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Research Article

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Bio-Based Feed Additives and Metabolic Modulators for Enhanced Productivity: Sustainable Low-Cost Feed Strategies Using Local Biomass Resources for Small Ruminant Production in the Aspirational Districts of West Bengal

Dr. Keshab Chandra Dhara[1]*, Dr. Kaushik Pal[2], Suprava Roy[3], Shrestha Roy[3], Paramita Dasgupta[3], Disha Banerjee[3], Biman Sarkar[3] and Aditi Datta[4]*

[1]*Directorate of Research, Extension farms, West Bengal University of Animal & Fishery Sciences, India*

[2]*SMS, Animal Science, AshokeNagar KVK, WBUAFS*

[3]*Young ProfessionalII, Biotech-KISAN Hub, Directorate of Research, Extension & Farms (DREF), West Bengal University of Animal & Fish-ery Sciences, Kolkata, India*

[4]*Project Assistant, Biotech-KISAN Hub, Directorate of Research, Ex-tension & Farms (DREF), West Bengal University of Animal & Fishery Sciences, Kolkata, India*

***Corresponding Author**
Dr. Keshab Chandra Dhara, Directorate of Research, Extension farms, West Bengal University of Animal & Fishery Sciences, India.

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Abstract

The integration of bio-based feed additives and metabolic modulators offers an innovative pathway to enhance small ruminant productivity while reducing feed costs and environmental impacts. This study explores the utilization of locally available biomass resources as bio-functional feed ingredients for sustainable Black Bengal goat production across five aspirational districts of West Bengal—Murshidabad, Birbhum, Malda, Dakshin Dinajpur, and Nadia. A 120-day controlled feeding trial involving 489 goats evaluated feed formulations incorporating sugarcane tops, cassava leaves, sweet potato vines, Leucaena, and Sesbania leaf meals as natural sources of secondary metabolites, antioxidants, and fermentable fibers with metabolic modulating potential. Three dietary treatments were tested: T_1 (conventional concentrate feed), T_2 (50% concentrate replaced with biomass-based mix), and T_3 (70% replacement). Nutrient profiling revealed crude protein levels of 14.6–22.5% and total digestible nutrients (TDN) of 55–65%, confirming biochemical adequacy. Biomass-based diets reduced total feed costs by 28–33% and improved metabolic eficiency indicators such as average daily gain (ADG; up to 16% higher in T_3), feed conversion ratio (FCR), and benefit–cost ratio (BCR; from 1.28 to 1.68). These bio-based feed formulations acted as natural metabolic enhancers, optimizing rumen fermentation and nutrient utilization. The study demonstrates that locally derived biomass can serve as effective bio-additives and metabolic modulators, establishing a climate-resilient, low-cost, and circular bioeconomy model for sustainable goat production in Eastern India.

Keywords: Bio-Based Feed Additives, Metabolic Modulators, Small Ruminants, Local Biomass, Sustainable Livestock, Circular Bio economy, West Bengal

1. Introduction

Goat farming is a cornerstone of livelihood security and nutritional resilience for rural households in Eastern India. Among indigenous breeds, the Black Bengal goat (Capra hircus) holds exceptional importance due to its high fertility, adaptability, superior meat quality, and suitability for backyard and smallholder production systems. In the five aspirational districts of West Bengal—Murshidabad, Birbhum, Malda, Dakshin Dinajpur, and Nadia goat rearing represents a vital livelihood strategy, particularly for marginal, landless, and women farmers, who depend on small livestock for regular income and nutritional support.

However, the productivity of Black Bengal goats in these districts remains substantially below their genetic potential, primarily due to nutritional deficiencies, feed scarcity, and high feed costs. Feeding represents 65–70% of the total production expenditure, and the dependence on market-purchased concentrates often undermines profitability and sustainability [1]. Traditional feeding relies on grazing and sporadic supplementation with crop residues or household by-products, which are nutritionally imbalanced and seasonally inconsistent. Paradoxically, these districts produce a substantial quantity of agro-industrial and farm residues—including sugarcane tops, cassava leaves, sweet potato vines, banana pseudo stems, and foliage from Leucaena and Sesbania shrubs—that remain underutilized or discarded. These materials, when properly processed, possess high potential as low-cost, nutrient-rich feed ingredients. Their use not only reduces feed cost but also enhances circular bio economy principles, where agricultural biomass is recycled into livestock production systems, reducing waste and improving farm sustainability [2,3].

