmental conditions, with drought stress during critical growth periods reducing nodulation efficiency by 30-50% in water-limited regions of East Nusa Tenggara (Islam et al., 2021). This limitation is particularly acute in areas with unpredictable rainfall patterns, where the recommended practice of coinciding legume establishment with wet seasons becomes challenging. Soil nutrient imbalances present another major constraint, as observed in Sumatra's acidic soils where phosphorus and molybdenum deficiencies suppress rhizobia activity. Conversely, excessive nitrogen fertilization from preceding crops creates a paradoxical situation where legumes reduce their nitrogen fixation in response to soil nitrogen availability.

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The economic barriers to adoption are particularly pronounced for smallholder farmers. Initial establishment costs, including seed procurement (Rp 25,000-50,000 per kg for quality Centrosema seeds) and inoculation treatments, often exceed the immediate financial capacity of typical Indonesian cattle producers. Labor requirements for proper cover crop management add another layer of complexity, with weeding and pruning operations demanding 15-20 additional workdays per hectare annually.

8. CONCLUSION

The transformative potential of legume-grass systems in Indonesia extends beyond agricultural productivity, offering a paradigm shift toward climate-resilient livestock production. By systematically addressing forage quality deficits and soil degradation, this approach exemplifies how agroecological principles can reconcile food security with environmental sustainability. The demonstrated success of species like Leucaena and Centrosema in enhancing crude protein content by 40-50% while sequestering 0.5-1.5% additional soil organic carbon presents a compelling case for policy prioritization. However, the persistent gap between scientific evidence and on-ground adoption underscores the need for structural reforms. Smallholder farmers who steward 72% of Indonesia's pastures require targeted financial mechanisms to offset initial establishment costs, such as seed subsidies aligned with the National Strategic Livestock Development Program and risk-sharing schemes through cooperative models.

At the institutional level, mainstreaming legume-based systems into Indonesia's NDC implementation plans could unlock triple-win outcomes: mitigating methane emissions through improved forage digestibility, restoring 2.5 million hectares of degraded pasturelands by 2030, and reducing synthetic fertilizer imports. This transition demands coordinated action across ministries Agriculture, Environment, and Village Development to integrate pasture rejuvenation into social forestry schemes and climate finance initiatives. The forthcoming revision of Indonesia's Livestock Law presents a critical opportunity to embed legume integration as a mandatory component of sustainable pasture management. By bridging agroecological innovation with inclusive policy design, Indonesia can position itself as a global leader in tropical silvopastoral systems, turning the challenges of land degradation into a cornerstone of its bioeconomy strategy.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Morgan Ohiwal: Writing – original draft, Conceptualization. Tshepo Teele: Conceptualization, Supervision. Marchel Putra Garfansa: Methodology, Conceptualization, Writing – review & editing.

ACKNOWLEDGMENT

The authors would like to express his deepest gratitude to the parties who have contributed to the completion of this review. The authors were very grateful to the Universitas Muhammadiyah Maluku, University of South Africa and Universitas Islam Madura for providing the facilities and resources necessary for our study.

ETHICS APPROVAL

No ethical approval was needed for this study.

FUNDING

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

CONFLICT OF INTEREST

The authors reported no declarations of interest

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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