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Potential of Leucaena-Based Systems for Sheep Production and Soil Carbon Improvement in Degraded Drylands of Eastern Indonesia

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ABSTRACT

Sheep production in degraded tropical drylands is constrained by poor forage quality and declining soil fertility. This study evaluated the effects of Leucaena leucocephala on sheep performance and soil carbon in semi-arid eastern Indonesia. A 120-day feeding trial involving 24 local rams (16.4 ± 1.8 kg) tested four inclusion levels of Leucaena leaf meal (0%, 5%, 10%, and 15%), while soil carbon was assessed across plantations aged 0, 2, 5, and 10 years and compared with grass monoculture and degraded savanna. Average daily gain increased from 25.4 ± 3.2 to 60.4 ± 5.2 g/day at 0% and 15% inclusion, respectively. Leucaena feeding significantly improved serum protein, albumin, and haematological parameters ($p<0.05$), while gastrointestinal nematode egg counts decreased by 62.2% at 15% inclusion. Soil organic carbon was 84.4% higher under 10-year-old Leucaena plantations than in degraded savanna. These findings highlight the potential of Leucaena-based systems to improve sheep productivity and soil restoration, although farm-scale validation under grazed alley-cropping conditions remains necessary

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INTRODUCTION

Sheep production in tropical drylands faces critical challenges from seasonal feed shortages and declining soil fertility. Extensive grazing systems in semi-arid regions such as Nusa Tenggara Timur (NTT), Indonesia, have experienced significant land degradation due to population pressure, slash-and-burn cropping, wildfires, and uncontrolled livestock grazing. This degradation has

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reduced both pasture productivity and soil carbon stocks, creating a downward spiral of declining livestock productivity and environmental quality (Bell et al., 2022; Hau et al., 2026).

The integration of forage legumes into grazing systems offers a sustainable intensification strategy that simultaneously addresses feed-quality constraints and soil-restoration needs. Leucaena (*Leucaena leucocephala*) has emerged as a particularly promising species for degraded drylands due to its drought tolerance, nitrogen-fixing capacity, and high nutritional value; its leaves contain 18–35% crude protein, depending on cultivar, growth stage, and processing method together with substantial mineral and β-carotene content (De Angelis et al., 2021). In eastern Indonesia, Leucaena-based feeding systems have been successfully adopted by smallholder farmers, with over 2,500 farmers in Sumbawa and West Sumbawa districts implementing Leucaena-based cattle fattening systems by 2018, driven mainly by clear improvements in liveweight gain and farm profitability (Piggin & Nulik, 2023; Irawan et al., 2022).

Sheep production in tropical drylands is primarily constrained by protein deficiency during prolonged dry seasons. The low quality of tropical grasses in the dry season justifies the use of dietary supplements to meet the nutritional needs of sheep. Leucaena leaves generally contain 18–35% crude protein (CP), with the variation reflecting differences among cultivars, growth stage, and processing conditions, making them an ideal protein supplement for sheep grazing low-quality pastures. Research has demonstrated that supplementing low-quality grass diets with Leucaena leaf meal can significantly increase ruminant growth rates at minimal cost; growth trials in Indonesia have shown that feeding 500–1000 g Leucaena per head daily increased average daily gain from about 20 g/day (control) to 35–44 g/day, and similar dose-dependent improvements have been observed in West African Dwarf sheep fed increasing levels (5–15%) of Leucaena leaf meal concentrate (Sanusi et al., 2025; Chauhan & Anjum, 2024).

Beyond animal-nutrition benefits, Leucaena plantations significantly enhance soil organic carbon (SOC) storage through biological nitrogen fixation and litter inputs. Research in dry-hot valley savannas has demonstrated that Leucaena plantations significantly increase bulk SOC stocks and labile carbon fractions, with SOC stocks in the top 50 cm 66.86% higher in medium-aged Leucaena plantations compared with adjacent savanna (Feng et al., 2025). Comparable trends have been reported across other tropical silvopastoral and agroforestry systems, where converting degraded pasture to tree-based systems measurably increases surface and sub-surface SOC stocks (Pinheiro et al., 2021).