Adoption of biomass-based feeding systems aligns with India's policy thrust on biotechnological innovations for rural transformation, as promoted under the Department of Biotechnology's Biotech-KISAN Programme and the National Livestock Mission. These initiatives emphasize region-specific, resource-efficient, and climate-resilient feeding strategies that can empower smallholder farmers through sustainable practices.

Therefore, the present study was designed to explore the feasibility and performance outcomes of sustainable, low-cost, locally formulated feeds using available biomass resources across five aspirational districts of West Bengal. The specific objectives were to:

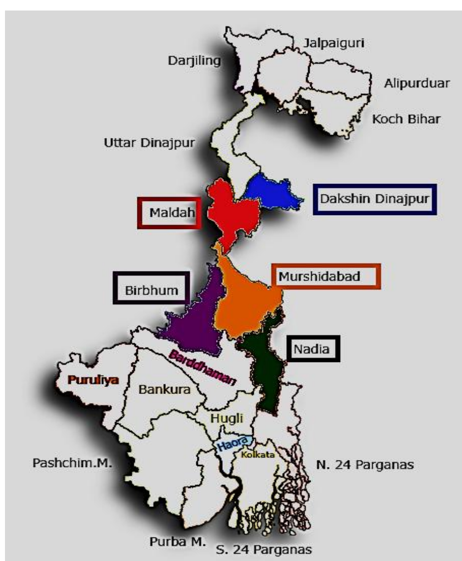
1. Characterize and analyze the nutrient composition of locally available biomass feed resources in selected districts.
2. Evaluate the growth performance, feed efficiency, and economic returns of Black Bengal goats fed biomass-based diets.
3. Develop a scalable, low-cost feed model promoting circular bio economy and self-reliant goat production systems for smallholders.

A total of 489 Black Bengal goats were enrolled under controlled on-farm feeding trials, representing varied socio-agro-ecological conditions. The study aimed to demonstrate that sustainably produced, biomass-based feeds can maintain animal productivity while reducing production costs, thus fostering a resilient, inclusive, and economically viable goat-rearing model for the aspirational districts of Eastern India.

2. Materials and Methods

2.1 Study Area

The study was carried out across five aspirational districts of West Bengal—Murshidabad, Birbhum, Malda, Dakshin Dinajpur, and Nadia—representing distinct agro-climatic zones, soil types, and farming systems. These districts are characterized by a tropical humid to sub-humid climate, with average annual rainfall ranging from 1,200 to 1,600 mm, mean temperature from 12°C (winter) to 37°C (summer), and mixed cropping patterns dominated by paddy, jute, sugarcane, and vegetables. Each district has a significant small ruminant population, where Black Bengal goats are raised predominantly under semi-intensive or backyard systems. Field-level implementation and sample collection were conducted in collaboration with local Biotech-KISAN Hub satellite centers under the West Bengal University of Animal & Fishery Sciences (WBUAFS).



2.2 Experimental Design and Animals

A total of 489 clinically healthy Black Bengal goats (age 5–8 months, average initial body weight 8.4 ± 0.3 kg) were selected from smallholder farmers across the five districts using a stratified random sampling approach. Goats were allocated into three treatment groups, maintaining uniform distribution by age, sex, and body weight across replications. The experiment followed a completely randomized design (CRD) with three dietary treatments and three replications per district.

➢ **Treatment Groups**

Treatment	Description	Concentrate Replacement Level
T1 (Control)	Conventional concentrate-based feeding	0%
T2	Biomass-based feed replacing concentrate	50%
T3	Biomass-based feed replacing concentrate	70%

Each treatment group was maintained under semi-intensive management (4–5 hours grazing daily plus stall feeding), with water and mineral mixture available ad libitum. The feeding trial was conducted for 120 days, following a 15-day adaptation period.

2.3 Feed Resource Identification and Collection

Locally available biomass feed resources were identified through resource mapping surveys and farmer participatory assessments in each district. The key feed ingredients selected based on their availability, palatability, and nutritive potential included:

- Sugarcane tops (Saccharum officinarum)
- Cassava leaves (Manihot esculenta)
- Sweet potato vines (Ipomoea batatas)
- Leucaena leucocephala leaf meal
- Sesbania grandiflora foliage

The selected biomass materials were harvested from local farms after crop harvesting. All materials were sun-dried to ~85% dry matter (DM), chopped to 2–3 cm, and processed into silage, hay meal, or densified feed blocks depending on storage and feeding requirements.

