Archives of Animal Nutrition

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/gaan20

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To cite this article: Gérard Xavier Gbenou, Mohamed Habibou Assouma, Denis Bastianelli, Timbilfou Kiendrebeogo, Laurent Bonnal, Nouhoun Zampaligre, Bérénice Bois, Souleymane Sanogo, Ollo Sib, Cécile Martin & Luc Hippolyte Dossa (2024) Supplementing zebu cattle with crop co-products helps to reduce enteric emissions in West Africa, Archives of Animal Nutrition, 78:2, 125-141, DOI: 10.1080/1745039X.2024.2356326

To link to this article: https://doi.org/10.1080/1745039X.2024.2356326

Published online: 22 Jun 2024.

ARCHIVES OF ANIMAL NUTRITION
2024, VOL. 78, NO. 2, 125–141
https://doi.org/10.1080/1745039X.2024.2356326

Supplementing zebu cattle with crop co-products helps to reduce enteric emissions in West Africa

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ABSTRACT

In Africa, a wide variety of diets (forage + crop co-products or other agricultural by-products) is being used by livestock farmers in different production systems to adapt to climate change. This study aimed to assess the performance of various local feeding strategies on Sudanese Fulani zebu cattle. Two experiments were carried out on 10 steers aged initially 33 months (142 kg body weight – BW). The animals were fed eight different diets at an intake level of 3.2% LW in dry matter (DM), including two control diets of 100% rangeland forage (100% RF) and six experimental diets made up of forage and crop co-products (75:25 DM ratio). In the first experiment, the control diet was made up of rangeland forage (RF) and supplements consisted of four cereal co-products (CC), i.e. maize, sorghum, millet, and rice straws. In the second experiment, the control diet consisted of *Panicum maximum* (Pmax) hay, and the supplements tested were two legume co-products (LC), i.e. cowpea and peanut haulms. Each experiment lasted 3 weeks, including 2 weeks of adaptation to the diet and 1 week of data collection on individual animals (intake, apparent digestibility, and enteric methane). The NDF content of the diets was different within each experiment ($p <$ 0.05). Among diets containing CC, DM intake [g/kg BW] was significantly higher (+31%; $p = 0.025$) for the diet containing rice straw than for the other diets, which showed similar levels to the RF diet. Among diets containing LC, intake was significantly higher ($p = 0.004$) than for the Pmax diet. Intake was higher for the peanut haulm diet than for the cowpea haulm diet. The DM digestibility was similar between the different

ARTICLE HISTORY
Received 6 January 2024
Accepted 13 May 2024

KEYWORDS
Crop residues; supplementary feeding; nutritive value; ruminants; enteric methane; mitigation; Sahel

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diets in each experiment. Enteric methane (eCH_4) yield [g/kg DMI] from the CC and LC-containing diets were reduced by an average of 23% and 20% compared to the RF and Pmax control diets respectively. Raising awareness among agro-pastoralists about the use of crop co-products offers real prospects for eCH_4 emissions mitigation in the Sahel region.

1. Introduction

Extensive livestock farming in Sub-Saharan Africa (SSA) is characterised by the predominant use of rangeland resources (Hiernaux and Le Houerou 2006). Feeding practices are based on daily selective grazing, transhumance, and supplementation. Natural resources are subject to seasonality, which affects their availability: abundance in the rainy season and shortage in the dry season (Amole et al. 2021). The very low quality of natural forage during dry seasons leads not only to a drop in performance (Mane et al. 2023), but also to impaired ruminal function. This in turn leads to low intake capacity and inefficient rumen fermentation, with increased enteric methane (eCH_4) emissions (Assouma et al. 2019).

In agro-pastoral systems, available crop co-products (cereal straws and legume haulms) are used to supplement ruminant basal diets, especially during periods of shortage (Gbenou et al. 2024). Cereal straws are known for their low nutritional value whereas legume haulms, which are more nutritious ([INRA] Institut National de la Recherche Agronomique 2018) are less accessible and more expensive (Sanon et al. 2018). Data on the nutritional value of these co-products is available, but little is known about their synergy with poor natural forage, in terms of intake, digestibility and eCH_4 emissions by local breeds, which are considered low-productive animals. The purpose of our work was therefore to select the six main crop co-products used in extensive livestock farming systems of SSA and to study their nutritional, digestive and methanogenic potential in local Sudanese Fulani zebu cattle.

2. Material and methods

The experimental procedures have been approved by the CIRDES (Centre International de Recherche Développement sur l'Elevage en zone Subhumide) Ethics Committee for Animal Experiments (Approval dated 15 April 2021 for application N° 006/Mars/2021/CE-CIRDES).

2.1. Study area

The study was carried out at the CIRDES experimental station in Bobo Dioulasso (11° 10'37″N and 4°17'52″W) in South-Western Burkina Faso. It was conducted during the hot dry season (March to June 2022) characterised by an ambient temperature of 33.3°C and rainfall of 186 mm.

