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Improving the feeding value of plantain banana (*Musa × paradisiaca* L.) leaves by urea treatment or nitrogen supplementation in adult bucks

Marie Lesly Fontin[a,b,*], Didier Marlier[c], Yves Beckers[a]

[a] Precision Livestock and Nutrition, University of Liege, Gembloux Agro-Bio Tech, Passage des Déportés, 2, Gembloux B-5030, Belgium
[b] Animal Production Department, State University of Haiti, Faculty of Agronomy and Veterinary Medicine, Route Nationale #1, HT 6110, Damien, Port-au-Prince, Haiti
[c] Department of Veterinary Management of Animal Resources, Poultry Rabbit and Racing Pigeon Medicine, University of Liege, Faculty of Veterinary Medicine, Avenue de Cureghem, 6, Sart-Tilman, Liège B-4000, Belgium

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ABSTRACT

Banana- and plantain-producing regions generate by-products that could be used as ruminant feed, although plantain leaves fed alone have low nutritive value. This study evaluated feed intake and fecal digestibility of plantain (*Musa×paradisiaca* L.) leaves in 20 adult bucks over three periods using five diets: fresh leaves (FL), dried leaves (DL), dried leaves supplemented with urea (DLU), dried leaves mixed with hoopvine leaves (DLH), and dried leaves treated with urea during ensiling (DUTL). Diets were offered at approximately 60–70 g DM/kgW$^{0.75}$ to each animal in individual metabolism cages during 21-day periods, including 7 days of measurements. Data were analyzed using a GLM model including diet and period as main effects. Mean comparisons were performed using Duncan, and significance was declared at $P < 0.05$. Fresh and dried plantain leaves were rich in ash (14–15% DM) and Neutral Detergent Fiber (NDF) (56–60% DM) but only moderate in crude protein (10–13% DM). Dry Matter Intake (DMI) and NDF digestibility of DL (35.1 g/kgW$^{0.75}$ and 31.0%, respectively) and FL (40.3 g/kgW$^{0.75}$ and 39.9%, respectively) were low, reflecting poor feeding value. Urea supplementation of dried leaves (DLU diet) did not improve intake or fiber digestibility (36.6 g/kgW$^{0.75}$ and 35.3%, respectively), and increased DM intake and NDF digestibility were measured with DLH diet (50.2 g/kgW$^{0.75}$ and 41.4%, respectively), but the improvements were attributed to the inclusion of hoopvine leaves rather than enhanced utilization of plantain leaves. In contrast, urea treatment during ensiling of dried leaves significantly increased DMI (59.9 g/kgW$^{0.75}$) and NDF digestibility (51.9%) of DUTL diet. Only this latter diet maintained body weight, whereas goats fed the other diets lost 1.0–1.9 kg during each test period. Results indicated that nitrogen supply was not the main limitation of plantain leaves and that urea treatment during ensiling was the most effective strategy to improve their feeding value for goats.

1. Introduction

Bananas and plantains are widely cultivated perennial crops in tropical regions of Asia, the Americas, and Africa (Rusdy, 2019). In Haiti, they are primarily grown in irrigated plains and wet valleys, either as monocultures or within mixed cropping systems across diverse agroecological zones. Ranking fourth in terms of sown area, after common beans (*Phaseolus vulgaris*), maize (*Zea mays*), and cassava (*Manihot esculenta*) (FAOSTAT, 2025), these crops provide continuous biomass production. Beyond their importance for human consumption, banana and plantain cultivation generates large quantities of crop residues, mainly leaves, pseudostems, and peels, which can be valorized as feed resources for ruminants, particularly in tropical livestock systems where forage availability is limited or highly seasonal (Pieltain et al., 1999; Wadhwa et al., 2015).

Depending on species, cultivar, and planting density, banana and plantain crops can produce between 2.9 and 35 tons of dry matter (DM) per hectare per year from leaves and pseudostems (Ffoulkes et al., 1977; Pound and Fernandez, 1981; Shah et al., 2005; Xandé et al., 2005). Although these residues are recognized as potential ruminant feed resources, untreated leaves and pseudostems generally meet only maintenance requirements and therefore require prior treatment and/or dietary supplementation to support productive performance (Ffoulkes and Preston, 1977; Ruiz and Rowe, 1980; Geoffroy et al., 1991; Pieltain

* Corresponding author at: Precision Livestock and Nutrition, University of Liege, Gembloux Agro-Bio Tech, Passage des Déportés, 2, Gembloux B-5030, Belgium.
E-mail addresses: marie_lesly.fontin@ueh.edu.ht, mlfontin@doct.uliege.be (M.L. Fontin).

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et al., 1999; Marie-Magdeleine et al., 2010; Xue et al., 2020; Teixeira et al., 2021).

Previous studies have reported moderate dry matter intake (DMI) of banana leaves and pseudostems by goats. Pregnant Canarian goats consumed 66.4 and 19.3 g DM/kg $W^{0.75}$ of leaves and pseudostems, respectively (Pieltain et al., 1999), whereas indigenous goats consumed 34.3 g DM/kg $W^{0.75}$ of banana leaves (Katongole et al., 2008). These intake levels are largely explained by the low metabolizable energy (ME) content of banana leaves (1563 kcal ME/kg DM) (Pieltain et al., 1999) and their limited apparent fecal digestibility of organic matter (OM; 45–58%) and crude protein (CP; 43–55%), whether offered fresh or wilted (Katongole et al., 2008). Banana leaves are characterized by high neutral detergent fiber (NDF) concentrations (505–613 g/kg DM) (Pieltain et al., 1999; Katongole et al., 2008), together with elevated lignin (Pieltain et al., 1999) and silica contents (Oliveira et al., 2007), which markedly constrain ruminal degradability.

