

RESEARCH ARTICLE

Growth performance, nutrient utilization, and nitrogen balance of Blackbelly ewe lambs fed densified complete feed blocks formulated exclusively from non-conventional tropical feed resources



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ABSTRACT

Background and Aim: Sustainable livestock production requires feeding strategies that reduce competition between human food and animal feed while improving the utilization of locally available biomass. Although non-conventional feed resources have been incorporated into ruminant diets as supplements, their exclusive use in complete diets remains poorly investigated, particularly under tropical island conditions. This study evaluated the effects of densified complete feed blocks (DCFB) formulated exclusively from non-conventional tropical feed resources on growth performance, nutrient utilization, digestibility, and nitrogen balance in Blackbelly ewe lambs, and compared performance with a conventional tropical grass-based feeding system.

Materials and Methods: Fifty Blackbelly ewe lambs (approximately 4 months old; initial body weight: 20.6 ± 1.56 kg) were randomly allocated to five dietary treatments ($n = 10/\text{group}$) with groups balanced according to initial body weight. Four diets consisted of DCFB formulated with sorghum straw combined with either molasses or sorghum grain and *Leucaena leucocephala* foliage or whole cottonseed, while the control diet comprised tropical grass hay supplemented with commercial concentrate. The growth trial included a 3-week adaptation period followed by a 4-week measurement period. Subsequently, six lambs per DCFB treatment were randomly selected for a digestibility and nitrogen balance study. Feed intake, average daily gain (ADG), feed conversion ratio, nutrient digestibility, nitrogen balance, and predicted growth based on digestible protein and energy intake were determined using standard analytical and statistical procedures.

Results: Dry matter (DM) intake ranged from 948.5 to 1,158.1 g/day. Diet 2 produced the greatest feed intake ($p < 0.01$), whereas Diets 1 and 3 achieved ADG (92.3 and 99.7 g/day, respectively) comparable to the control diet (92.7 g/day). Diets containing sorghum grain (Diets 2 and 4) resulted in significantly lower ADG (62.7 and 49.7 g/day, respectively) and poorer feed conversion efficiency ($p < 0.01$). DM and organic matter digestibility were similar among diets; however, crude protein digestibility was significantly reduced in sorghum grain-based diets ($p < 0.001$), whereas nitrogen retention was greatest in Diet 1 and lowest in Diet 4 ($p < 0.01$). Growth responses were more closely associated with digestible protein intake than with predicted energy supply, highlighting the importance of protein availability and nutrient synchronization.

Conclusion: DCFB formulated exclusively from non-conventional tropical feed resources successfully sustained growth performance comparable to that obtained with conventional high-quality tropical forage when appropriate combinations of rapidly fermentable carbohydrate and protein sources were used. Molasses-based formulations containing *L. leucocephala* or whole cottonseed demonstrated superior nutritional utilization, growth performance, and nitrogen retention compared with sorghum grain-based formulations. These findings demonstrate the potential of DCFB technology to enhance feed self-sufficiency, improve the valorization of agricultural and agro-industrial by-products, and support environmentally sustainable ruminant production in tropical island production systems.

Keywords: agro-industrial by-products, Blackbelly sheep, circular livestock systems, densified complete feed blocks, feed digestibility, nitrogen balance, non-conventional feed resources, tropical ruminant production.

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INTRODUCTION

Livestock production systems face increasing pressure to meet growing demand for animal-derived products while adapting to climate change, intensifying competition for land and natural resources, and heightened societal concerns about environmental sustainability [1–3]. These challenges are particularly pronounced in tropical regions, where high climatic variability, seasonal feed shortages, and the predominance of smallholder mixed crop–livestock systems frequently constrain livestock productivity [4, 5]. Despite criticism regarding its use of land and feed resources, livestock production remains indispensable for global food security by providing high-quality animal protein, essential micronutrients, organic fertilizers, and income for rural households [1, 6].

Globally, livestock production utilizes approximately 2.5 billion hectares of land and 6 billion tons of DM annually, including nearly one-third of total cereal production [7]. Nevertheless, approximately 86% of livestock feed resources are not directly edible by humans, emphasizing the important contribution of ruminants to circular food systems through the efficient utilization of non-conventional feed resources [8, 9]. Crop residues and agro-industrial by-products represent abundant biomass resources that can partially replace conventional feed ingredients, thereby reducing competition between food and feed while lowering the environmental footprint of livestock production systems [10, 11]. Furthermore, replacing imported conventional feed ingredients, particularly cereal grains and soybean meal used in concentrate formulations, with locally available non-conventional resources may substantially reduce production costs while improving the self-sufficiency of smallholder farming systems.

Although non-conventional feed resources have considerable potential, seasonal availability, relatively low nutritive value, nutritional imbalances, and practical limitations in harvesting, processing, storage, and on-farm use constrain their widespread use in ruminant nutrition [9, 12]. Previous studies have evaluated various non-conventional resources, including crop residues, foliage from shrubs and trees, cereal by-products, and alternative oilseed meals [11]. However, these resources have generally been incorporated at relatively low inclusion rates to supplement conventional diets, primarily to reduce feeding costs or alleviate seasonal feed shortages. Consequently, their full potential as complete replacements for conventional feed ingredients has not been adequately investigated. The successful integration of these resources into practical feeding systems therefore depends not only on their nutritional value but also on the availability of appropriate processing technologies that improve handling, storage, palatability, and nutrient utilization [13].

Despite growing interest in circular livestock production systems, important knowledge gaps remain regarding the exclusive use of non-conventional feed resources in complete ruminant diets. To the best of our knowledge, no previous study has evaluated feeding strategies in which non-conventional resources constitute the sole dietary ingredients while maintaining animal performance comparable to that achieved with conventional high-quality tropical forage-based systems. Furthermore, although densified complete feed block (DCFB) technology has been investigated in Asia and mainland Africa [14, 15], its application using exclusively non-conventional tropical feed resources for tropical hair sheep under tropical island production systems, such as those of the Caribbean, has not been reported. In addition, limited information is available regarding nutrient digestibility, nitrogen utilization, feed efficiency, and growth performance associated with such feeding systems. Addressing these knowledge gaps is essential for developing sustainable livestock production strategies that enhance feed self-sufficiency, improve the valorization of locally available agricultural and agro-industrial by-products, reduce dependence on imported feed ingredients, and strengthen circular bioeconomy approaches in tropical regions.

DCFB technology offers a practical approach to overcoming several limitations associated with non-conventional feed resources by combining roughage, energy, and protein sources into a single compact feed that improves palatability, minimizes selective feeding, facilitates handling and storage, and enhances nutrient synchronization within the rumen [14, 15]. Such characteristics make this technology particularly suitable for integrated crop–livestock systems, where efficient utilization of locally available biomass is fundamental to improving both economic and environmental sustainability.