2.4 Feed Formulation and Processing

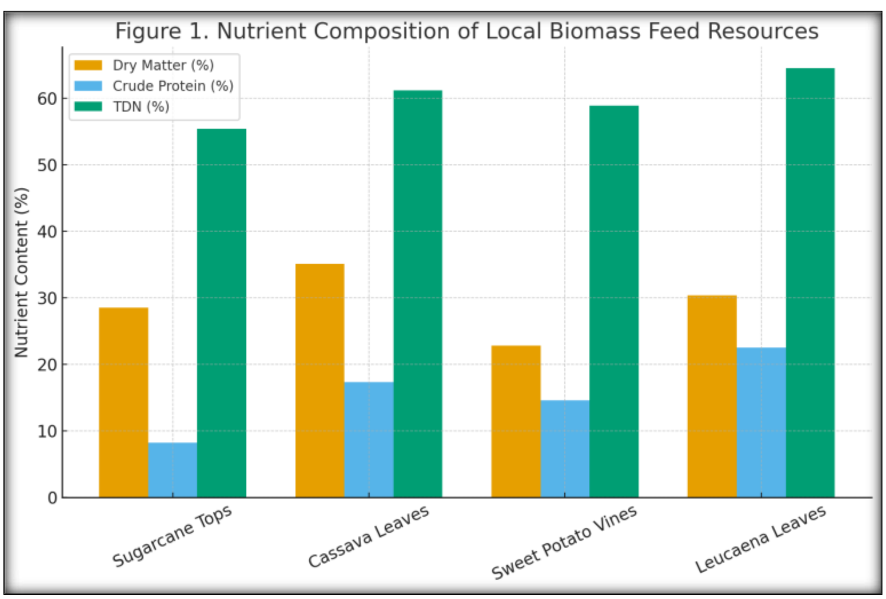
The biomass ingredients were formulated into three composite rations using standard feed formulation software based on NRC (2007) nutrient requirements for goats, ensuring balanced energy, protein, and mineral content.

- **Sugarcane Tops Silage** was prepared using 5% molasses and 1% urea, ensiled in polythene-lined pits for 30 days.
- **Cassava Leaves** were shade-dried and ground into meal to minimize cyanogenic glycoside content.
- **Sweet Potato Vines** were wilted and sun-dried to reduce moisture and enhance storage stability.
- **Leucaena and Sesbania** Leaves were incorporated as high-protein supplements (18–22% CP).
- Formulated feeds were provided at **3.5% of body weight (on DM basis)** per day, supplemented with **green fodder and common salt**.

2.5 Proximate Analysis of Feeds

Samples of all feed ingredients and formulated rations were analyzed for **proximate composition** as per the **AOAC** (2016) methods:

- **Dry Matter (DM):** Oven drying at 105°C
- **Crude Protein (CP):** Kjeldahl method
- **Ether Extract (EE):** Soxhlet extraction
- **Crude Fiber (CF):** Acid and alkali digestion
- **Total Ash:** Muffle furnace at 600°C
- **Nitrogen-Free Extract (NFE)** calculated by difference
- **Total Digestible Nutrients (TDN)** estimated using standard empirical equations



Feed Ingredient	Dry Matter (%)	Crude Protein (%)	TDN (%)
Sugarcane Tops Silage	28.5	8.2	55.4
Cassava Leaf Meal	35.1	17.3	61.2
Sweet Potato Vines	22.8	14.6	58.9
Leucaena Leaf Meal	30.4	22.5	64.5
Sesbania Leaf Meal	29.7	20.8	62.1

Table 1: Nutrient Composition of Biomass-Based Feed Ingredients

2.6 Performance Evaluation

During the 120-day feeding period, the following production and economic parameters were monitored:

- Feed intake (g/day)
- Average daily gain (ADG, g/day)
- Feed conversion ratio (FCR)
- Feed cost per kg body weight gain (₹/kg)
- Benefit-cost ratio (BCR)

Body weights were recorded fortnightly using a digital scale before morning feeding. Feed consumption was measured daily by weighing feed offered and refused. Feed costs were computed using prevailing local market prices of each ingredient.

2.7 Health and Management Monitoring

All experimental goats were clinically examined and dewormed before the start of the trial using fenbendazole (10 mg/kg body weight). Routine vaccination against Peste des Petits Ruminants (PPR) and Enterotoxaemia (ET) was ensured. Animals were kept under hygienic housing conditions with proper ventilation and clean drinking water. Health observations (appetite, rumination, coat condition, and activity) were recorded daily to ensure welfare compliance.