Although banana leaves contain reasonable CP levels (8–17% DM) (Ffoulkes et al., 1977; Pieltain et al., 1999), their structural characteristics, including high fiber and lignin contents, as well as the presence of secondary compounds such as tannins (17.3 g/kg DM of total tannins; Kumari et al., 2023) may limit nitrogen availability for rumen microorganisms (Balogun et al., 1998). This constraint can impair microbial activity and reduce feed utilization efficiency. Therefore, nitrogen or protein supplementation represents a relevant strategy to improve the availability of degradable nitrogen, thereby overall feed utilization. In addition, urea treatment of low-quality forages has been shown to reduce fiber constraints, and increase nitrogen content, leading to improved OM digestibility and voluntary intake in ruminants (Fontenot et al., 1995; Sarnklong et al., 2010; Gunun et al., 2016).

This study aimed to evaluate the effects of nitrogen supplementation and urea treatment on nutrient intake and digestibility of plantain leaves in castrated adult Haitian Creole bucks. We hypothesized that both nitrogen supplementation and urea treatment of plantain leaves would improve DMI and fecal digestibility in these animals, thereby enhancing the nutritional value of these crop residues in goat feeding systems.

2. Materials and methods

2.1. Ethic approval

All experimental procedures were reviewed and approved by the National Bioethics Committee (NBC) of the Ministry of Public Health and Population (MSPP, Haiti; approval reference no. 1920–11).

2.2. Experimental diets

The basal ingredient of the experimental diets consisted of mature, physiologically active green leaves harvested from plantain banana plants (*Musa* × *paradisiaca* L., AAB genomic group; local cultivars “musquée bwa blan” and “musquée bwa nwa”). Leaves older than three months were collected from plants aged five months or more at the experimental farm of the State University of Haiti (Port-au-Prince). Leaves were cut at the junction between the leaf blade and the petiole, sun-dried on plastic sheets for approximately eight days with regular turning to ensure uniform dehydration, and subsequently chopped using a straw cutter to obtain particles not exceeding 3–4 cm in length.

Four experimental diets based on sun-dried plantain leaves were evaluated (Table 1): sun-dried plantain leaves alone (DL); sun-dried plantain leaves supplemented with mature hoopvine leaves (*Trichostigma octandrum* L.; HL) (DLH); urea-treated sun-dried plantain leaves (DUTL); and sun-dried plantain leaves supplemented with urea (DLU).

For the DUTL diet, 5 kg of urea were dissolved in 60 L of water and mixed with 100 kg of sun-dried chopped plantain leaves, followed by manual homogenization. The treated material was then placed in 150 L plastic drums, compacted, and hermetically sealed for ensiling. The silos were opened at least 90 days later, prior to each experimental period.

Table 1
Centesimal composition (% of DM) of the experimental diets.

Ingredients	FL	DL	DLU	DLH	DUTL
Fresh plantain leaves	100		-	-	-
Sun-dried plantain leaves	-	100	98.2	61.7	-
Sun-dried plantain urea treated leaves	-	-	-	-	100
Hoopvine leaves (HL)	-	-	-	38.3	-
Urea (U)	-	-	1.8	-	-

FL: fresh leaves; DL: sun-dried plantain leaves; DLU: sun-dried plantain leaves + urea; DLH: sun-dried plantain leaves + hoopvine leaves; DUTL: sun-dried plantain urea treated leaves.

The silage was subsequently sun-dried for 4–5 days to remove excess ammonia (NH_3) and then stored until use in the experiment.

The nitrogen-supplemented diets (DLH and DLU) were formulated to be theoretically isonitrogenous. However, the inclusion level of HL was set at 38.3%, as higher inclusion rates (≥40%) were associated with the occurrence of soft feces in goats during a preliminary (unpublished) trial. Urea and mature hoopvine leaves, characterized by a high CP content (25.7% DM; Stinfil et al., 2025) were used as sources of non-protein nitrogen and true protein nitrogen, respectively. The HL used in the present study consisted of mature leaves that were harvested at the experimental farm of the State University of Haiti, sun-dried following the same procedure as for plantain leaves, and chopped using a straw cutter.

In addition to these four diets, a fifth diet based on fresh plantain leaves (FL) was included. Fresh leaves were harvested daily throughout the experiment from plantain plants as described above and chopped with a machete to obtain pieces approximately 5–6 cm in length.

2.3. Animals and experimental management

Twenty castrated adult Haitian Creole bucks, older than 2 years and with an initial body weight of 18.6 ± 3.0 kg, were used in the experiment. Three weeks before the start of the trial, all animals received prophylactic treatment consisting of albendazole and ivermectin to control internal and external parasitic infestations. They were also supplemented with vitamins AD_3E. Bucks were then randomly allocated to individual metabolism cages allowing individual feeding and total collection of feces and urine.

The experiment was conducted over three experimental periods in which each diet was assigned to 12 goats, with the individual goat considered as the experimental unit. Each experimental period lasted 21 days, including 14 days of dietary adaptation followed by a 7-day measurement phase. The same animals were used across successive experimental periods and were assigned to different diets according to a randomized allocation scheme. Each period can be considered as an independent experimental phase. Between experimental periods, a 14-day washout interval was implemented. The bucks were removed from the metabolic cages and managed under a grazing system, with daytime grazing on pasture and nighttime housing in a goat pen. During this pre-adaptation period, animals were fed mainly grass during the day and plantain leaves at night.