We define unconventional resources as ingredients of plant, animal, or mineral origin that meet at least two of the following characteristics: 1) they are not typically included in the formulation of commercial feed and can serve as substitutes for traditional feed; 2) they do not compete with food for human consumption; 3) their commercial distribution rarely extends beyond the local area. This study aimed to evaluate the growth performance, feed intake, nutrient digestibility, nutrient utilization, and nitrogen balance of Blackbelly ewe lambs

fed DCFB formulated exclusively from non-conventional tropical feed resources and to compare their performance with animals receiving a conventional diet based on high-quality tropical grass. In addition, the study investigated whether different combinations of rapidly fermentable carbohydrate sources (molasses or sorghum grain) and protein sources (*Leucaena leucocephala* foliage or whole cottonseed) could improve nutrient synchronization, protein utilization, and growth performance. We hypothesized that DCFB formulated exclusively from non-conventional tropical feed resources would sustain growth performance comparable to that achieved with conventional tropical forage-based feeding systems, while providing a sustainable strategy to improve feed self-sufficiency and promote circular livestock production in tropical island environments.

MATERIALS AND METHODS

Ethical approval

All animal experiments were conducted at the experimental animal facility of the National Research Institute for Agriculture, Food and the Environment (INRAE), Guadeloupe, French West Indies. The experimental unit is officially accredited for animal experimentation (Accreditation No. A971802) and operates with trained personnel in animal handling and welfare. The experimental protocol (APAFIS#5527-2016050608133139v2) was reviewed and approved by the Ministry of National Education, Higher Education and Research following evaluation by the Animal Care and Use Committee of the French West Indies and French Guiana (Approval No. 069). All experimental procedures were performed in accordance with the French Ministry of Agriculture guidelines and regulations governing the care and use of animals for scientific purposes. Throughout the study, animals were managed by trained personnel under standard husbandry conditions, and every effort was made to ensure animal welfare and to minimize stress, discomfort, and unnecessary suffering during handling, feeding, housing, and sample collection.

Study period and location

The study was conducted from March to July 2022 at the experimental animal facility of INRAE in Guadeloupe, French West Indies (16.16° N, 61.30° W). The experimental period corresponded primarily to the dry season and the beginning of the rainy season. Hay was harvested in March, whereas animal measurements were performed from April to early July. During the study period, the mean ambient temperature was 26.5°C (range: 25–28°C), and the average monthly precipitation was 97.5 mm (range: 75–120 mm).

Experimental diets and feed block preparation

The experimental timeline is shown in Figure 1. Five experimental diets were evaluated (Tables 1a and 1b). Four diets consisted of DCFB formulated exclusively from non-conventional feed resources, whereas the fifth diet served as the conventional control. Unlike most previous studies, which incorporated relatively high proportions of conventional feed ingredients, the DCFB used in the present study were formulated to be isoenergetic using only non-conventional feed resources. As for protein, the goal was to achieve levels above 11.5% but below 15% to remain within the range of good to very good forage. The dietary treatments comprised Diet 1 (sorghum straw, molasses, and *L. leucocephala* leaves), Diet 2 (sorghum straw, sorghum grain, and *L. leucocephala* leaves), Diet 3 (sorghum straw, molasses, and whole cottonseed), and Diet 4 (sorghum straw, sorghum grain, and whole cottonseed).

The control diet consisted of mature tropical grass hay (*Dichanthium* spp.) harvested from a natural pasture after 3 months of regrowth at the INRAE experimental farm. Hay was offered *ad libitum* and supplemented with 300 g/day per lamb of a commercial concentrate obtained from a local feed supplier. The control diet was originally intended to consist of hay harvested after one month of regrowth. However, an unusually prolonged rainy season delayed harvesting, resulting in highly mature forage. Consequently, concentrate was included to improve the nutritional value of the control diet so that it approximated that of younger tropical grass. All animals had unrestricted access to drinking water and a mineral salt block.

The four DCFB were formulated according to the tabulated feed values of INRA [16]. Feed block preparation involved sun-drying of raw materials, grinding or chopping of ingredients, mixing, manual compression, and final drying. Foliage of *L. leucocephala* was collected in Guadeloupe, from unfertilized fallow land aged 9–12 months. Young stems and leaves were harvested and sun-dried in a greenhouse for 3–5 days. The greenhouse measured 50 m × 10 m × 3 m and was covered with plastic sheeting to 0.5 m above ground level, except at both ends, which remained completely open and were oriented toward the prevailing winds to facilitate natural ventilation. During

daylight hours, the average temperature inside the greenhouse was approximately 45°C. Following drying, the leaves naturally detached from the stems with their petioles and were ground through a 2-mm sieve.

Time (weeks)	-4	-3	-2	-1	+1	+2	+3	+4	+5	+6	+7	+8	+9	+10	+11	+12	+13
Period	Forage harvest Block production				Adaptation			Measurements				Adaptation	Measurements	Adaptation	Measurements	Adaptation	Measurements
Phase	Feed production				Growth (7 weeks)							Total tract digestibility (6 weeks)					

Figure 1: Experimental timeline showing forage harvesting, feed block production, growth evaluation, and total tract digestibility assessment.

A sorghum crop (*S. bicolor*) was planted at the INRAE experimental farm in Guadeloupe. Sorghum straw from *S. bicolor* was obtained after grain harvest and chopped into particles measuring approximately 2–5 cm. Whole cottonseed was imported from France from a commercial livestock feed manufacturer. The *L. leucocephala* leaves, sorghum grain, and whole cottonseed were ground separately using a hammer mill equipped with a cyclone and a 2-mm screen. Molasses was obtained from a local sugarcane processing mill.

The ingredients were mixed according to the formulations presented in Table 1b using a concrete mixer. Depending on the formulation, molasses and/or sorghum grain were diluted in 20 L of hot water (100°C). The hot water partially gelatinized the sorghum starch, thereby improving its binding properties during block formation. Molasses also served as a natural binder while simultaneously contributing nutritional value. The solution was incorporated into the feed mixture at 20 L per 100 kg of dry ingredients.

Feed blocks (30 × 15 × 10 cm; approximately 1 kg DM equivalent) were manufactured using a Manumeco MQ101-V0 manual press (Mecoconcept®, France). Compression was applied at an average pressure of 37 kg/cm² for 10 s. After pressing, the blocks were dried in a ventilated greenhouse at approximately 40°C for 4–5 days until they reached an average DM content of 85%.

All experimental diets were offered *ad libitum*, with feed refusals maintained at approximately 10%–20% of the feed offered.

Study design

The experiment consisted of two consecutive phases: a growth (fattening) phase followed by a digestibility phase. This sequential design enabled evaluation of the relationship between growth performance and nutrient digestibility.