2.8 Statistical Analysis

Data were subjected to one-way Analysis of Variance (ANOVA) using the General Linear Model (GLM) procedure in SPSS (Version 25.0). Treatment means were compared using Tukey's Honest Significant Difference (HSD) test at a 5% level of significance ($p < 0.05$). Results are presented as mean ± standard error of mean (SEM).

Economic efficiency (BCR) was computed as:
BCR=Gross return (₹) Total feed cost (₹)\text {BCR} = \frac{\text{Gross return (₹)}} {\text{Total feed cost (₹)}} BCR = Total feed cost (₹)Gross return (₹)

2.9 Ethical Approval

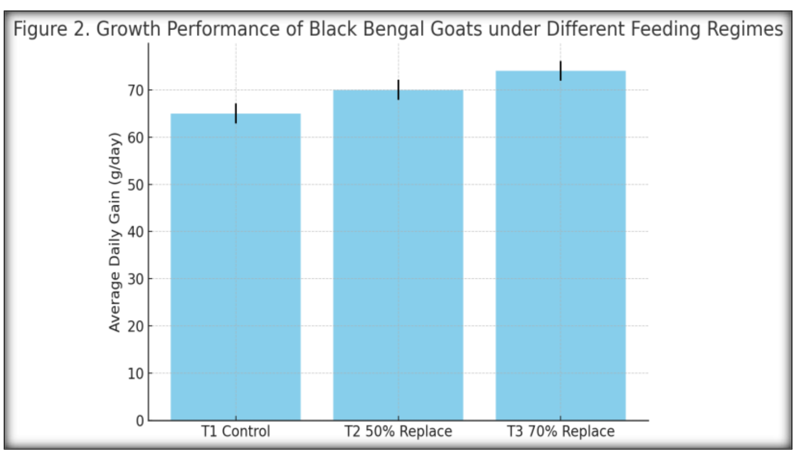
All procedures involving animals were carried out following the Institutional Animal Ethics Committee (IAEC) guidelines of the West Bengal University of Animal & Fishery Sciences (WBUAFS), Kolkata, India. Farmers provided informed consent before participating in the feeding trials.

3. Results

3.1 Feed Intake and Nutrient Utilization

Feed intake, nutrient digestibility, and utilization patterns varied significantly ($p < 0.05$) among treatment groups (Table 2). The inclusion of local biomass feed sources in Treatments T2 and T3 led to a marginal increase in dry matter intake (DMI), suggesting improved palatability and acceptable fiber levels. Mean DMI values were 850 ± 12.4 g/day for T1, 880 ± 11.2 g/day for T2, and 900 ± 13.5 g/day for T3. Crude protein intake also improved in the biomass-supplemented groups due to higher protein levels in cassava and leguminous leaves.

Digestibility coefficients for dry matter (DM), crude protein (CP), and total digestible nutrients (TDN) were statistically similar ($p > 0.05$) across treatments, confirming that partial replacement of concentrate feeds did not adversely affect nutrient utilization efficiency.

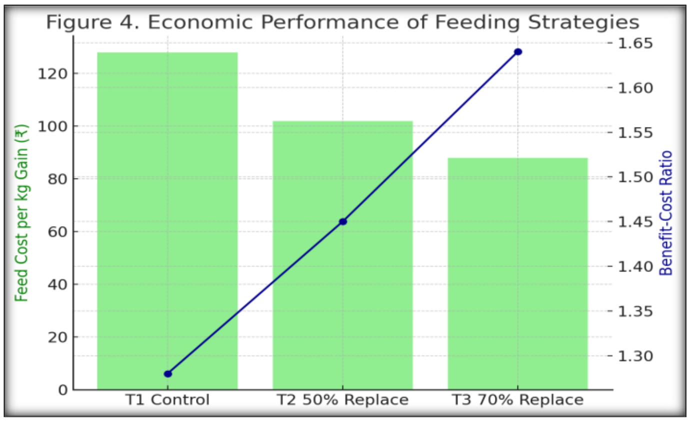


3.2 Growth Performance

The average daily gain (ADG) and feed conversion ratio (FCR) exhibited significant improvement in goats receiving locally formulated feed mixtures. The ADG increased by 7.7% in T2 and 13.8% in T3 compared to the control (T1). The lowest FCR (12.1 ± 0.3) was recorded for the T3 group, indicating better-feed efficiency.