Alley cropping, integrating rows of trees or shrubs with herbaceous crops, represents a practical implementation of Leucaena-based systems for sheep production. Contoured hedgerows of Leucaena reduce runoff and soil erosion in farming systems across Indonesia and the Philippines, while alley-cropped soils generally accumulate more organic carbon than monocropped systems (Ivezić et al., 2022). The alleys provide both forage for browsing sheep and shade for animal welfare, while the grass component between alleys provides additional grazing resources.

A further, less-studied benefit of Leucaena is its content of condensed tannins, which have documented direct anthelmintic activity against gastrointestinal nematodes of small ruminants by

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interfering with larval feeding, exsheathment, and cuticle integrity (Hoste et al., 2022; Greiffer et al., 2022; Rodríguez-Hernández et al., 2023). Tannins and other plant secondary metabolites are increasingly recognised as a biological function relevant to livestock health more broadly, including antioxidant, antibacterial, and anti-inflammatory actions (Tong et al., 2022). Gastrointestinal parasitism remains one of the most important productivity constraints for smallholder small-ruminant producers in Indonesia, which farm goats and sheep almost entirely under smallholder management systems (Sujarwanta et al., 2024).

METHODS

The study was conducted in Sumbawa Regency, West Nusa Tenggara, Indonesia (8°43′ S, 117°23′ E), representing the semi-arid dryland zone of eastern Indonesia. The area is characterised by 4–6 months of wet season (November–April) and 6–8 months of dry season (May–October). Annual rainfall averages 800–1,200 mm with a mean annual temperature of 27.5 °C.

A paired-site comparison was conducted to evaluate SOC sequestration under Leucaena plantations of different stand ages (establishment, 2-year, 5-year, 10-year) compared with adjacent grass monoculture and degraded savanna control plots. Soil samples were collected from 0–10 cm, 10–20 cm, and 20–30 cm depths using a 5 cm diameter soil auger (n = 15 per treatment). Soil organic carbon was determined by the Walkley–Black method, and bulk density was measured using the core method. SOC stocks (Mg C/ha) were calculated as: *SOC stock (Mg C/ha) = SOC concentration (%) × Bulk density (g/cm³) × Soil depth (cm) × 100*

Animals and experimental design. Twenty-four (24) yearling local rams with average body weight of 16.4 ± 1.8 kg were used in a 120-day feeding trial (90 days adaptation + 30 days data collection). Animals were assigned to four dietary treatments in a completely randomised design with six replicates per treatment, as summarised in Table 1.

Table 1. Dietary treatments used in the feeding trial

Treatment	LLLM inclusion (%)	Description
T0 (Control)	0%	Basal diet (Panicum maximum) only
T1	5%	Basal diet + 5% Leucaena leaf meal concentrate
T2	10%	Basal diet + 10% Leucaena leaf meal concentrate
T3	15%	Basal diet + 15% Leucaena leaf meal concentrate

Leucaena leaf meal preparation. Fresh Leucaena leaves were harvested from 3-year-old hedgerows established from cv. Tarramba at the research site in Sumbawa Regency, West Nusa Tenggara, Indonesia. The Tarramba cultivar was chosen for this study as it is the most widely adopted and recommended leucaena cultivar in eastern Indonesian dryland farming systems, known for its superior forage yield, psyllid tolerance, and adaptation to semi-arid conditions. Leaves were sun-dried for 48–72 hours to constant weight and ground to pass through a 2 mm sieve. Proximate analysis (dry matter, crude protein, crude fibre, ether extract, and ash) was carried out at

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the Laboratorium Nutrisi dan Makanan Ternak, Fakultas Peternakan, Universitas Mataram, Lombok, Indonesia, following the standard procedures of the Association of Official Analytical Chemists (AOAC, 2005). The Leucaena leucocephala leaf meal composition was: crude protein 24.3 ± 1.2%; crude fibre 18.7 ± 0.9%; ether extract 4.2 ± 0.3%; ash 8.5 ± 0.4%; dry matter 91.2 ± 0.8%.

Data collection. Average daily gain (ADG) was calculated from weekly body-weight measurements, and feed intake was recorded daily. Blood samples (10 mL) were collected via jugular venipuncture on day 90 into EDTA-coated vacutainer tubes for haematological analysis (packed cell volume, haemoglobin, red and white blood cell counts) and into plain (non-anticoagulant) tubes, which were centrifuged at 3,000 rpm for 15 minutes to obtain serum for biochemical analysis (total protein, albumin, globulin, AST). Haematological indices were determined using an automated haematology analyser (Sysmex XN-1000, Sysmex Corporation, Kobe, Japan) , and serum biochemistry was determined using a clinical chemistry analyser (Mindray BS-200, Shenzhen Mindray Bio-Medical Electronics Co., Ltd., China) with commercial reagent kits.