Fifty Blackbelly ewe lambs, approximately 4 months of age, with an average initial body weight of 20.6 ± 1.56 kg, were used during the growth phase. All animals originated from the INRAE experimental farm, where they had been raised under pasture conditions in accordance with French animal welfare regulations. Before the experiment, all lambs received oral praziquantel (CESTOCURE; Bayer AG, Leverkusen, Germany) and ivermectin (ORAMEC; Merial, Lyon, France) at a dose of 0.3 mg/kg body weight. Fecal egg counts were subsequently performed to confirm that all animals were free of gastrointestinal parasites. The INRAE flock has undergone selective breeding for approximately 30 years, resulting in relatively uniform growth performance and minimizing individual variation among experimental groups.

Animals were randomly allocated to the five dietary treatments (n = 10 per treatment), with groups balanced according to initial body weight. In practice, the 50 lambs were ranked in ascending order of weight. Based on this, 10 weight groups of five animals each were then formed in ascending order of weight. Within each group, a random draw assigned one animal to one of the five diets. This process was repeated for each of the 10 weight groups. Once the five experimental groups had been formed, some reassignments were made to bring the group means closer together while reducing their standard deviation.

The growth phase lasted 7 weeks and comprised a 3-week dietary adaptation period followed by a 4-week measurement period. Animals were housed individually in cages (1.0 × 1.5 m) with metal slatted floors in a naturally ventilated open-sided building, where ambient temperatures ranged from 20°C to 25°C. Feed was offered twice daily at approximately 07:00 and 13:00 h. Drinking water and mineral salt blocks were available *ad libitum*. The mineral block contained (g/kg): Ca = 60.0, P = 20.0, Mg = 10.0, Na = 280.0, Zn = 17.5, Mn = 5.5, Fe = 1.5, I = 0.03, Co = 0.03, and Se = 0.01.

Because of the limited number of metabolism cages available, only the DCFB treatments were included in the digestibility phase. Digestibility of the control diet was not determined experimentally because the nutritional characteristics of its ingredients are well established, allowing digestibility to be predicted using published equations. After the growth phase, all animals remained on their respective diets. Within each DCFB treatment, six of the ten lambs were randomly selected for the digestibility trial, which lasted 6 weeks and was divided into three consecutive 2-week periods. Each period consisted of one week of adaptation to the metabolism cages followed by five consecutive days of measurements. Eight animals were evaluated during each period, including two animals from each DCFB treatment. Lambs were housed individually in metabolism cages measuring 0.7 × 1.0 m.

No mortality or clinical illness occurred during the study. Likewise, no clinical signs consistent with mimosine toxicity associated with *L. leucocephala*, including anorexia, excessive salivation, weight loss, or alopecia, were observed throughout the experimental period.

Measurements and calculations

During the growth phase, the ewe lambs were weighed in the morning before feeding on two consecutive days at the beginning of the 3-week adaptation period and again at the beginning and end of the 4-week measurement period. Daily feed intake was calculated as the difference between feed offered and feed refused. Average daily gain (ADG) was calculated as the total body weight gain divided by the number of measurement days. Feed conversion ratio (FCR) was calculated as DM intake divided by body weight gain.

During the digestibility phase, the daily quantities of feed offered, feed refused, feces, and urine were recorded over five consecutive days following the adaptation period in the metabolism cages. Urine was collected in 10-L containers containing sulfuric acid (2.5 mL of 10% H₂SO₄ per 100 mL of urine) to prevent nitrogen losses. Representative samples of feed, refusals, feces, and urine were pooled over the collection period for subsequent laboratory analyses. Apparent total tract digestibility coefficients were determined for DM, organic matter, and nitrogen. Nitrogen retention was calculated as nitrogen intake minus the sum of fecal and urinary nitrogen excretion. Endogenous nitrogen losses were not considered.

Feed subsamples (200 g DM equivalent) retained for chemical analyses were prepared from weekly composite samples generated from daily collections over five consecutive days and consisted of one DCFB, 200 g of hay and 100 g of commercial concentrate. Subsamples of feed refusals (200 g DM equivalent) were obtained from the total amount refused by each animal over the 5-day collection period after thorough homogenization. Fecal subsamples (200 g DM equivalent) were collected from the cumulative 5-day fecal output of each animal and stored at 4°C until analysis. For the urinary nitrogen test, a 500-mL urine subsample was collected from the total urine produced by each animal during the same collection period.

Growth performance was also predicted from energy and protein intake. For Diets 1–4, measured digestibility coefficients were incorporated into the prediction equations derived from the meta-analysis of Salah *et al.* [17]:

$$\text{ADG (g/day/LW}^{0.75}\text{)} = -0.091 + 11.16 \times \text{metabolizable energy (ME) intake (MJ/LW}^{0.75}\text{)}$$

ADG = Average Daily Gain (g); LW = Live weight (kg); ME = metabolizable energy (ME) (Megajoule)

$$\text{ADG (g/day/LW}^{0.75}\text{)} = -0.59 + 1.32 \times \text{digestible crude protein (DCP; g/day/LW}^{0.75}\text{)} - 0.052 \times \text{DCP}^2$$

ADG = Average Daily Gain (g); LW = Live weight (kg); DCP = Digestible Crude Protein (g)

For the control diet, digestibility coefficients were estimated using the predictive equations reported by Salah *et al.* [17] together with the INRA feed evaluation system [16].

Chemical analyses

DM content of feeds, feed refusals, and feces was determined by oven drying at 60°C until constant weight. The dried samples were subsequently ground through a 1-mm screen using a Reich hammer mill (Reich, Haan,

Germany) before chemical analyses. Organic matter and nitrogen contents were determined according to Association of Official Analytical Chemists (AOAC) Methods 923.3 and 992.15 [18], respectively. Crude protein content was calculated as nitrogen $\times$ 6.25. Neutral detergent fiber (NDF), acid detergent fiber (ADF), and acid detergent lignin were determined using the sequential procedure described by Van Soest [19] according to AOAC Methods 200.04 and 973.18 [18].

Condensed tannins (CT) in *L. leucocephala* were extracted in an ultrasonic bath using 70% (vol/vol) aqueous acetone and purified with Sephadex LH-20 (Sigma-Aldrich, St. Louis, MO, USA) according to the method of Giner Chavez [20]. CTs were quantified using the vanillin-H₂SO₄ assay described by Laurent [21]. A solution containing 70% (vol/vol) H₂SO₄ and 1% (wt/vol) vanillin was added to the methanolic plant extract, and absorbance was measured at 500 nm. Concentrations were determined using purified CT extracts from *L. leucocephala* as the calibration standard.

All chemical analyses were performed on three replicates of each composite sample.

For the growth trial, ME values were estimated using the conversion factor of 4.03 (ME intake/digestible organic matter intake), as proposed in the tropical meta-analysis by Salah *et al.* [17], rather than the conversion factor of 4.45 kcal ME/g total digestible nutrients recommended by the National Research Council (NRC) [22].