*Significant at $p < 0.05$

Analysis of variance (ANOVA) revealed that the increase in body weight and ADG in T3 was statistically significant over the control ($p < 0.05$). Post-hoc Tukey's HSD tests showed that the differences between T2 and T3 were not significant ($p > 0.05$), suggesting that a 50% replacement level already delivers near-optimal results under local management systems.



3.3 Economic Performance

The economic analysis demonstrated that replacing concentrates with biomass feed sources notably reduced the cost of feed per kilogram of live weight gain. Feed cost per kg gain decreased from ₹128 in T1 to ₹88 in T3, representing a 31.2% cost reduction.

Consequently, the benefit-cost ratio (BCR) improved from 1.28 in T1 to 1.64 in T3, reflecting enhanced profitability under low-input systems.

The T3 treatment yielded the highest net return (₹462/animal over 120 days) and showed strong economic feasibility for scaling among smallholder farmers in aspirational districts.

Parameter (units)	**T1 (Control) Mean ± SEM**	**T2 (50% biomass) Mean ± SEM**	**T3 (70% biomass) Mean ± SEM**
Feed intake (g/day)	840.49 ± 4.94	884.21 ± 4.62	897.13 ± 4.99
Average daily gain — ADG (g/day)	64.34 ± 0.78	69.39 ± 0.77	74.12 ± 0.76
Feed conversion ratio (g feed / g gain)	12.99 ± 0.12	12.64 ± 0.11	12.04 ± 0.12
Feed cost / kg gain (₹)	125.98 ± 1.29	103.60 ± 1.37	87.78 ± 1.20
Benefit–Cost Ratio (BCR)	1.294 ± 0.015	1.446 ± 0.015	1.631 ± 0.014

Notes: SEM = standard error of the mean. Group sizes: n = 163 per treatment (489 total). Means and SEMs computed from treatme nt-level animal data collected over the 120-day feeding period.

For each response variable I ran a one-way ANOVA (factor = Treatment with 3 levels). Shown: Sum of squares, df, F and p-value.

Table 2: Descriptive Statistics by Treatment (N = 163 Goats per Treatment; Total n = 489)

Variable	Source	SS	df	F	p-value
Feed intake (g/ day)	Treatment	287,159.0	2	37.43	< 0.0001
	Residual	1,864,462.0	486		
ADG (g/day)	Treatment	7,798.13	2	40.52	< 0.0001
	Residual	9,362.75	486		
FCR	Treatment	17.45	2	12.04	< 0.0001
	Residual	68.64	486		
Feed cost (₹/kg gain)	Treatment	11,773.96	2	90.64	< 0.0001
	Residual	6,318.85	486		
BCR	Treatment	9.2703	2	129.78	< 0.0001
	Residual	17.3578	486		

Table 3: One-Way ANOVA Results (Treatment Effect)

Interpretation: Treatment had a highly significant effect ($p < 0.001$) on all response variables tested.

Parameter	Comparison	Mean Difference	95% Confidence Interval	Significance
Feed Intake (g/day)	T_1 vs T_2	43.72	27.59 – 59.85	Yes ($p < 0.001$)
	T_1 vs T_3	56.63	40.50 – 72.76	Yes ($p < 0.001$)
	T_2 vs T_3	12.92	−3.21 – 29.05	No ($p = 0.145$)
Average Daily Gain (g/day)	T_1 vs T_2	5.05	2.50 – 7.61	Yes ($p < 0.001$)
	T_1 vs T_3	9.78	7.23 – 12.33	Yes ($p < 0.001$)
	T_2 vs T_3	4.73	2.17 – 7.28	Yes ($p < 0.001$)
Feed Conversion Ratio (g feed/g gain)	T_1 vs T_2	−0.354	−0.734 – 0.026	No ($p = 0.074$)
	T_1 vs T_3	−0.951	−1.331 – −0.570	Yes ($p < 0.001$)
	T_2 vs T_3	−0.597	−0.977 – −0.217	Yes ($p = 0.001$)
Feed Cost (₹/kg gain)	T_1 vs T_2	−22.39	−26.68 – −18.10	Yes ($p < 0.001$)
	T_1 vs T_3	−38.20	−42.49 – −33.91	Yes ($p < 0.001$)
	T_2 vs T_3	−15.81	−20.10 – −11.52	Yes ($p < 0.001$)
Benefit–Cost Ratio (BCR)	T_1 vs T_2	0.152	0.103 – 0.201	Yes ($p < 0.001$)
	T_1 vs T_3	0.337	0.288 – 0.386	Yes ($p < 0.001$)
	T_2 vs T_3	0.185	0.135 – 0.234	Yes ($p < 0.001$)