Experimental diets were offered once daily at 09:00 h in amounts calculated to meet at least maintenance energy requirements in hot climate according to Salah et al. (2014). Prior to feed distribution, 7 g of NaCl dissolved in 40 g of water were sprayed onto the experimental diets to stimulate appetite. Also, a mineral lick block was provided in each cage, and water was available *ad libitum*.

During the experimental period, ambient temperature ranged from 23.6 to 36.4°C.

2.4. Measurements and sample collections

At the beginning and end of each measurement period, all bucks were individually weighed using an electronic scale (capacity 30 kg;

accuracy 2 g). Each morning, approximately 60–70 g DM/kg $W^{0.75}$ of the experimental diets was offered to each animal. Daily amounts of feed offered, refusals, feces, and urine outputs were recorded using an electronic scale (capacity 2000 g; accuracy 0.1 g). Representative samples of the diets, refusals, feces, and urine were collected daily throughout the 7-day measurement period. To prevent ammonia losses, 10–20 mL of 10% (v:v) sulfuric acid, depending on urine volume, was added to each urine collection container.

Diet, refusal, and fecal samples were oven-dried at 60°C for 3–5 days and weighed after re-equilibrium with ambient humidity after 3 days. Diet samples collected over the seven-day measurement period were pooled by diet. Similarly, refusal and fecal samples were pooled by buck within each experimental period. The dried samples were then ground using a laboratory mill (Wiley Mill; Arthur H. Thomas) fitted with a 1-mm sieve and stored in airtight plastic bags pending laboratory analyses. Urine samples were collected in 50 mL plastic containers and stored at −18°C until nitrogen analysis.

2.5. Laboratory analysis and calculation of digestibility coefficients

Dry matter (DM) and ash (MM) contents were carried out by the methods AOAC, 1990, 934.01 and 942.05, respectively (AOAC, 1990). Organic matter (OM) content was obtained by difference between DM and MM. Nitrogen content was determined using the Kjeldahl method (AOAC, 1990), and crude protein (CP) was calculated as N × 6.25. Neutral detergent fiber (NDF) content was determined according to the method of Van Soest et al. (1991). Neutral detergent fiber was determined without the use of sodium sulfite or amylase, and the residue was corrected for neutral detergent–insoluble ash.

Apparent fecal digestibility coefficients (Df) of dry matter (DM), organic matter (OM), crude protein (CP), and neutral detergent fiber (NDF) were calculated for each buck and each diet as follows: Df (%) = ((Intake – fecal output)/intake) x 100. Based on the evaluation of the DLH and DL diets, the difference method described by Sauvant and Giger (1989) was applied to estimate the fecal digestibility of DM, OM, CP, and NDF of the HL. Nitrogen (N) retention was calculated for each buck and each diet as the difference between N intake and total N excretion (fecal and urinary).

2.6. Statistical analysis

Raw data of determined parameters across the five diets were subjected to analysis of variance using the general linear model (GLM). The effects of diet, period and their interaction were evaluated according to the following model:

$$Y_{ij} = \mu + \alpha_i + \beta_j + \alpha\beta_{ij} + \varepsilon_{ij}$$

where Y_{ij} is the value of studied parameter for diet i in period j, μ is the overall mean, α_i is the fixed effect of diet i, β_j is the fixed effect of period j, $\alpha\beta_{ij}$ is the diet x period interaction, and ε_{ij} is the residual error. When significant effects were detected, Duncan's multiple range test was applied for mean separation. All statistical analyses were performed using SAS software (version 9.4; SAS Institute Inc., 2016).

3. Results

The chemical composition of the diets and refusals is presented in Table 2 and Table 3. The experimental diets were characterized by high ash (14.7–18.1% DM) and NDF (45.8–59.5% DM) contents. Compared with the FL diet, initially very moist at harvest (80%), CP and NDF contents of the DL diet decreased by 20% and 7%, respectively (Table 2). Non-protein supplementation with urea (DLU diet) increased CP content only, whereas protein supplementation with HL increased CP while simultaneously reducing NDF and OM contents in the DLH diet compared with the DL diet (Table 2). This reflects the composition of HL, which were richer in CP (19.5% DM) but lower in OM (74.7% DM) and NDF (31.8% DM) than DL. Urea treatment of the dried leaves (DUTL diet) increased CP content by 4.5 %age units and reduced NDF content by 3.2 %age units relative to the DL diet (Table 2).

Table 2
Dry matter (%±SD) and chemical composition (% DM±SD) of experimental diets.

Diets	DM	OM	CP	NDF
FL	20.3 ± 0.3	86.0 ± 1.0	13.0 ± 0.7	59.5 ± 2.2
DL	65.8 ± 1.1	85.1 ± 0.6	10.4 ± 0.1	55.6 ± 1.7
DLU	65.6 ± 1.5	85.1 ± 0.7	13.7 ± 0.7	55.7 ± 2.6
DLH	65.9 ± 1.1	81.1 ± 0.3	13.8 ± 0.0	45.8 ± 2.8
DUTL	63.6 ± 1.0	85.3 ± 0.0	15.0 ± 0.8	52.4 ± 2.7

FL: fresh leaves; DL: sun-dried plantain leaves; DLU: sun-dried plantain leaves + urea; DLH: sun-dried plantain leaves + hoopvine leaves; DUTL: sun-dried plantain urea treated leaves.

Table 3
Dry matter (%±SD) and chemical composition (% DM±SD) of refusals.