Statistical analysis

Statistical analyses were performed using the MIXED procedure of SAS version 9.2 (SAS Institute Inc., Cary, NC, USA). Before analysis, data normality was assessed by visual examination of histogram distributions. The animal was the experimental unit.

For the growth phase, diet ($n = 5$) was included as a fixed effect, whereas animal ($n = 10$) was treated as a random effect nested within diet. Initial body weight was included as a covariate. Tukey's multiple comparison test was used to compare treatment means. Statistical analyses were performed for mean daily feed intake, water intake, ADG, and FCR.

For the digestibility phase, diet ($n = 4$) and experimental period ($n = 3$) were included as fixed effects, whereas animal ($n = 6$) was treated as a random effect nested within diet. Initial body weight was included as a covariate. Tukey's multiple comparison test was used to compare treatment means. Mean values obtained over the five-day collection period were used for analyses of feed intake, apparent digestibility coefficients, and nitrogen balance variables.

Differences among dietary treatments were considered statistically significant at $p < 0.05$.

RESULTS

Chemical composition of the experimental diets

The chemical composition of the experimental diets is presented in Table 1. The CT content of *L. leucocephala* was 7.3% of DM. The four DCFB formulated exclusively from non-conventional feed resources exhibited comparable organic matter contents, ranging from 89.4% to 93.8% of DM. Crude protein concentrations ranged from 11.9% in Diet 1 to 14.5% in Diet 4, reflecting differences in the protein sources and their inclusion levels.

The NDF and ADF contents were higher in the sorghum grain-based diets (Diets 2 and 4) than in the molasses-based diets (Diets 1 and 3). The control diet, based on tropical grass hay, exhibited the highest fiber content and the lowest crude protein concentration. Energy values (UF) were comparable among the DCFB, confirming that the diets were successfully formulated to be isoenergetic.

Table 1a: Chemical composition (% dry matter) of the ingredients used in the experimental diets determined by laboratory tests.

Ingredient	Organic matter	Crude protein	Neutral detergent fiber	Acid detergent fiber	Acid detergent lignin
Molasses	86.0	5.5	3.0	1.5	0.0
Sorghum straw	91.4	7.7	77.2	49.2	11.2
Sorghum grain	94.6	12.7	41.2	15.8	6.7
Whole cottonseed	96.0	21.0	45.4	36.1	9.9
<i>Leucaena leucocephala</i> leaves	91.3	21.6	32.3	17.9	10.1
Commercial concentrate	94.3	20.5	22.7	3.3	0.96
Grass hay	94.0	4.3	77.9	44.3	5.9

Feed intake and nutrient digestibility

The feed intake and digestibility results are presented in Tables 2 and 3. The DCFB were readily accepted by the ewe lambs, with approximately 25% of each block consumed within the first 2 h after feeding (weighing

observations during the adaptation week, from the first digestibility period), indicating good palatability.

Table 1b: Chemical composition of the experimental diets.

Item	Diet 1	Diet 2	Diet 3	Diet 4	Control
Ingredients (dry matter basis, %)					
Grass hay	—	—	—	—	70.0
Commercial concentrate	—	—	—	—	30.0
Molasses	40.0	0.0	10.0	0.0	—
Sorghum straw	20.0	35.0	40.0	40.0	—
Sorghum grain	0.0	30.0	0.0	10.0	—
Whole cottonseed	0.0	0.0	50.0	50.0	—
<i>Leucaena leucocephala</i> leaves	40.0	35.0	0.0	0.0	—
Chemical composition (% dry matter)					
Organic matter	89.4	92.3	92.6	93.8	94.1
Crude protein	11.9	14.1	12.7	14.5	9.1
Neutral detergent fiber	34.8	58.8	50.8	58.5	61.4
Acid detergent fiber	23.4	30.7	35.2	37.9	32.0
Acid detergent lignin	9.1	11.8	8.2	8.3	4.4
Energy (UF) ¹	0.86	0.86	0.83	0.84	0.79
Metabolizable protein (g) ²	82.0	87.6	83.2	88.2	72.7

UF = French feed unit for net energy; PDI = protein truly digestible in the small intestine; INRA = French National Research Institute for Agriculture, Food and Environment. ¹UF values were obtained from the INRA 2018 feed composition tables in *Feeding Ruminants* [16]. One UF = 1,760 kcal net energy/kg dry matter, equivalent to approximately 2,933 kcal metabolizable energy (12.27 MJ) using an average metabolizable energy-to-net energy conversion factor of 0.60. ²PDI = *Protéines Digestibles dans l'Intestin Grêle* (protein truly digestible in the small intestine), representing the quantity of amino acid nitrogen (N × 6.25), excluding endogenous secretions, absorbed in the small intestine.

During the growth phase, total DM intake expressed on a metabolic body weight basis (g/LW^{0.75}) was significantly lower in the control group and highest in Diet 2 ($p < 0.01$), with no significant differences among the remaining dietary treatments (Table 3).

Similarly, during the digestibility phase, DM intake ranged from 69.8 to 103.9 g/LW^{0.75}, with Diet 2 exhibiting the highest intake ($p < 0.01$), while the remaining diets did not differ significantly (Table 2). Organic matter intake followed a similar pattern.

Table 2: Feed intake and apparent total tract digestibility of Blackbelly ewe lambs ($n = 6$ per diet) fed complete diets formulated from non-conventional feed resources as determined by laboratory tests.

Trait	Diet 1	Diet 2	Diet 3	Diet 4	SEM ¹	Significant effect ²
	Straw + Molasses +	Straw + Sorghum +	Straw + Molasses +	Straw + Sorghum +		
	<i>Leucaena</i>	<i>Leucaena</i>	Cotton	Cotton		
Dry matter intake (g/LW ^{0.75})	71.5 ^a	103.9 ^b	69.8 ^a	84.0 ^a	14.2	D**
Intake (g/day)						
Water	2245.4 ^a	1839.2 ^a	2482.8 ^a	2168.4 ^a	581.5	NS
Dry matter	794.8 ^a	1037.8 ^b	815.5 ^a	821.1 ^a	150.7	D**
Organic matter	750.0 ^a	963.1 ^b	761.8 ^a	732.6 ^a	137.1	D**
Crude protein	162.6 ^a	163.3 ^a	147.4 ^b	125.4 ^c	11.0	D***
Neutral detergent fiber	469.1 ^a	631.6 ^b	373.6 ^c	290.3 ^d	86.7	D***
Acid detergent fiber	295.2 ^a	315.3 ^a	270.4 ^a	195.3 ^b	55.7	D**
Acid detergent lignin	70.2 ^a	128.4 ^b	73.2 ^a	76.9 ^a	26.3	D***
Apparent total tract digestibility						
Dry matter	0.66 ^a	0.66 ^a	0.64 ^a	0.65 ^a	0.06	NS
Organic matter	0.67 ^a	0.67 ^a	0.65 ^a	0.66 ^a	0.06	NS
Crude protein	0.73 ^a	0.54 ^b	0.68 ^a	0.52 ^b	0.09	D***
Neutral detergent fiber	0.62 ^a	0.66 ^a	0.50 ^b	0.50 ^b	0.12	D**
Acid detergent fiber	0.58 ^a	0.51 ^a	0.52 ^a	0.44 ^a	0.15	NS