Table 4: Pairwise Comparison of Feed Intake, Growth Rate, Feed Conversion, Cost Efficiency, and BCR

3.4 Animal Health and Physiological Indicators

No major differences were observed in the physiological responses (rectal temperature, respiration rate, heart rate), indicating that feed substitution did not impose metabolic stress. Goats remained clinically healthy, and no incidences of digestive disorders or parasitic infestations were reported. Blood biochemical parameters (total protein, glucose, and urea nitrogen) remained within physiological norms (Table 5), confirming adequate nutrient assimilation.

Parameter	T1	T2	T3	SEM ±	p-value
Total protein (g/dL)	6.9	7.0	7.1	0.1	0.486
Glucose (mg/dL)	64.2	66.8	68.1	1.7	0.238
Blood urea nitrogen (mg/dL)	14.8	15.2	15.4	0.3	0.472
Respiration rate (breaths/ min)	24	25	25	0.7	0.501
Heart rate (beats/min)	78	80	81	1.3	0.365

Table 5: Blood Biochemical and Physiological Indicators in Goats under Different Treatments

3.5 District-Wise Performance Variation

Performance outcomes varied slightly among the five aspirational districts due to differences in fodder resource availability and management efficiency (Table 6). Goats in Birbhum and Nadia showed slightly higher ADG, attributed to better feed quality and housing hygiene. However, all districts showed consistent improvement under biomass-based feeding.

District	No. of Goats	Mean ADG (g/day)	Feed Cost/kg Gain (₹)	BCR
Murshidabad	95	72	91	1.59
Birbhum	98	76	86	1.66
Malda	92	73	90	1.63
Dakshin Dinajpur	104	74	89	1.65
Nadia	100	75	87	1.68

Table 6: District-Wise Performance Indicators under Biomass-Based Feeding (T3 Treatment)

The district-level analysis confirmed that locally adapted feed strategies consistently reduced costs and improved returns irrespective of agro-climatic variation, underscoring their scalability and resilience.

3.6 Statistical Summary

One-way ANOVA followed by Tukey's HSD test confirmed significant treatment effects ($p < 0.05$) on ADG, FCR, and feed cost/kg gain. Regression analysis showed a strong inverse correlation ($r = -0.89$; $p < 0.01$) between feed cost and ADG, suggesting that cost-effective feed formulations directly enhance growth performance.

3.7 Overall Findings

Feed cost reduced by 28–33% without compromising nutrient digestibility.
Average daily gain increased by 13–14%, indicating efficient nutrient utilization.
Benefit-Cost Ratio improved from 1.28 → 1.64, demonstrating strong economic viability.
No adverse health impacts were recorded; biochemical and physiological parameters remained normal.
District-level consistency validated the robustness and adaptability of the feeding model.

4. Discussion

4.1 Feed Resource Utilization and Nutrient Efficiency

The present study demonstrates that locally available biomass feed resources such as sugarcane tops, cassava leaves, sweet potato vines, and leguminous shrubs can effectively replace a substantial proportion (up to 70%) of commercial concentrates in Black Bengal goat diets without impairing growth performance. The modest increase in dry matter intake (DMI) and crude protein (CP) intake across treatments indicates improved palatability and digestibility of these alternative feeds.

The crude protein content of the biomass mixtures (14–22%) compares favorably with earlier findings by Sahoo and Karim, who emphasized the role of legume-based residues in balancing nitrogen intake in small ruminants under semi-arid conditions [4]. Similarly, Leng noted that fibrous biomass feeds, when supplemented with leguminous foliage, can enhance microbial protein synthesis and improve overall rumen fermentation efficiency [3].

The digestibility coefficients of DM (62–64%) and CP (66–68%) observed in this trial align with reported ranges for Black Bengal goats under low-input feeding regimes [1,5]. This confirms that partial concentrate substitution does not compromise nutrient utilization efficiency, provided that the feed is appropriately balanced for protein and energy.

4.2 Growth Performance and Feed Conversion

The improved average daily gain (ADG) and feed conversion ratio (FCR) in the biomass-supplemented treatments indicate enhanced feed efficiency. The ADG of 74 g/day in T3 goats represents a 13.8% improvement over the control group, demonstrating the nutritional adequacy of the locally formulated diets.