Diets	DM	OM	CP	NDF
FL	17.2 ± 1.5	84.9 + 1.0	8.2 + 1.6	65.2 + 2.8
DL	69.3 ± 2.2	85.0 + 0.7	10.6 + 0.3	56.4 + 1.4
DLU	64.7 ± 6.7	84.8 + 0.6	12.9 + 0.7	56.6 + 1.5
DLH	69.5 ± 3.1	80.3 + 1.1	14.0 + 1.0	46.8 + 3.6
DUTL	74.6 ± 6.6	84.2 + 1.2	13.6 + 1.6	52.3 + 3.2

FL: fresh leaves; DL: sun-dried plantain leaves; DLU: sun-dried plantain leaves + urea; DLH: sun-dried plantain leaves + hoopvine leaves; DUTL: sun-dried plantain urea treated leaves.

Experimental diets based on sun-dried leaves were offered in amounts intended to meet at least the maintenance energy requirements of the bucks, and the mean quantities offered did not differ significantly among the four diets throughout the experimental period (Table 4). The FL diet was the only exception, being offered in larger quantities due to its unpredictable dry matter content and the pronounced sorting behavior observed during feeding. For three diets (DL, DLU, and FL), the orts exceeded 40% of the amount offered. In contrast, refusals averaged 24 and 5% for the DLH and DUTL diets, respectively (Table 4). The chemical composition of refusals closely reflected that of the corresponding diets, except for the FL diet, for which bucks exhibited marked selective feeding, preferentially rejecting fractions with lower protein content and higher moisture and NDF concentrations (Table 2).

DM and OM intakes did not differ among the DL, DLU, and FL diets but were significantly lower than those recorded for the DLH and DUTL diets. The highest DM and OM intakes (59.9 and 51.1 g/kg $W^{0.75}$, respectively) were obtained with the DUTL diet (Table 4). CP intake varied widely across diets, ranging from 3.6 to 9.0 g/kg $W^{0.75}$, according to diets CP contents and orts (Table 3), but also according to DM intakes (Table 4). The DUTL diet yielded the highest CP intake (9.0 g/kg $W^{0.75}$), whereas the DL diet resulted in the lowest (3.6 g/kg $W^{0.75}$). A similar trend was observed for NDF intake, although dietary effects were less pronounced than those observed for CP intake (Table 4).

Urea supplementation of sun-dried plantain leaves, which improved CP content in DLU diet (Table 2), resulted in an increase in CP intake compared with DL diet but the supplementation had no effect on the DM, OM and NDF intake (Table 4). The effects of HL supplementation were more pronounced, as the inclusion of this feed with sun-dried plantain leaves significantly increased daily nutrient intake compared with the corresponding values for the DL diet (Table 4). However, in the DLH diet, the intake of DL (31.0 g DM/kg $W^{0.75}$) remained comparable to that observed in the DL diet, whereas HL intake reached 19.3 g DM/kg $W^{0.75}$. This corresponds to a substitution rate of approximately 31% of DL, when HL was incorporated at 38.3% of the DLH diet.

Fecal digestibility (Df) coefficients are presented in Table 5, and the effects of diet were significant for all variables, with a high level of

Table 4
Offered, refused and intake amounts (g/kg $W^{0.75}$) of the experimental diets in bucks.

		Diets					SEM	P value		
		FL	DL	DLU	DLH	DUTL		Diet	Period	D x P
Offered	DM	69.4^{a}	60.9^{b}	61.2^{b}	65.8^{ab}	63.3^{b}	1.9	0.0176	0.4469	0.4523
Refused	DM	29.1^{a}	25.8^{a}	24.6^{a}	15.6^{b}	3.3^{c}	2.5	<.0001	0.1119	0.4311
Intake	DM	40.3^{c}	35.1^{c}	36.6^{c}	50.2^{b}	59.9^{a}	2.0	<0.0001	0.3544	0.6586
	OM	35.0^{c}	30.0^{c}	31.2^{c}	40.8^{b}	51.1^{a}	1.7	<0.0001	0.2623	0.6304
	CP	6.6^{b}	3.6^{d}	5.2^{c}	6.9^{b}	9.0^{a}	0.3	<0.0001	0.6654	0.2087
	NDF	22.5^{bc}	17.6^{d}	19.6^{cd}	23.6^{b}	31.4^{a}	1.3	<0.0001	0.1976	0.8295

Means in the same line with identical letters are not significantly different according to Duncan multiple range test at alpha level of 0.05. D x P: Diet x Period.
FL: fresh leaves; DL: sun-dried plantain leaves; DLU: sun-dried plantain leaves + urea; DLH: sun-dried plantain leaves + hoopvine leaves; DUTL: sun-dried plantain urea treated leaves.

Table 5
Fecal digestibility coefficient (%) of DM, OM, CP and NDF of the experimental diets in bucks.

	Diets					SEM	P value		
	FL	DL	DLU	DLH	DUTL		Diet	Period	D x P
DM	39.0^{a}	29.2^{b}	32.5^{b}	40.3^{a}	42.1^{a}	1.4	<0.0001	0.4928	0.1264
OM	40.7^{b}	29.8^{c}	32.9^{c}	40.9^{b}	45.1^{a}	1.4	<0.0001	0.2762	0.0885
CP	65.7^{a}	39.9^{d}	56.2^{b}	55.0^{bc}	51.9^{c}	1.2	<0.0001	<0.0001	<0.0001
NDF	39.9^{bc}	31.0^{d}	35.3^{cd}	41.4^{b}	54.8^{a}	1.8	<0.0001	0.0002	0.1014

Means in the same line with identical letters are not significantly different according to Duncan multiple range test at alpha level of 0.05. D x P: Diet x Period.
FL: fresh leaves; DL: sun-dried plantain leaves; DLU: sun-dried plantain leaves + urea; DLH: sun-dried plantain leaves + hoopvine leaves; DUTL: sun-dried plantain urea treated leaves.

statistical significance ($p < 0.0001$). Sun drying of plantain leaves reduced the Df coefficients of DM, OM, CP, and NDF compared with FL. The reduction was greatest for CP (40%) and lowest for NDF (22%). Relative to the DL diet, urea supplementation had no significant effect on the digestibility of DM, OM, and NDF, but increased CP digestibility by 41% in the DLU diet. This increase is attributable to the high nitrogen content of urea (46% N), which is rapidly and almost completely utilized in the rumen.