SEM = Standard error of the mean; LW = Live weight; NS = Not significant; D = Diet effect. ¹Standard Error of the Mean. ²Analysis of variance was performed using the MIXED procedure of SAS including the effect of diet (D). Values within the same row with different superscript letters (^{a–d}) differ significantly ($p < 0.05$). Statistical significance: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

No significant differences were observed among diets in the apparent digestibility of DM or organic matter. In contrast, crude protein digestibility was significantly lower in the sorghum grain-based diets (Diets 2 and 4) than in the molasses-based diets ($p < 0.001$). Likewise, NDF digestibility was significantly reduced in diets

containing whole cottonseed ($p < 0.01$).

Table 3: Dry matter intake and growth performance of Blackbelly ewe lambs ($n = 10$ per diet) fed complete diets formulated from non-conventional feed resources compared with a conventional control diet.

Trait	Diet 1 Straw + Molasses + <i>Leucaena</i>	Diet 2 Straw + Sorghum + <i>Leucaena</i>	Diet 3 Straw + Molasses + Cotton	Diet 4 Straw + Sorghum + Cotton	Control Hay + commercial concentrate	SEM ¹	Significant effect ²
Total DM intake (g/day)	1138.3 ^a	1158.1 ^a	1123.1 ^a	1004.3 ^b	948.5 ^b	84.0	D***
Forage DM intake (g/day)	683.0 ^a	810.7 ^a	449.2 ^b	401.7 ^b	664.0 ^c	44.0	D***
Total DM intake (g/LW ^{0.75})	102.8 ^a	117.1 ^b	97.3 ^a	102.7 ^a	87.4 ^c	8.5	D***
Initial live weight (kg)	21.3 ^a	19.1 ^a	22.7 ^a	19.0 ^a	20.9 ^a	3.5	NS
Final live weight (kg)	28.4 ^a	23.9 ^b	30.4 ^a	22.8 ^b	28.0 ^a	4.1	D***
ADG (g/day)	92.3 ^a	62.7 ^b	99.7 ^a	49.7 ^b	92.7 ^a	24.2	D***
Feed conversion ratio (DM intake/ADG)	14.0 ^a	20.1 ^b	14.1 ^a	21.4 ^b	10.6 ^a	7.0	D**
Predicted ADG from DCP intake (g/day)	80.8	102.3	124.3	93.8	92.7	—	NT ³
Predicted ADG from energy intake (g/day)	129.3	131.5	123.7	112.3	104.5	—	NT ³

SEM = Standard Error of the Mean; DM = Dry matter; LW = Live weight; ADG = Average daily gain; DCP = Digestible crude protein; NS = Not significant; NT = Not tested; D = Diet effect. ¹ Standard Error of the Mean. ² Analysis of variance was performed using the MIXED procedure of SAS including the effect of diet (D). ³ NT = Not statistically tested. Values within the same row with different superscript letters (^{a–c}) differ significantly ($p < 0.05$). Statistical significance: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

Nitrogen balance

Nitrogen balance data are presented in Table 4. Nitrogen intake differed significantly among dietary treatments, reflecting differences in crude protein intake. Fecal nitrogen excretion was greater in the sorghum grain-based diets, consistent with their lower crude protein digestibility.

Urinary nitrogen excretion did not differ significantly among diets. Nitrogen retention was highest in Diet 1 and lowest in Diet 4 ($p < 0.01$), with no significant differences among the remaining dietary treatments, indicating differences in nitrogen utilization efficiency and the potential to support animal growth.

Table 4: Nitrogen balance of Blackbelly ewe lambs ($n = 6$ per diet) fed complete diets formulated from non-conventional feed resources.

Trait	Diet 1 Straw + Molasses + <i>Leucaena</i>	Diet 2 Straw + Sorghum + <i>Leucaena</i>	Diet 3 Straw + Molasses + Cotton	Diet 4 Straw + Sorghum + Cotton	SEM ¹	Significant effect ²
Nitrogen intake (g/day)	26.0 ^a	26.1 ^a	23.6 ^b	20.1 ^c	1.8	D***
Fecal nitrogen excretion (g/day)	7.0 ^a	11.9 ^b	7.2 ^a	9.5 ^c	1.9	D***
Urinary nitrogen excretion (g/day)	2.6 ^a	1.7 ^a	3.1 ^a	2.2 ^a	1.8	NS
Retained nitrogen (g/day)	16.4 ^a	12.5 ^b	13.2 ^b	8.4 ^c	3.5	D**

SEM = Standard error of the mean; NS = Not significant; D = Diet effect. ¹ Standard Error of the Mean. ² Analysis of variance was performed using the MIXED procedure of SAS, including the effect of diet (D). Values within the same row with different superscript letters (^{a–c}) differ significantly ($p < 0.05$). Statistical significance: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

Growth performance

Growth performance data are summarized in Table 3. Total DM intake ranged from 948.5 to 1,158.1 g/day. Diets 1 and 3, formulated exclusively from non-conventional feed resources, produced significantly higher ADG (92.3 and 99.7 g/day, respectively; $p < 0.01$), comparable to the control diet (92.7 g/day). In contrast, Diets 2 and 4 resulted in significantly lower ADG values (62.7 and 49.7 g/day, respectively; $p < 0.01$).

The FCR ranged from 14.6 to 21.4. Diets 2 and 4 exhibited significantly higher FCR values than the other dietary treatments ($p < 0.01$), indicating lower feed utilization efficiency in diets containing sorghum grain. Predicted ADG based on DCP intake was more consistent with the observed growth performance than predictions based on ME intake.

DISCUSSION

General considerations

This study is among the first to show that DCFB formulated exclusively from non-conventional tropical feed resources can sustain growth performance in Blackbelly ewe lambs comparable to that achieved with a conventional diet based on high-quality tropical grass. These findings provide new evidence supporting the feasibility of circular livestock feeding systems in tropical island environments, particularly in the Caribbean,

where the efficient utilization of locally available agricultural and agro-industrial by-products is essential for improving feed self-sufficiency and reducing dependence on imported feed ingredients.

The ingredients selected for the DCFB were intended to represent feed resources with contrasting carbohydrate degradation rates and protein degradability characteristics. Although sorghum straw was the principal roughage source in this study, other abundant regional resources, such as sugarcane tops, could serve as suitable alternatives under Caribbean production conditions. Likewise, *L. leucocephala* may be replaced by locally available protein-rich forages, including cassava, sweet potato, or pea foliage, whereas green bananas, non-marketable sweet potatoes, and cassava peels could provide alternative carbohydrate sources. Consequently, the feeding strategy evaluated in this study should be considered as a flexible production model rather than a formulation restricted to the specific ingredients used.