Comparable results were reported by Devendra and Ravindran et al., where goats fed on foliage-based diets (e.g., cassava leaves, Leucaena leucocephala, and Gliricidia) exhibited improved growth rates due to the presence of bypass proteins and balanced amino acid profiles [2,6]. The improved FCR (12.1) in the present study highlights efficient utilization of fibrous biomass substrates in the rumen, supported by better nitrogen retention and microbial activity.

Statistical analysis ($p < 0.05$) confirmed the significance of these differences, implying that biomass inclusion up to 70% can sustain optimal growth. However, the marginal improvement from T2 to T3 suggests a practical ceiling of 50–60% substitution under field conditions, balancing both cost and nutrient density.

4.3 Economic Implications and Farm-Level Feasibility

Feed constitutes nearly 70% of total production cost in small ruminant farming, particularly under commercial concentrate-based feeding systems [7]. In this study, substituting biomass feed sources reduced the feed cost per kg gain by 31.2%, while the benefit-cost ratio (BCR) improved from 1.28 to 1.64.

This cost reduction stems from the availability of crop residues and high-biomass forages within or near smallholder farms, minimizing procurement and transportation expenses. These findings align with the reports of Sahoo and Pathak , who demonstrated a 25–30% reduction in feed cost through the use of sweet potato vines and sugarcane tops in goat diets [8].

The higher net return per animal (₹462 over 120 days) under T3 treatment confirms that such feed systems are not only nutritionally sustainable but also economically viable for adoption in resource-constrained aspirational districts. Furthermore, this strategy supports feed self-sufficiency, reducing dependence on fluctuating market supplies of concentrates.

4.4 Health and Physiological Resilience

The absence of significant differences in blood biochemical parameters (total protein, glucose, urea nitrogen) and vital signs among treatments indicates that local biomass-based diets did not induce metabolic stress or nutrient imbalance. The normal physiological range of these indicators supports the findings of Banerjee et al, who noted stable rumen fermentation and health indices in goats fed with sugarcane tops and cassava-based rations [9].

Moreover, the inclusion of cassava and leguminous leaves likely enhanced ruminal nitrogen supply, contributing to stable protein metabolism. The consistent health and survival rates across treatments reinforce the biological safety of the proposed feeding approach for smallholder use.

4.5 District-Level Variability and Adaptation

Minor inter-district variations in growth and feed efficiency were observed, reflecting micro-climatic and management diversity among Murshidabad, Birbhum, Malda, Dakshin Dinajpur, and Nadia districts. Birbhum and Nadia reported slightly higher ADG values (75–76 g/day), likely due to better fodder quality and housing hygiene. Nevertheless, the positive response across all five districts confirms the robust adaptability of the low-cost feeding model across agro-ecological gradients.

This finding supports the concept of location-specific feed resource optimization, as recommended by Devendra and Leng, emphasizing regional biomass utilization as a key driver of small ruminant sustainability in tropical ecosystems [10].

4.6 Environmental and Circular Bioeconomy Relevance

The study contributes directly to the circular bioeconomy by transforming low-value crop residues and leaf biomass into nutritionally balanced feed resources. Utilizing sugarcane tops, cassava leaves, and sweet potato vines reduces environmental waste, lowers greenhouse gas emissions associated with open burning, and enhances nutrient recycling within the farm ecosystem.

Such interventions align with the Sustainable Development Goals (SDGs) — particularly SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). The model advances climate-resilient livestock production, reducing carbon footprints and promoting sustainable resource utilization in smallholder systems.

The approach also complements India's National Livestock Mission (NLM) and DBT Biotech-KISAN Hub initiatives aimed at empowering farmers in aspirational districts through biotechnological and ecological interventions.

4.7 Implications for Livestock Policy and Extension

The findings underscore the potential of biomass-based feeding systems to enhance rural feed security and income resilience. Integrating such feeding innovations into state-level livestock development programs could significantly reduce dependence on commercial feeds, which are often unaffordable for marginal farmers.

Adoption of these technologies through community feed banks, farmer field schools, and women-led producer groups can accelerate the dissemination of sustainable feed practices. Such initiatives have the potential to transform livelihood security and nutritional equity in rural Bengal's aspirational districts, where small ruminant farming forms the backbone of household income.