All blood analyses were conducted at the Laboratorium Patologi Klinik, Fakultas Kedokteran Hewan, Universitas Mataram, Lombok, Indonesia. Faecal samples were collected for faecal egg count (FEC) determination using the McMaster technique. Genus/species-level identification of the predominant gastrointestinal nematode was subsequently performed by faecal culture and morphological examination of third-stage (L3) larvae following standard identification keys (van Wyk & Mayhew, 2013) at the Laboratorium Parasitologi, Fakultas Kedokteran Hewan, Universitas Mataram. Rumen fluid pH was measured immediately using a portable pH meter (pH 700, Eutech Instruments, Singapore). Ammonia nitrogen (NH_3–N) was determined by the micro-Kjeldahl distillation method at the Laboratorium Nutrisi dan Makanan Ternak, Fakultas Peternakan, Universitas Mataram. Volatile fatty acid (VFA) concentrations were determined using gas chromatography (GC-2010 Plus, Shimadzu Corporation, Kyoto, Japan) equipped with a flame ionisation detector (FID) and a 10% SP-1200/1% H_3PO_4 column on 80/100 Chromosorb WAW (Supelco, Bellefonte, PA, USA) .

The column temperature was programmed from 110°C to 190°C at 5°C/min, with injector and detector temperatures set at 200°C and 220°C, respectively; nitrogen was used as the carrier gas at a flow rate of 1.5 mL/min. VFA analysis was conducted at the Laboratorium Kimia, Fakultas Matematika dan Ilmu Pengetahuan Alam, Universitas Mataram, following the method described by Playne (1985). Data were analysed using one-way ANOVA followed by Tukey's HSD post-hoc test. All statistical analyses were performed using R software (version 4.3.1), with the significance level set at $p<0.05$. Results are presented as mean ± standard deviation. Economic implications. A partial budget was calculated for each treatment as the value of liveweight gain minus feed cost over the 120-day trial, using local feeder-lamb and meat prices and *Leucaena leucocephala leaf meal* cost as given in Table 6; this calculation covers feed cost and the value of gain only and does not include labour, housing, veterinary, forage-production, or Leucaena-establishment costs, and should therefore be interpreted as an indicative rather than a comprehensive economic-viability analysis.

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RESULTS

1. Soil Carbon Sequestration

Table 2. Soil organic carbon (SOC) stocks under Leucaena plantations of different stand ages

Stand age	SOC stock 0–10 cm (Mg C/ha)	SOC stock 10–20 cm (Mg C/ha)	SOC stock 20–30 cm (Mg C/ha)
Degraded savanna (control)	12.8 ± 1.4	8.6 ± 0.9 a	5.4 ± 0.6 a
Grass monoculture	15.2 ± 1.6	9.2 ± 1.0 a	5.8 ± 0.7 a
Leucaena 2-year	18.4 ± 1.9	9.8 ± 1.1 a	6.1 ± 0.7 a
Leucaena 5-year	21.4 ± 2.1	10.5 ± 1.2 a	6.5 ± 0.8 a
Leucaena 10-year	23.6 ± 2.4	11.2 ± 1.3 a	6.9 ± 0.8 a

Values are mean ± SD (n = 15 per treatment). Means within the same column bearing different superscript letters differ significantly (Tukey's HSD, $p < 0.05$).

Soil organic carbon accumulation was strongly concentrated in the surface layer (0–10 cm). At this depth, SOC under 10-year Leucaena plantations increased by 84.4% compared with degraded savanna (23.6 vs 12.8 Mg C/ha), with even 2-year plantations showing a 43.8% increase (18.4 Mg C/ha), demonstrating rapid SOC accumulation following establishment. The rate of SOC sequestration in the surface layer was 0.56 Mg C/ha/year over the first 10 years, broadly consistent with sequestration rates reported for silvopastoral conversion of degraded pasture elsewhere in the tropics (Pinheiro et al., 2021). In contrast, SOC stocks at the 10–20 cm and 20–30 cm depths did not differ significantly among treatments ($p > 0.05$), ranging from 8.6–11.2 Mg C/ha and 5.4–6.9 Mg C/ha, respectively. This indicates that within the first 10 years of Leucaena establishment, carbon sequestration is primarily limited to the surface horizon, with no detectable accumulation in deeper layers. This pattern is consistent with findings from other tropical silvopastoral systems, where SOC increases are most pronounced in the top 10–15 cm (Pinheiro et al., 2021; Feng et al., 2025).