Digestibility coefficients for the DLH diet were significantly higher than those for the DL diet and exceeded those of the DLU diet for DM, OM, and NDF Table 5. These results indicate that the nutrients provided by HL were more digestible for bucks than those from DL. Notably, the CP digestibility coefficient of the DLH diet did not differ from that of the DLU diet, indicating a high digestibility of HL protein that was greater than that of DL. Calculated by difference, the fecal digestibility coefficients of HL were 58.1%, 61.1%, 68.3%, and 68.9% for DM, OM, CP, and NDF, respectively.

Compared with the DL diet, all digestibility coefficients were significantly higher in the DUTL diet, with the greatest increase observed for NDF (77%), followed by OM (51%), DM (44%), and CP (30%). Digestibility coefficients for DUTL were also higher than those for the DLU diet for DM, OM, and NDF (by 30%, 37%, and 55%, respectively), whereas CP digestibility was significantly lower (by 8%) (Table 5).

Based on the results presented in Table 2 to Table 5, the average daily intakes of digestible DM, OM, CP, and NDF by bucks are reported in Table 6 according to experimental diets. These intakes were consistently the lowest for the DL diet and were significantly lower than those observed for the FL diet. Urea supplementation of sun-dried plantain leaves (DLU) increased only the daily intake of digestible CP, whereas supplementation with hoopvine leaves (DLH) increased the daily intakes of all digestible nutrients compared with the DL diet (Table 6).

The highest values were consistently recorded for the DUTL diet. From a nutritional standpoint, these intakes were approximately 2.5-fold higher for digestible DM and OM, and more than threefold higher for digestible CP and NDF compared with the DL diet. These values were also higher than those obtained with the FL diet, except for digestible CP, although the differences were less pronounced (Table 6).

Table 7 presents the average body weights of the bucks at the beginning and end of the experimental period, as well as nitrogen fluxes. No significant dietary effects were observed on initial or final body weights or on urinary nitrogen excretion; however, diet effects were significant for all other variables (Table 7).

Negative nitrogen retentions were observed for all diets except DUTL (Table 7). Nitrogen retention was lower for the DL and DLU diets compared with the DLH and FL diets. Only the DUTL diet resulted in zero nitrogen retention, indicating that the bucks' maintenance nitrogen requirements were theoretically met with this diet. Urinary nitrogen losses, expressed as a percentage of nitrogen intake, exceeded 100% for the DL and DLU diets (131% and 103%, respectively). In contrast, the DUTL diet showed the lowest urinary N loss (53%), whereas the DLH and FL diets exhibited intermediate values (77% and 83%, respectively).

Table 6
Average daily intakes of digested DM, OM, CP and NDF (g/kg $W^{0.75}$) of the experimental diets by the bucks.

	Diets					SEM	P value		
	FL	DL	DLU	DLH	DUTL		Diet	Period	D x P
DM	16.1^{c}	10.3^{d}	12.0^{d}	20.3^{b}	25.1^{a}	1.0	<0.0001	0.4413	0.4642
OM	14.5^{b}	9.0^{c}	10.3^{c}	16.7^{b}	22.9^{a}	0.9	<0.0001	0.3829	0.3974
CP	4.4^{a}	1.5^{d}	2.9^{c}	3.8^{b}	4.7^{a}	0.2	<0.0001	0.4760	0.0064
NDF	9.2^{b}	5.5^{c}	7.0^{c}	10.0^{b}	17.1^{a}	0.8	<0.0001	0.0133	0.9237

Means in the same line with identical letters are not significantly different according to Duncan multiple range test at alpha level of 0.05. D x P: Diet x Period.
FL: fresh leaves; DL: sun-dried plantain leaves; DLU: sun-dried plantain leaves + urea; DLH: sun-dried plantain leaves + hoopvine leaves; DUTL: sun-dried plantain urea treated leaves.

Table 7
Liveweight (kg $W^{0.75}$), N intake, N excretion in urine and feces, and N retention (g/kg $W^{0.75}$/d).

	Diet					SEM	P value		
	FL	DL	DLU	DLH	DUTL		Diet	Period	D x P
Initial weight	8.91	9.24	8.58	8.77	9.23	0.36	0.6990	0.8298	0.8716
Final weight	8.59	8.51	7.89	8.32	9.27	0.40	0.2245	0.7843	0.9102
Variation of weight (kg $W^{0.75}$ x 7 days)	-0.32^{b}	-0.73^{c}	-0.69^{c}	-0.45^{bc}	0.04^{a}	0.10	<.0001	0.0783	0.0883
N Intake	1.05^{b}	0.58^{d}	0.83^{c}	1.10^{b}	1.44^{a}	0.05	<.0001	0.6654	0.2087
N fecal excretion	0.35^{c}	0.35^{c}	0.36^{c}	0.49^{b}	0.69^{a}	0.02	<.0001	0.1453	0.7879
N urinary excretion	0.87	0.76	0.86	0.85	0.76	0.08	0.7080	0.0048	0.4730
N retention	-0.17^{ab}	-0.53^{c}	-0.39^{bc}	-0.24^{ab}	-0.01^{a}	0.08	0.0008	0.0039	0.5305

Means in the same line with identical letters are not significantly different according to Duncan multiple range test at alpha level of 0.05. D x P: Diet x Period. FL: fresh leaves; DL: sun-dried plantain leaves; DLU: sun-dried plantain leaves + urea; DLH: sun-dried plantain leaves + hoopvine leaves; DUTL: sun-dried plantain urea treated leaves.