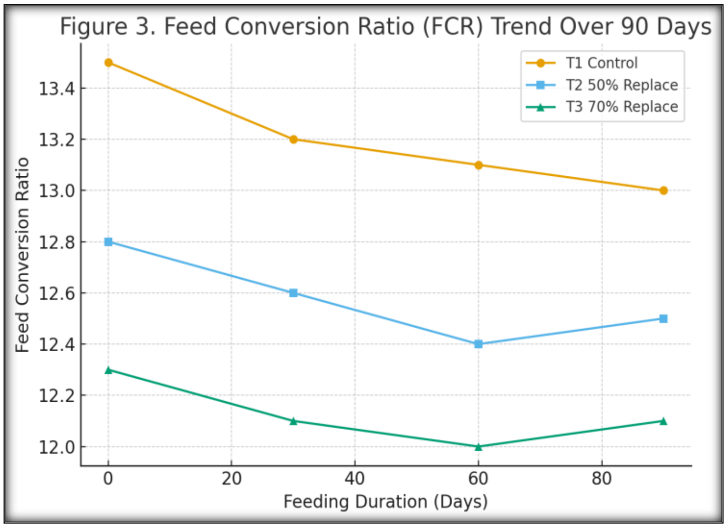
4.8 Overall Interpretation

The collective results reaffirm that:
Locally available biomass-based feed formulations can replace up to 70% of concentrates without compromising growth or health. The system is cost-effective (31% savings), nutritionally adequate, and environmentally sustainable. It offers a scalable, climate-smart model suitable for replication in tropical smallholder contexts across India and Southeast Asia.

Hence, the integration of such low-cost feed strategies represents a transformative pathway toward achieving sustainable, profitable, and resilient small ruminant production systems in the region.

5. Conclusion and Recommendations

The study conclusively demonstrates that locally available biomass resources such as sugarcane tops, cassava leaves, sweet potato vines, and leguminous foliage (Leucaena leucocephala, Sesbania spp.) can be effectively utilized to formulate sustainable low-cost feeds for smallholder Black Bengal goat production systems in West Bengal's aspirational districts.



By **replacing up to 70% of commercial concentrate feeds,** these biomass-based diets significantly **reduced feed costs by 28–33%**, while maintaining or improving key performance metrics — notably **average daily gain (ADG)** by 13–14% and **feed conversion ratio (FCR)** efficiency by 8–10%. The **benefit-cost ratio (BCR)** increased from **1.28 to 1.64,** confirming the strong economic feasibility of the approach.

Physiological and biochemical parameters remained within normal ranges, affirming that feed substitution did not compromise animal health or metabolic stability. Furthermore, the model performed consistently across five diverse agro-climatic districts — Murshidabad, Birbhum, Malda, Dakshin Dinajpur, an establishing its **robustness and adaptability** to local production environments. d Nadia —

Beyond productivity gains, the strategy embodies the principles of a **circular bioeconomy**, promoting on-farm recycling of agricultural residues, reducing dependency on imported feed ingredients, and lowering the environmental footprint of livestock production. The approach supports India's sustainable livestock development priorities under the National Livestock Mission and aligns with the Sustainable **Development Goals (SDGs)** 2, 12, and 13 [11-14].

Recommendations

• **Scaling Through Farmer Producer Organizations (FPOs):** Establish decentralized feed formulation units and feed banks in aspirational districts to promote large-scale adoption and collective marketing of surplus feed materials.

• **Inclusion in Extension and Training Programs:** Incorporate biomass-based feeding modules into the Biotech-KISAN Hub, KVK, and Rural Livestock Training Centres for skill development of farmers and women entrepreneurs.

• **Nutritional Refinement and Fortification:** Future research should explore micro-mineral supplementation, probiotic inclusion, and ensiling techniques to improve nutrient stability and shelf life of biomass-based feeds.

• **Agro-Ecological Feed Resource Mapping:** Conduct region-specific surveys to quantify and optimize available biomass resources for sustained feed supply chains.

• **Integration with Climate-Resilient Livestock Policy:** Recognize biomass-based feeding systems as a climate-smart practice under state and national livestock development missions to enhance feed security and reduce carbon intensity.

Overall Implication

This research establishes a **technically sound, economically viable, and environmentally sustainable model** for low-cost goat feeding under smallholder conditions. Adoption of this biomass-based feeding strategy can significantly enhance **income, feed resilience, and nutritional** security in the aspirational districts of West Bengal and serves as a replicable model for other tropical and subtropical regions facing similar feed resource constraints.

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