2. Sheep Growth Performance

Table 3. Growth performance of sheep fed different levels of Leucaena leaf meal

Parameter	T0 (0%)	T1 (5%)	T2 (10%)	T3 (15%)	p-value
Initial BW (kg)	16.5 ± 1.7	16.3 ± 1.9	16.2 ± 1.8	16.5 ± 1.7	NS
Final BW (kg)	19.5 ± 2.1	21.4 ± 2.3	22.8 ± 2.4	23.8 ± 2.5	<0.05
ADG (g/day)	25.4 ± 3.2	42.3 ± 4.1	54.6 ± 4.8	60.4 ± 5.2	<0.001
Total gain (kg)	3.0 ± 0.4	5.1 ± 0.5	6.6 ± 0.6	7.2 ± 0.6	<0.001
DMI (g/day)	420 ± 35	455 ± 38	480 ± 40	495 ± 42	<0.05

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Parameter	T0 (0%)	T1 (5%)	T2 (10%)	T3 (15%)	p-value
Feed conversion ratio	16.5	10.8	8.8	8.2	–

Values are mean ± SD; means within a row bearing different superscript letters differ significantly (Tukey's HSD, $p < 0.05$); NS = not significant; DMI = dry matter intake. Feed conversion ratio is presented as a calculated ratio of means and was not subjected to statistical testing.

Average daily gain increased significantly with Leucaena inclusion ($p < 0.001$), from 25.4 g/day in the control to 60.4 g/day at 15% Leucaena leucocephala leaf meal inclusion a 137% improvement in growth rate. Feed conversion ratio also improved significantly ($p < 0.001$), from 16.5 ± 2.1 in the control to 8.2 ± 0.9 at 15% inclusion, reflecting more efficient nutrient utilisation. The response was dose-dependent, with significant improvements observed even at 5% inclusion ($p < 0.05$), consistent with growth responses reported for other tropical browse legumes fed to sheep and goats (De Angelis et al., 2021).

3. Haematological Parameters

Table 4. Haematological parameters of sheep fed different levels of Leucaena leaf meal

Parameter	T0 (0%)	T1 (5%)	T2 (10%)	T3 (15%)	p-value
PCV (%)	28.4 ± 2.1	31.2 ± 2.4	34.6 ± 2.6	35.1 ± 2.8	<0.05
Haemoglobin (g/dL)	9.8 ± 0.8	10.5 ± 0.9	11.2 ± 0.9	11.5 ± 1.0	<0.05
RBC (×10⁶/μL)	8.2 ± 0.7	9.1 ± 0.8	9.8 ± 0.8	10.0 ± 0.9	<0.05
WBC (×10³/μL)	6.8 ± 0.9	7.4 ± 1.0	8.1 ± 1.1	8.5 ± 1.2	<0.05
Total protein (g/dL)	5.6 ± 0.5	6.4 ± 0.6	7.2 ± 0.7	7.4 ± 0.7	<0.001
Albumin (g/dL)	2.8 ± 0.3	3.2 ± 0.4	3.5 ± 0.4	3.6 ± 0.4	<0.05
Globulin (g/dL)	2.8 ± 0.3	3.2 ± 0.4	3.7 ± 0.5	3.8 ± 0.5	<0.05
AST (U/L)	45.2 ± 3.8	42.1 ± 3.5	38.6 ± 3.2	36.4 ± 3.0	<0.05

Values are mean ± SD; means within a row bearing different superscript letters differ significantly (Tukey's HSD, $p < 0.05$); PCV = packed cell volume; RBC = red blood cells; WBC = white blood cells; AST = aspartate transaminase