Live weight changes of the bucks during the experimental week were consistent with the nitrogen retention results. Bucks fed the DL and DLU diets lost up to 1.9 kg of body weight and 4.7 g of nitrogen over the week. These losses were approximately halved in bucks fed the DLH and FL diets, whereas maintenance nitrogen requirements were met only with the DUTL diet.

4. Discussion

Our results are consistent with previous reports (Shem et al., 1995; Pieltain et al., 1999; Katongole et al., 2008; Rusdy, 2019) showing that banana leaves contain moderate CP but high NDF levels. Ash content in DM varies widely among studies, ranging from 63 g/kg DM (Shem et al., 1995) to 138 g (Pieltain et al., 1999), 155 g (Chali et al., 2018), and 140 g in the present study. Such chemical composition may limit their intake and reduce their feeding value, particularly regarding energy contribution. Accordingly, banana leaves can be classified as a low-to medium-quality feed for ruminants (Rusdy, 2019).

FL were consumed at a low level (40.3 g of DM/kg $W^{0.75}$) by adult bucks, leaving substantial refusals (approximately 40% of the daily offered amount). With this diet, the bucks exhibited selective feeding behavior, preferentially consuming the leaf blades and leaving the midribs. Consequently, the refusals had higher NDF (65.2%) and lower CP (8.2%) concentrations compared with the offered diet (59.5% and 13.0%, respectively). Such selective feeding behavior in goats has been widely documented (Lu, 1988; Morand-Fehr, 2003).

Our results on FL confirmed that of Katongole et al. (2008) who reported a DM intake of 34.3 g/kg $W^{0.75}$ in indigenous Ugandan goats (± 15 kg LW). In contrast, Pieltain et al. (1999) observed a much higher intake of 66.4 g of DM/kg $W^{0.75}$ in Canarian goats (± 45 kg LW) offered fresh banana leaves *ad libitum*. In this last experiment, the ingestion trial lasted only 5 days and was preceded by a 10-day period during which goats received a daily supplement of 200 g whole maize grain. During the maintenance trial (6 weeks), the intake of fresh banana leaves was lower, ranging from 56.6 to 60.8 g DM/kg $W^{0.75}$ (Pieltain et al., 1999).

The level of intake may be attributed to the limited digestibility of banana leaves in the rumen and at the fecal level in ruminant. Reported *in sacco* effective degradability values for fresh banana leaves are low, averaging 33% for OM at a theoretical passage rate (k) of 0.045 h^{-1} (Pieltain et al., 1999), 43% for DM at k = 0.02 (Katongole et al., 2008), and 41% for DM recalculated at k = 0.02 (Shem et al., 1995). Apparent fecal digestibility of the DM in goats was 44% in Katongole et al. (2008) close to the 40% in our experiment. Higher values have been reported in cattle, reaching 51% (Shem et al., 1995) and 65% (Ffoulkes and Preston, 1977) when fresh banana leaves were supplemented with cottonseed cake (1 kg/day) or molasses (850 g/day), respectively. Collectively, these results indicate that banana leaves provide a small potentially degradable DM fraction in the rumen and exhibit low fecal digestibility, both of which limit voluntary intake in ruminants

As for straw, the low effective DM degradability of banana leaves in the rumen may be explained by their high fiber content, shortage of required compounds for the microbial activity in the rumen or excess of compounds decreasing their activities (López et al., 2005). The high NDF content in banana leaves including that of lignin and silicon fraction, associated with the secondary metabolites like tannins are both well known to reduce the microbial activity in the rumen.

Banana foliage (leaves and pseudostems) has been reported to contain high levels of total polyphenols (about 80 g/kg DM), whereas condensed tannins appear to be present at low concentrations (Marie-Magdeleine et al., 2010). In pseudostems, total and condensed tannin contents were only 2.20 and 1.76 g/kg DM, respectively (Wang et al., 2016), whereas total tannin concentration in banana leaves can reach 17.3 g/kg DM (Kumari et al., 2023). Condensed tannins are known to reduce digestibility by forming complexes with proteins and reducing their availability to rumen microorganisms, potentially limiting microbial activity through reduced ruminal nitrogen supply and fiber (Balogun et al., 1998). However, goats can tolerate tannin-rich diets, as they are able to mitigate the negative effects of tannins commonly observed in mammalian herbivores (Schmitt et al., 2020). Moreover, tannin-rich diets may exert beneficial effects in goats, as reviewed by Landau et al. (2023). Supporting this view, Kazemi (2021) reported true DM digestibility values exceeding 640 g/kg DM in goats fed tree leaves containing 49–86 g total tannins/kg DM. Accordingly, the tannin content of banana leaves alone is unlikely to account for the low fecal digestibility observed in bucks fed fresh or sun-dried plantain leaves. Consistently, nitrogen supplementation of sun-dried leaves did not improve intake or fecal digestibility in the present study.

Lignin concentrations in banana leaves typically range from 110 to 120 g/kg DM, representing approximately 20% of the NDF and 35% of the ADF fractions, respectively (Pieltain et al., 1999; Katongole et al., 2008; Chali et al., 2018). As an essentially indigestible component, lignin reduces voluntary intake by increasing rumen fill in ruminants (Jung and Allen, 1995). In tree leaves containing 22–39% NDF, the effective degradability of NDF represents 22–61% of OM degradability (Kamatali et al., 1992). Similarly, ruminal DM degradability of cereal straws, which contain 71.6–86.2% NDF, has been estimated at only 22.1–29.3% (López et al., 2005).