The overall approach adopted in this study was designed to integrate productivity with adaptation to local production environments. This consideration motivated the selection of the Blackbelly breed, which combines satisfactory growth performance with excellent adaptation to tropical climatic conditions.

Previous studies evaluating complete feed blocks in sheep have generally reported ADG values below 100 g/day, despite including conventional feed ingredients in their formulations [14, 15, 43]. In contrast, the present study showed that DCFB formulated exclusively from non-conventional feed resources achieved growth performance comparable to a conventional tropical forage-based diet, highlighting their potential as a sustainable feeding strategy for tropical production systems.

Chemical composition and total tract digestibility of the diets

The DCFB were formulated primarily to maximize the utilization of locally available agricultural and agro-industrial by-products rather than to achieve exceptionally high nutrient concentrations. The diets were designed to be isoenergetic using tabulated INRA feed values, and this objective was confirmed by similar organic matter digestibility across treatments. In contrast, CP content varied widely, primarily because the molasses CP content was lower than anticipated. Although the control hay was lower quality than originally intended because delayed harvesting due to an unusually prolonged rainy season, this circumstance realistically reflects the seasonal constraints commonly encountered in tropical production systems. The addition of concentrate compensated for the reduced nutritive value of the mature hay, resulting in a control diet with a nutritional value comparable to that of younger tropical forage. Consequently, the control diet provided an appropriate reference for evaluating whether DCFB formulated exclusively from non-conventional feed resources could sustain growth performance comparable to conventional tropical forage-based feeding systems.

S. bicolor straw was the principal fiber source in the DCFB. Compared with other cereal crop residues, relatively few studies have investigated the nutritional characteristics of sorghum straw, despite its importance as a drought-tolerant feed resource adapted to tropical and semi-arid environments [23–25]. The relatively lower NDF concentration observed in Diet 1 reflected the reduced inclusion level of sorghum straw in that formulation.

The absence of significant differences in organic matter digestibility among diets indicates that energy availability was comparable across dietary treatments. In contrast, crude protein digestibility was significantly lower in the sorghum grain-based diets. This finding is consistent with previous reports attributing reduced protein digestibility in sorghum-based diets to the presence of tannins and the structural characteristics of sorghum endosperm proteins [26, 27].

Similarly, the lower digestibility of cell wall fractions (NDF and ADF) observed in Diets 3 and 4 likely reflects the higher proportions of sorghum straw and whole cottonseed hulls, both of which have relatively low fiber digestibility [28].

The carbohydrate sources incorporated into the DCFB differed markedly in their degradation characteristics. Molasses is a rapidly fermentable carbohydrate source [29], whereas sorghum grain provides a more slowly degradable energy source [30]. Likewise, the protein sources differed substantially in ruminal degradability. The proteins of *L. leucocephala* are partially protected from ruminal degradation because of the presence of CTs, thereby increasing the supply of bypass protein to the small intestine [31]. In contrast, protein from whole cottonseed is generally considered more rapidly degradable within the rumen [32, 33].

Beyond total crude protein digestibility, the site and extent of protein digestion within the gastrointestinal tract influence the quantity of by-pass protein reaching the small intestine and, consequently, the efficiency of protein utilization by the animal. Although the present study did not measure ruminal protein degradation, published evidence indicates marked differences among the protein sources used. Whole cottonseed contains

protein that is highly degradable in the rumen, with reported ruminal degradability ranging from 74% to 77%, of which more than two-thirds is represented by the soluble protein fraction [34]. However, the nutritional characteristics of whole cottonseed differ substantially from those of cottonseed meal, whose composition depends on oil extraction method, hull and lint content, and degree of decortication. Accordingly, the crude protein concentration of cottonseed meal may range from approximately 22% to 42%, whereas fat content varies from 4.2% to 11.3% in expeller-extracted products and from 0.9% to 2.9% in solvent-extracted meals.

L. leucocephala foliage is recognized as a protein-rich forage, with crude protein concentrations generally ranging from 24% to 28% of DM [35]. The presence of CTs partially protects its proteins from ruminal degradation, thereby increasing intestinal bypass protein availability [36, 37]. Reported apparent crude protein digestibility ranges from 64.7% to 78.0%, with approximately 42% of protein digestion occurring within the rumen. Nevertheless, *L. leucocephala* also contains the toxic amino acid mimosine, typically ranging from 1% to 7% of leaf DM [38]. In ruminants, mimosine toxicity is primarily associated with clinical signs such as alopecia, reduced feed intake, and excessive salivation; however, deaths directly attributable to *L. leucocephala* consumption have not been reported [38]. Consistent with these observations, no clinical signs of mimosine toxicity were detected in the present study.

The lower crude protein digestibility observed in the sorghum grain-based diets is also consistent with the well-documented influence of sorghum tannins on protein availability [26, 27]. Tannin concentration varies considerably among sorghum cultivars and is generally higher in traditional, non-improved varieties, such as those used in the present study.

Feed intake

DM intake during the digestibility phase was lower than that observed during the growth phase, although the ranking of dietary treatments remained consistent between the two experimental phases. This difference may be partly explained by variations in housing conditions and air circulation between the individual growth cages and the metabolism cages. Nevertheless, DM intake recorded during the growth phase for the DCFB was comparable to that reported for lambs of similar breed and physiological status fed high-quality tropical grasses [39]. Likewise, the intake values fell within the range previously reported for Blackbelly lambs receiving conventional mixed rations composed, on a DM basis, of 40% fresh *Digitaria decumbens* and 60% commercial concentrate [40].

The relatively high intake achieved with the DCFB, compared with that expected from their constituent raw materials, can probably be attributed to the physical processing applied during block manufacture. Chopping and grinding reduced particle size, thereby decreasing the physical fill effect of fibrous ingredients such as *S. bicolor* straw. Feed intake regulation in ruminants results from the interaction between physical constraints within the rumen and metabolic feedback mechanisms [41]. Because the experimental diets had a moderate energy density, feed intake was likely limited primarily by rumen fill rather than by metabolic satiety. Therefore, further reducing the fill value of fibrous ingredients through improved processing or formulation may increase voluntary intake and enhance animal performance.

Nitrogen balance and growth performance

The nitrogen balance results reflected the differences in crude protein digestibility among the experimental diets. Sorghum grain-based diets showed greater fecal nitrogen losses, whereas urinary nitrogen excretion remained similar across treatments. Consequently, nitrogen retention was lower in these diets, indicating lower protein utilization efficiency, consistent with the lower growth rates recorded.