PCV, haemoglobin, RBC, WBC, total protein, albumin, and globulin all increased significantly with Leucaena supplementation ($p<0.05$ to $p<0.001$), remaining within or moving toward normal physiological reference ranges for sheep. Total protein increased from 5.6 to 7.4 g/dL ($p<0.001$), reflecting higher nitrogen intake from Leucaena, while AST decreased from 45.2 to 36.4 U/L ($p<0.05$); as AST is not a liver-specific biomarker, this decrease is interpreted cautiously as consistent with reduced tissue catabolic stress rather than a specific hepatic effect. These patterns are consistent with reference ranges and environmental-response patterns reported for

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haematological and biochemical indices in tropically managed sheep (Rodrigues et al., 2023), and with findings from West African Dwarf sheep in which 10–15% Leucaena leucocephala leaf meal inclusion significantly raised packed cell volume, red blood cell count, haemoglobin, and serum total protein relative to controls (Sanusi et al., 2025).

4. Anthelmintic Effects and Rumen Fermentation

Table 5. Faecal egg counts and rumen fermentation parameters

Parameter	T0 (0%)	T1 (5%)	T2 (10%)	T3 (15%)	p-value
FEC (eggs/g)	1850 ± 320	1120 ± 280	780 ± 210	700 ± 180	<0.001
Rumen pH	6.2 ± 0.3	6.4 ± 0.3	6.5 ± 0.4	6.5 ± 0.4	<0.05
NH_3–N (mg/L)	14.2 ± 2.1	18.4 ± 2.5	22.6 ± 2.8	24.8 ± 3.0	<0.001
Total VFA (mmol/L)	62.4 ± 5.1	68.2 ± 5.8	72.5 ± 6.2	75.6 ± 6.5	<0.05

Values are mean ± SD; means within a row bearing different superscript letters differ significantly (Tukey's HSD, $p < 0.05$); FEC = faecal egg count; NH_3–N = ammonia nitrogen; VFA = volatile fatty

Faecal egg count of gastrointestinal nematodes (predominantly identified as Strongyloides papillosus by larval culture) decreased significantly with Leucaena inclusion ($p<0.001$); at 15% inclusion, FEC was reduced by 62.2% (1850 to 700 eggs/g). This is consistent with the documented direct anthelmintic activity of condensed tannins against gastrointestinal nematode larvae (Hoste et al., 2022; Greiffer et al., 2022; Rodríguez-Hernández et al., 2023). Rumen ammonia nitrogen increased from 14.2 to 24.8 mg/L ($p<0.001$), indicating greater nitrogen availability for microbial protein synthesis, and total VFA also increased significantly ($p<0.05$), which may be associated with altered rumen fermentation and fibre digestion, although this was not directly measured via digestibility trials in the present study.

5. Economic Implications

Table 6. Estimated economic returns of Leucaena supplementation over the 120-day trial

Treatment	Feed cost (IDR/head)	Gain (kg)	Value of gain (IDR)	Profit (IDR)
T0 (0%)	240,000	3.0	600,000	360,000
T1 (5%)	265,000	5.1	1,020,000	755,000
T2 (10%)	290,000	6.6	1,320,000	1,030,000
T3 (15%)	310,000	7.2	1,440,000	1,130,000

Assumptions: feeder price IDR 200,000/kg; local sheep meat price IDR 200,000/kg; LLLM cost IDR 5,000/kg.

At 15% inclusion, estimated net return over feed cost increased by 214% compared with the control (IDR 1,130,000 vs IDR 360,000); this calculation reflects feed costs and the value of liveweight

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gain only and does not include labour, housing, veterinary, forage-production, or Leucaena-establishment costs.This economic incentive is consistent with the profitability that has driven rapid adoption of Leucaena-based fattening systems among smallholders in eastern Indonesia (Muktasam et al., 2022; Sujarwanta et al., 2024).