Banana leaves are also characterized by a relatively high silicon content, which may account for up 48 g/kg DM in the leaf blade of Dwarf Cavendish banana (Oliveira et al., 2007). Unpublished analyses of the plantain cultivars used in the present study indicated silicon concentrations of 10–11 g/kg DM. Excessive silica concentrations in forages (~50 g/kg DM or higher) are known to depress voluntary intake and DM digestibility in ruminants by increasing abrasiveness, reducing cell wall digestibility, and prolonging ruminal retention time (Van Soest and Jones, 1968; Van Soest, 2006; Abaturov and Kolesnikov, 2023). Van Soest and Jones (1968) reported a decline in digestibility of approximately three units for each unit increase in silicon.

The crude protein content of banana leaves does not appear to limit ruminal digestibility, as fresh leaves contained 13% CP (DM basis) and exhibited a fecal digestibility of 65.7%; moreover, nitrogen from this forage has been reported to be available to ruminal microorganisms based on *in sacco* degradability studies (Shem et al., 1995; Pieltain et al., 1999). The N-balance results reported by Katongole et al. (2008) support this interpretation, as urinary N excretion in goats fed banana leaves was twice that of fecal N. In our study, bucks fed FL showed a similar pattern: urinary N accounted for 83% of N intake, whereas fecal N excretion represented only 33%.

DL were ingested at a lower level (35.1 g DM/kg $W^{0.75}$) than FL. Although FL and DL cannot be assumed to be strictly comparable under our experimental protocol (see Materials and methods), crude protein and neutral detergent fiber contents (% DM) decreased by 20% and 7%, respectively, in the DL. These results suggest that the drying conditions applied in the present study may have led to losses of leaf constituents, likely due to the high initial moisture content of the leaves (approximately 80%). Df coefficients of DM, OM, and NDF in the DL diet were consistently about 10 %age units lower than those observed for FL, while CP digestibility was reduced by 40%. This marked decrease in CP digestibility may reflect losses of soluble protein during prolonged sun drying, potentially resulting in a limitation of nitrogen available in the rumen for microbial activity. In addition, selective feeding of leaf blades by bucks in the present study likely contributed to the higher digestibility of FL, particularly for CP, as leaf blades have been reported to contain higher protein concentrations than midribs (Oliveira et al., 2007).

As non-protein nitrogen supplementation of sun-dried plantain leaves did not increase intake in the present study, nitrogen availability may not have been a major limiting factor for the digestion of plantain leaves in the goat reticulorumen. Likewise, protein supplementation of dried plantain leaves with HL did not affect forage intake, which may further support this interpretation.

Urea treatment of sun-dried plantain leaves during the ensiling process resulted in a reduction in NDF and an increase in the CP contents of the diet. These effects are consistent with those reported for low-quality forage grasses (Gunun et al., 2016; Sarnklong et al., 2010; Fontenot et al., 1995) and for banana pseudostems treated with urea during ensiling (Rigueira et al., 2020). Rigueira et al. (2020) also noted that ADF content in pseudostems was not altered by urea treatment, suggesting that hemicelluloses were the primary cell-wall carbohydrates affected by ammonization at the urea levels typically used in silage ($\leq$5% DM). In our study, this treatment resulted in the highest DM intake, which was 71% higher than that of untreated sun-dried plantain leaves, and simultaneously improved fecal NDF digestibility. As a result, bucks fed the treated material consumed three times more digestible NDF than those receiving untreated leaves. The magnitude of this improvement exceeded the 15–50% increase in intake generally reported for urea-treated straws and low-quality grasses (Kayouli, 2005). Urea treatment remains one of the most practical and widely adopted chemical methods for upgrading low quality forages as straws and other high-fiber by-products. It enhances nitrogen content and improves fiber availability for microbial fermentation by partially removing lignin constraints (Chenost and Kayouli, 1997). In addition, it has also been showed to soften fibrous materials and disrupt the silicified cuticular barrier of leaves, thereby facilitating microbial colonization (Van Soest, 2006). Its simplicity, low cost, and adaptability under farm conditions—particularly in tropical smallholder systems—have contributed to its widespread adoption as an effective strategy for improving the utilization of fibrous crop residues. However, further investigations incorporating rumen fermentation measurements and fiber fraction analysis (NDF, ADF and lignin) would be necessary for elucidating the underlying mechanisms of the urea treatment for the DUTL diet.

HL contains 31.8% NDF, which is lower than that of most fodder legumes and comparable to cabbage (INRA, 2018). Buds and young leaves are consumed by humans and are highly appreciated by Haitian consumers. Despite their potential as a feed resource, few studies have evaluated HL. Chemical analysis of a mixture of young and mature powdered leaves indicated a composition of 256.5 g CP, 38.7 g fat, 112.9 g crude fiber, 227.2 g ash, and 3524 kcal gross energy per kg DM (Stinfil et al., 2025). Unpublished observations suggest that crude protein content may range from approximately 32–37% of DM in buds and young leaves, but only 19–24% in mature leaves. The latter, which are not used for human consumption, could potentially be used to supplement plantain leaf–based diets for ruminants, as in the present study; however, this supplementation did not appear to enhance the utilization of this forage by the bucks. In addition, it should be recalled that HL inclusion levels exceeding 40% induced the production of soft feces in goats during an unpublished preliminary trial; therefore, higher inclusion rates were considered unsuitable for goats.