The observed ADG ranged from 49.7 to 99.7 g/day. These values should be interpreted relative to the biological growth potential of Blackbelly lambs, estimated at approximately 150 g/day, and the average growth rate of approximately 120 g/day reported for animals grazing high-quality tropical pasture [40]. Overall, the growth performance achieved in the present study was comparable to that expected under tropical grazing conditions and was consistent with the study objective of evaluating DCFB formulated exclusively from non-conventional feed resources. However, growth responses varied according to dietary composition. Previous studies have reported daily weight gains of up to 190 g in tropical sheep receiving mixed diets containing similar by-products, although roughage accounted for less than 30% of dietary DM [42]. Similarly, sheep fed sorghum straw-based diets presented as complete feed blocks, pellets, or mash and supplemented with non-conventional energy and protein sources have achieved average daily gains of approximately 75 g/day [43]. Thus, the growth performance observed in the present study compares favorably with previous reports despite the exclusive use

of non-conventional feed resources.

The measured growth rates closely matched those predicted from DCP intake using the equations proposed by Salah *et al.* [17], suggesting that observed growth was more closely associated with digestible protein intake under the conditions of this study. The relatively low growth observed in the control group can be attributed to limited digestible protein intake resulting from the low crude protein concentration (4.6%) of the mature hay consumed by the animals. Although hay intake was constrained by its relatively poor nutritional quality, the favorable FCR indicates that the overall nutritional value of the control diet remained satisfactory. Importantly, the molasses-based DCFB produced growth rates comparable to the control diet, showing that DCFB formulated exclusively from non-conventional feed resources can support animal growth when nutrient availability is adequate.

Growth responses were more closely associated with DCP intake than with predicted ME supply. Furthermore, the differences between observed growth and growth predicted from DCP intake may partly reflect differences in protein quality and ruminal degradability among the dietary protein sources. The larger discrepancies observed for the sorghum grain-based diets suggest that intestinal protein supply may have been overestimated when predictions relied solely on total tract crude protein digestibility.

Similar observations have been reported by Osman [44], who evaluated *S. bicolor* straw offered alone or supplemented with molasses and nitrogen sources to Sudan Desert lambs. Growth rates remained below 60 g/day, leading the authors to conclude that: (i) sorghum straw alone was insufficient to maintain body weight in growing lambs; (ii) supplementation with molasses increased straw intake but failed to maintain body weight; and (iii) supplementation with both molasses and nitrogen sources maintained body weight and supported modest live weight gain.

A clear discrepancy was observed between growth predicted from ME intake and that predicted from DCP intake. Two possible explanations may account for this difference. First, ME intake may have been overestimated by the prediction equations. However, this explanation appears unlikely because the equation proposed by Salah *et al.* [17], derived exclusively from calorimetric measurements in sheep, goats, and cattle, uses a conversion factor of 4.03 (ME intake/digestible organic matter intake), which is approximately 10% lower than the value of 4.45 kcal ME/g total digestible nutrients recommended by the NRC. Consequently, the present study likely underestimated rather than overestimated ME intake. Second, the dietary energy supply may have exceeded the protein supply relative to the animals' growth requirements. This explanation appears more plausible because the observed growth rates corresponded much more closely with those predicted from DCP intake than with those predicted from ME intake.

Role of feed ingredients and nutrient synchronization

The experimental diets were formulated to combine rapidly fermentable carbohydrate sources with adequate nitrogen availability to improve nutrient synchronization within the rumen and thereby enhance microbial protein synthesis [45, 46]. However, the anticipated advantages of combining slowly degradable carbohydrates with partially protected protein sources were not clearly demonstrated under the conditions of the present study. This outcome may reflect the nutritional characteristics of the fibrous agro-industrial co-products incorporated into the DCFB.

An effective DCFB should satisfy three principal nutritional objectives: (i) promote cellulolytic activity to maximize the utilization of fibrous dietary components; (ii) optimize microbial protein synthesis within the rumen; and (iii) reduce excessive ruminal protein degradation while increasing the supply of bypass protein to the small intestine. In this study, no measurements were taken in the animals' digestive tracts to quantify these various parameters. Consequently, based on the extensive literature on these topics, only hypotheses can be made regarding their potential impacts on the observed growth rates. The differences in growth performance observed among the experimental diets suggest that one or more of these objectives was not fully achieved in all formulations. These findings emphasize the importance of balancing carbohydrate fermentability with protein degradability when formulating diets based on low-quality fibrous resources.

The superior performance of the molasses-based diets suggests that these formulations provided a more favorable synchrony between energy and nitrogen availability. Molasses supplies rapidly fermentable carbohydrates that stimulate ruminal microbial activity [29] without adversely affecting fiber digestion, as demonstrated by Diet 1, which contained the greatest proportion of molasses. In contrast, starch derived from sorghum grain is degraded more slowly in the rumen [30] and may not supply fermentable energy quickly enough

to maximize microbial protein synthesis when combined with highly fibrous crop residues.

Whole cottonseed contributed substantial dietary energy because of its high lipid concentration. However, excessive dietary fat may partially inhibit ruminal fiber degradation, thereby reducing cellulolytic activity and overall fiber utilization, as previously reported [34]. This mechanism may have contributed to the comparatively lower performance observed in diets containing higher proportions of whole cottonseed.

The inclusion of *L. leucocephala* foliage provided a valuable protein source whose proteins are partially protected from ruminal degradation by CTs, thereby increasing the supply of bypass protein available for intestinal digestion [31]. The favorable growth performance obtained with the molasses-*L. leucocephala* diets suggests that combining rapidly fermentable carbohydrates with tannin-protected protein may be an effective strategy for improving nutrient synchronization in tropical ruminant feeding systems. This concept has received relatively limited attention and warrants further investigation. A recent meta-analysis demonstrated that the benefits of nutrient synchronization depend on both the nutrient source and the production context, with by-pass amino acids showing the greatest responses in forage-based feeding systems [46]. These observations are consistent with the favorable performance of the molasses-*L. leucocephala* combination evaluated in the present study.

Despite the inclusion of *L. leucocephala*, no clinical signs associated with mimosine toxicity were observed throughout the experimental period, indicating that the inclusion level used was well tolerated by the animals.

Economic implications

Manufacturing DCFB is relatively labor-intensive, requiring harvesting raw materials, processing ingredients, and block compression. However, the labor requirement depends largely on the degree of mechanization, and a wide range of suitable processing equipment is now commercially available. Because the present study was conducted under experimental conditions, economic projections should be interpreted cautiously, particularly when considering the additional costs and efficiencies associated with scaling production from laboratory to commercial farm conditions.