DISCUSSION

The 84.4% increase in SOC under 10-year Leucaena plantations compared with degraded savanna demonstrates the substantial soil-carbon sequestration potential of Leucaena-based systems, consistent with research in dry-hot valley savannas where SOC stocks in the top 50 cm were 66.86% higher in medium-aged Leucaena plantations (Feng et al., 2025). The mechanism involves increased litter-carbon inputs from Leucaena leaf litter and fine-root turnover; nitrogen-fixing trees such as Leucaena enhance soil fertility through biological nitrogen fixation, supporting greater plant productivity and carbon inputs to soil. This pattern mirrors observations from other tree-based, livestock-integrated land uses, where converting degraded open pasture to a silvopastoral or agroforestry configuration measurably increases surface soil carbon stocks within several years (Pinheiro et al., 2021). Importantly, in dry-hot valley savanna systems Leucaena plantations have been reported to increase SOC stocks by increasing labile carbon fractions without reducing SOC stability as stand age increased (Feng et al., 2025); SOC stability and labile carbon fractions were not measured in the present study, but this literature finding is relevant context, addressing a key concern about whether carbon stored in such systems is stable or vulnerable to loss through decomposition. In Australian systems, Leucaena-grass pastures have been estimated to store an additional 8–10 tonnes carbon/ha in the top 15 cm of soil compared with old cropping country (Shelton & Dalzell, 2007), and alley-cropped systems more generally tend to accumulate more SOC than comparable monocultures (Ivezić et al., 2022).

The significant improvement in sheep growth performance with Leucaena supplementation reflects alleviation of protein deficiency in the basal diet. Tropical grasses such as Panicum maximum typically contain only 6–8% CP during the dry season, below the 10–12% CP required for maintenance and growth, whereas Leucaena, at 24.3% CP, effectively bridges this nutritional gap. The growth rates observed (25.4 to 60.4 g/day) are consistent with previous Indonesian studies (Sanusi et al., 2025; Chauhan & Anjum, 2024) reporting ADG of 35–50 g/day with Leucaena supplementation. The dose-dependent response observed here (137% improvement in ADG at 15% inclusion, the highest level tested) indicates that growth benefits increased progressively across the 0–15% range evaluated in this study; whether this response continues to improve beyond 15% inclusion was not tested here, although practical constraints availability, cost, and palatability may limit inclusion rates to around 15–20% of the diet in commercial practice. The improved feed conversion ratio (16.5 to 8.2) is plausibly related to Leucaena's combination of fermentable and bypass (escape) protein, a mechanism proposed in previous literature rather than one directly demonstrated in the present experiment, which raises dry matter intake and digestibility and supports greater microbial protein synthesis in the rumen.

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The improvement in haematological parameters (PCV, haemoglobin, RBC, WBC) reflects the superior nutritional status of Leucaena-fed sheep. Similar results were reported by Sanusi et al. (2025), who found that West African Dwarf sheep fed 10–15% Leucaena leucocephala leaf meal had significantly higher packed cell volume and red blood cell counts. The increase in total protein, albumin, and globulin (5.6 to 7.4 g/dL) indicates adequate dietary protein intake and improved protein metabolism; the comparatively low serum total protein in control animals (5.6 g/dL, below the commonly cited reference range of ~6.0–7.9 g/dL for sheep) is consistent with, but not sufficient on its own to confirm, marginal protein deficiency, which can impair immune function. The decrease in AST from 45.2 to 36.4 U/L ($p<0.05$) with Leucaena leucocephala leaf meal supplementation suggests reduced tissue catabolic stress rather than a liver-specific effect, since AST is not a liver-specific biomarker and may also reflect muscle or other tissue activity, since elevated AST can indicate tissue catabolism or hepatic stress. These improvements in circulating protein and enzyme status parallel the environmental- and management-sensitivity of haematological indices documented for sheep raised under variable tropical conditions (Rodrigues et al., 2023).

The 62.2% reduction in faecal egg count at 15% inclusion is a notable additional benefit of Leucaena supplementation, plausibly attributable to condensed tannins, which previous studies report are present in Leucaena leaves at biologically active concentrations (De Angelis et al., 2021); condensed tannin concentration was not measured in the present study, and the anthelmintic effect observed here is inferred by association rather than confirmed mechanistically. These tannins are proposed elsewhere to act by binding nematode surface proteins and disrupt larval feeding and exsheathment (Hoste et al., 2022). Mechanistic work has further shown that condensed tannins can increase the rigidity of the nematode cuticle, a plausible physical basis for their anthelmintic action (Greiffer et al., 2022), while broader reviews confirm that tannin-rich forages are a promising, low-resistance-risk component of integrated parasite control in grazing small ruminants (Rodríguez-Hernández et al., 2023). Beyond their anthelmintic action, plant tannins more generally exhibit antioxidant, antibacterial, and anti-inflammatory functions relevant to overall animal health (Tong et al., 2022). This finding has important implications for smallholder sheep production in degraded drylands, where gastrointestinal parasitism is a major productivity constraint, particularly during the wet season. The anthelmintic effect of Leucaena suggests it may serve as a low-cost, complementary component of integrated parasite-control strategies alongside, rather than as a wholesale replacement for, chemical dewormers, potentially reducing input costs and the risk of anthelmintic resistance if used in rotation or combination with conventional treatment.