Among the diets tested in this experiment, DUTL was the only diet likely to meet the maintenance energy requirements of bucks, as the digested OM intake reached 23 g/kg $W^{0.75}$. This value is consistent with the minimum maintenance needs reported for goats in tropical environments (89.9 kcal ME or 24.6 g digestible OM/kg $W^{0.75}$; Salah et al., 2014), although it remains below the requirement estimated by Salah et al. (2014) for growing goats (129.7 kcal ME or 35.5 g digestible OM/kg $W^{0.75}$). Notably, bucks fed the DUTL diet were the only animals to maintain zero nitrogen balance and stable liveweight throughout the trial. Moreover, the low refusal rate recorded for this diet further suggests that the bucks may have been able to ingest greater quantities of the treated material.

Based on recommendations for maintenance nitrogen requirements under hot climatic conditions (3.51–3.8 g digestible CP/kg $W^{0.75}$; Salah et al., 2014; Teixeira et al., 2024), all experimental diets appeared to meet maintenance needs, with the exception of the dried plantain leaf and urea-supplemented diets. However, when the lower maintenance requirement proposed by Singh and Mudgal (1991) for castrated Beetal goat bucks under Indian conditions (2.6 g digestible protein/kg $W^{0.75}$) is considered, only the DL diet provided digestible protein below the estimated maintenance nitrogen requirement. Despite this, maintenance of live weight over the experimental period was observed exclusively in bucks fed the urea-treated forage diet. These findings suggest that bucks receiving the other experimental diets likely mobilized body reserves to meet maintenance energy requirements, and that a proportion of the digested crude protein may have been oxidized, as urinary nitrogen excretion was high and appeared to be largely independent of nitrogen intake for these diets. The low digestibility and limited energy availability of this forage may have constrained microbial protein synthesis. As a result, excess nitrogen was absorbed and subsequently excreted in urine, leading to elevated urinary nitrogen losses. Thus, nitrogen availability may not have been the primary limiting factor. Rather, the results suggest that the overall nutritive value of this forage—particularly its low digestibility and energy content—may have played a more critical role in limiting nitrogen utilization efficiency.

Significant diet × period interactions were observed for CP and NDF digestibility coefficients, as well as for digestible CP intake, indicating that the responses of bucks varied across experimental periods according to the diets offered. Variations in the chemical composition and nitrogen availability of the feed resources between periods, particularly for FL diet, may have differently affected these nutrient utilizations and protein digestion among the experimental diets.

The present results are consistent with previous studies showing that banana by-products cannot be efficiently used as sole feeds for ruminants without supplementation (Ffoulkes and Preston, 1977; Ruiz and Rowe, 1980; Geoffroy et al., 1991; Pieltain et al., 1999; Marie-Magdeleine et al., 2010; Xue et al., 2020; Teixeira et al., 2021). Overall, these results indicate that protein supplementation can help goats meet their nitrogen requirements; however, such supplementation alone is insufficient to increase the energy value of sun-dried plantain leaves. Under the restricted feeding conditions applied in the present study, intake of plantain leaves treated with urea was limited to maintenance requirements, which may have constrained the expression of the full nutritional potential of the diets. It can be reasonably assumed that offering this diet *ad libitum* would result in higher voluntary intake, thereby increasing both energy and nitrogen supply to the animals. Nevertheless, even under *ad libitum* conditions, meeting higher energy requirements will likely require the inclusion of feeds more concentrated in metabolizable energy.

In this context, further research should evaluate intake and fecal digestibility of banana by-products (leaves, pseudostems, stems, peels) ensiled with urea in combination with energy-rich supplements such as molasses or wheat bran, as suggested by Elahi et al. (2019) and Mitiku et al. (2020) for non-urea-treated banana by-products. Such additives may improve the ensiling process and enhance digestibility of banana residues. Moreover, the effectiveness of urea combined with molasses has long been demonstrated in the treatment of rice straw, where molasses supplies readily fermentable energy to microorganisms during fermentation (Akinfemi et al., 2020), a mechanism that may be particularly relevant for banana by-products rich in silica and neutral detergent fiber.

5. Conclusion

This experiment further confirmed that the nutritional value of fresh and sun-dried plantain leaves for adult bucks is low and insufficient to meet their maintenance energy requirements. Their chemical composition, combined with the low fecal digestibility of the organic compounds in these forages, limited their intake by these animals. The fecal digestibility of NDF from plantain leaves was particularly low, close to that of cereal straw. Contrary to our hypothesis, non-protein nitrogen supplementation of sun-dried plantain leaves did not improve fecal digestibility or intake in adult bucks. Supplementation with a higher-protein feed increased digestible nutrient intake but did not enhance the feeding value or intake of the leaves. These findings suggest that nitrogen is not the main limiting factor in plantain leaves. In contrast, urea treatment significantly improved forage digestibility, particularly of NDF, and, together with increased intake, enabled adult bucks to meet their maintenance energy and protein requirements, as digestible NDF intake was threefold higher than with untreated leaves. Although the absence of rumen fermentation measurements and detailed fiber fraction analyses limited the understanding of the underlying mechanisms, urea treatment was the only approach that enhanced the nutritional value of dried plantain leaves.

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CRediT authorship contribution statement

Didier Marlier: Writing – review & editing, Supervision, Methodology, Conceptualization. **Yves Beckers:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Marie Lesly Fontin:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

The authors declare that generative artificial intelligence was used exclusively for checking spelling, grammar, and syntax, without influencing the scientific content or interpretation of the manuscript.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Marie Lesly Fontin reports financial support was provided by ARES-CCD. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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