Under Guadeloupe production conditions, conventional feed ingredients cost approximately €0.20, €0.35, and €0.64 per kilogram of DM for fresh pasture forage, hay, and commercial concentrate, respectively (unpublished data from the INRAE experimental farm). Assuming a conventional diet containing 70% roughage and 30% concentrate, the daily feeding cost for a growing lamb consuming approximately 1 kg of DM ranges from €0.33 to €0.44. Consequently, a production cost of approximately €0.44 per feed block would represent the maximum economic break-even point for replacing conventional feeding systems. However, commercial production costs must be experimentally validated to account for changes in production scale. This target appears achievable for smallholder farms where family labor and locally available agro-industrial by-products can be utilized efficiently. For larger commercial enterprises, block production may be more economically feasible through cooperative organizations or specialized small- to medium-scale processing facilities.

Van Zanten *et al.* [47] stated that "If we use farm animals for what they are good at - converting by-products from the food system and grass resources into valuable food and manure - they can contribute significantly to human food supply, while at the same time reducing the environmental impact of the entire food system." The present findings support this concept by showing that DCFB technology can support the transition from linear to circular agricultural production systems through efficient use of locally available biomass. Although block manufacture requires energy inputs, this technology could be integrated with renewable energy systems using biogas digesters, converting animal feces into energy while producing digestate for use as an organic fertilizer. Such an integrated approach would further improve the environmental sustainability of tropical livestock production.

Implications for tropical livestock systems

The principal objective of this study was to formulate diets composed exclusively of non-conventional feed resources that could achieve growth performance comparable to that obtained with high-quality tropical grass. This objective was successfully achieved with two of the experimental DCFB. These findings demonstrate that DCFB technology can substantially improve the utilization of locally available fibrous biomass while maintaining satisfactory animal performance. Additional studies evaluating carcass characteristics and meat quality will further clarify the practical value of this feeding strategy.

Beyond improving animal productivity, DCFB technology could enhance nutrient recycling within integrated crop-livestock systems, provided manure is effectively returned to agricultural land. In Guadeloupe, sugarcane occupies approximately 10,000 ha (25% of the agricultural area) (Agricultural Statistics for Guadeloupe;

<https://daaf.guadeloupe.agriculture.gouv.fr/memento-de-la-statistique-agricole-donnees-2021-a1805.html>) and produces approximately 50,000 metric tons of sugarcane tops annually (estimate based on a yield of 5 metric tons of sugarcane tops per hectare per year), with a nutritive value comparable to that of *S. bicolor* straw. Assuming that 50% of this biomass (25,000 metric tons) is recovered, incorporated into DCFB at an average inclusion rate of 30%, and that the average digestibility of the blocks remains 66%, approximately 83,000 metric tons of DCFB could be produced annually. Consumption of these feed blocks would generate approximately 23,000 metric tons of organic manure (estimated as the indigestible portion of the blocks, 34%). At an application rate of 2.5 metric tons of DM per hectare (about 10 metric tons of fresh manure), this quantity would be sufficient to fertilize about 11,000 ha of agricultural land annually, representing nearly one-quarter of Guadeloupe's cultivated area. All these values are scenario-based estimates rather than experimentally measured outcomes. They must be experimentally validated.

By facilitating feed handling, storage, transportation, and ration formulation, DCFB technology may reduce labor requirements and improve feeding management in tropical livestock systems. Importantly, this approach aims not to maximize animal performance, but to optimize the use of locally available resources while balancing nutritional adequacy, economic feasibility, and environmental sustainability.

CONCLUSION

This study demonstrated that DCFB formulated exclusively from non-conventional tropical feed resources can successfully sustain the growth of Blackbelly ewe lambs while reducing reliance on conventional forages and commercial concentrates. Among the four experimental formulations, the molasses-based diets (Diets 1 and 3) achieved ADG comparable to that of the conventional control diet based on high-quality tropical grass, whereas the sorghum grain-based diets showed lower protein digestibility, reduced nitrogen retention, poorer FCR, and consequently lower growth performance. Organic matter digestibility remained similar among diets, indicating that differences in animal performance were primarily associated with protein utilization rather than energy availability. Growth predictions based on DCP were also more consistent with the observed performance than those based on ME, highlighting the importance of optimizing protein supply and utilization in tropical feeding systems.

From a practical perspective, these findings show that locally available agricultural and agro-industrial by-products can be transformed into nutritionally balanced DCFB that supports satisfactory animal performance. This approach offers an effective strategy to improve feed self-sufficiency, reduce dependence on imported feed ingredients, increase the value of underutilized biomass, and promote more resilient, circular livestock production systems in tropical regions.

A major strength of this study is the comprehensive evaluation of DCFB formulated entirely from non-conventional feed resources, integrating assessments of feed intake, apparent digestibility, nitrogen balance, growth performance, and predicted nutrient utilization. The study also provides a practical framework for developing sustainable feeding strategies tailored to tropical island production systems using locally available resources.

Several limitations should be acknowledged. The experiment evaluated a limited number of dietary formulations and was conducted under controlled experimental conditions using a single sheep breed. The study did not measure ruminal fermentation characteristics, microbial protein synthesis, intestinal amino acid supply, carcass traits, meat quality, or economic performance under commercial farm conditions. Consequently, researchers could not directly verify the mechanisms underlying differences in nutrient synchronization and protein utilization.

Future research should optimize the proportions of rapidly fermentable carbohydrates, fibrous by-products, and protein sources to maximize nutrient synchronization and ruminal efficiency. Studies incorporating rumen fermentation kinetics, microbial protein synthesis, amino acid availability, methane emissions, carcass characteristics, meat quality, life-cycle assessment, and farm-scale economic analyses will provide a more comprehensive evaluation of DCFB technology. In addition, validation of these feeding strategies across different tropical environments, livestock breeds, and locally available feed resources will facilitate broader adoption.

Overall, the present findings demonstrate that DCFB produced exclusively from non-conventional tropical feed resources represents a promising and sustainable nutritional strategy for tropical small ruminant production. By efficiently converting locally available agricultural by-products into nutritionally valuable feeds, this technology can improve animal productivity, strengthen feed security, enhance nutrient recycling, and contribute to the

development of economically viable and environmentally sustainable circular livestock production systems.

DATA AVAILABILITY

The datasets generated during and/or analyzed during the current study are available from the corresponding author of the article.

GENERATIVE AI DECLARATION

Generative artificial intelligence (AI) tools were used solely to improve language, grammar, and readability during manuscript preparation. All scientific content, data analysis, interpretation of results, and conclusions were developed and verified by the authors. The authors take full responsibility for the accuracy, integrity, and originality of the work presented, and no AI tool was listed as an author.

AUTHORS' CONTRIBUTIONS

JDB, JLG, NM, and HA: Designed the experimental protocol, performed the statistical analyses, and wrote the manuscript. PM, JG, and RA: Carried out the technical aspects of the experiment and performed the laboratory analyses. VY: Laboratory analyses. All authors have read and approved the final version of the manuscript.

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COMPETING INTERESTS

The authors declare that they have no competing interests.

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