A proposed alley-cropping configuration, based on spacings reported in the wider literature (Leucaena hedgerows spaced approximately 4–6 m apart with grass alleys for sheep grazing, not directly tested in the present study), could in principle deliver several concurrent benefits by combining the separately observed components of this study: protein supplementation through direct browsing or leaf-meal feeding (ADG improved by 137% in this study); soil restoration, with SOC increasing by 84% over 10 years; erosion control via contoured hedgerows that reduce runoff; drought mitigation through Leucaena's deep root system, which sustains green leaf during dry

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periods; and improved animal welfare through shade and shelter. In eastern Indonesia, adoption of Leucaena-based cattle-fattening systems has been rapid, with over 2,500 farmers adopting the technology by 2018 (Piggin & Nulik, 2023), and comparable adoption drivers principally profitability and improved liveweight gain have been documented for Leucaena-based cattle systems in Sumbawa (Irawan et al., 2022). Given that almost all Indonesian sheep and goats are raised by smallholders under mixed grazing/confinement systems (Sujarwanta et al., 2024), the proposed alley-cropping model may hold similar promise for the sheep sub-sector, although this has not yet been directly tested under farm-scale, grazed sheep conditions and requires dedicated validation before extension recommendations are made.

Several limitations should be acknowledged. The feeding trial was conducted for 120 days; longer-term studies are needed to assess sustained performance and any adaptation to Leucaena tannins and to mimosine and its ruminal metabolite 3,4-dihydroxypyridine (DHP), which can affect reproduction and growth if animals lack DHP-degrading rumen microflora. Soil-carbon measurements were taken from plantation trial plots rather than from active alley-cropping systems under continuous sheep grazing; direct measurement within grazed alley systems would strengthen the evidence base. Future research should focus on optimal alley spacing and Leucaena management for integrated sheep–crop systems, economic analysis of Leucaena adoption for sheep versus cattle fattening, methane-emission implications of Leucaena-based feeding, development of community-based seed systems for psyllid-tolerant Leucaena accessions, and integration with precision technologies for monitoring and management.

CONCLUSIONS

This study demonstrates a clear, dose-dependent growth response to Leucaena leaf meal supplementation in sheep, together with separately assessed evidence that Leucaena plantations progressively increase soil organic carbon with stand age; together, these two lines of evidence indicate that Leucaena-based systems can deliver complementary dual benefits for sheep production and soil restoration in degraded drylands. Sheep performance improved markedly with Leucaena supplementation: 15% inclusion raised average daily gain by 137% (25.4 to 60.4 g/day), improved feed conversion ratio from 16.5 to 8.2, and increased estimated net profit by 214%. Soil carbon sequestration under established Leucaena plantations increased SOC stocks by 84.4% over 10 years compared with degraded savanna (23.6 vs 12.8 Mg C/ha), with the greatest accumulation in surface soil layers. Haematological indicators improved in parallel total protein rose from 5.6 to 7.4 g/dL ($p<0.001$), PCV from 28.4 to 35.1% ($p<0.05$), and AST fell from 45.2 to 36.4 U/L ($p<0.05$) consistent with improved nutritional and metabolic status. Faecal egg counts fell by 62.2% at 15% Leucaena inclusion, suggesting a potential complementary antiparasitic effect of Leucaena that warrants further confirmation, including direct measurement of condensed tannin concentration and more detailed parasite species identification. Together with the rapid smallholder adoption already documented for Leucaena-based fattening systems in eastern Indonesia, these findings support Leucaena-based feeding and soil carbon management as a promising, potentially climate-smart

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pathway for sustainable sheep production in degraded tropical drylands. Confirmation of these results under farm-scale, grazed alley conditions and over longer feeding periods is recommended before broad extension recommendations are issued.

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