2.2. Animals, feed, and experimental design

The study involved 10 Sudanese Fulani zebu steers (initial age and body weight of 33.5 ± 2.5 months and 142 ± 4.6 kg respectively) kept in individual pens (3 × 3 m with the floor concreted without bedding that was cleaned every morning) for 15 sequential weeks (W1 to W15) in an experimental barn. The animals were fed at an intake level of 3.2% of LW in dry matter. Access to lick stone and water was *ad libitum*.

In Experiment 1 from week 1 to week 9 (W1 to W9), the basic forage was rangeland forage (RF) directly collected in the field during the hot dry season, predominantly *Andropogon gayanus* Kunth, *Hyparrhenia hirta*, and *Pennisetum pedicellatum*. It was cut on rangeland within the same grazing area and stored straight away. In Experiment 2 (W10 to W15), the basic forage was *Panicum maximum* hay (Pmax). The change of forage for Experiment 2 was due to a shortage of RF at the end of the dry season. It was replaced by Pmax harvested at maturity given their comparable chemical compositions with RF. These feeds were provided as stand-alone control diets (100% RF and 100% Pmax) or mixed with six crop co-products in constant proportions (75:25 on a DM basis). Co-products were selected as the most commonly used for livestock feed, based on a survey of around 50 agro-pastoralists in the region of Bobo Dioulasso. The RF was supplemented with four cereal co-products (CC), namely maize straw (MaS), sorghum straw (SoS), millet straw (MiS) and rice straw (RiS), and Pmax was supplemented with two legume co-products (LC), i.e. cowpea haulm (CoH) and peanut haulm (PeH) (Table 1). Daily diets were split into two meals served at 8:30 h and 16:30 h. Pellets were supplied as bait via an automatic feeder (GreenFeed® system – GF, C-Lock Inc., Florida, USA) in addition to the diets. The bait was made up of natural rangeland forage and molasses (90:10 ratio on a DM basis). The forage was ground through a sieve with a pore size of 1 mm before being mixed with the molasses. The homogeneous mixture was then pelleted (8 mm diameter). In each experiment, 10 steers were fed the control diet whereas each of the two experimental batches comprised five animals. Each diet was

Table 1. Formulation of diets offered to Sudanese Fulani zebu steers during the 15-week trial.

	Exp. 1 (5 diets)					Exp. 2 (3 diets)		
Trial weeks	1 to 3	4 to 6	4 to 6	7 to 9	7 to 9	10 to 12	13 to 15	13 to 15
Diet	RF – control1 (*N* = 10)	RF+MaS (*N* = 5)	RF+SoS (*N* = 5)	RF+MiS (*N* = 5)	RF+RiS (*N* = 5)	Pmax – control2 (*N* = 10)	Pmax+CoH (*N* = 5)	Pmax+PeH (*N* = 5)
RF	100%	75%	75%	75%	75%	–	–	–
MaS	–	25%	–	–	–	–	–	–
SoS	–	–	25%	–	–	–	–	–
MiS	–	–	–	25%	–	–	–	–
RiS	–	–	–	–	25%	–	–	–
Pmax	–	–	–	–	–	100%	75%	75%
CoH	–	–	–	–	–	–	25%	–
PeH	–	–	–	–	–	–	–	25%
Total DM offered	3.3% BW	3.2% BW	3.3% BW	3.2% BW	3.2% BW	3.3% BW	3.2% BW	3.2% BW

RF: dry rangeland forage harvested in hot dry season, MaS: maize straw, SoS: sorghum straw, MiS: millet straw, RiS: rice straw, Pmax: Panicum maximum C1 hay harvested at maturity stage, CoH: cowpea haulm, PeH: peanut haulm, *N* = animal number, DM: dry matter, BW: body weight.

administered for 3 weeks, with 2 weeks of adaptation and 1 week of data collection (D1 to D7).

2.3. Measurements

2.3.1. Body weight, intake, and digestibility

Body weight was recorded at the beginning and end of each week of data collection. Voluntary feed intake was measured daily by weighing offered and refused diets per animal. Representative samples of diets offered and refused (300 g of diet and 300 g of pellets) were collected and kept individually.

All excreted faeces were collected daily (D1 to D7) from bags fitted to each animal. Those bags were emptied twice a day. After weighing the total amount collected, a representative sample of 800 g of faeces per animal was taken each day. Seven samples of offered feed, 70 samples of refusals and 70 faeces samples were thus collected for each control diet (RF and Pmax). For each experimental diet, 7 samples of offered feed, 35 samples of refusals and 35 faeces samples were collected. All samples were then dried (at 55°C for 72 hours) and ground through a sieve with a pore size of 1 mm (SM 100, Retsch GmbH, Hann, Germany) before being analysed for their chemical composition.

2.3.2. Enteric methane emissions

Enteric methane emissions were measured using a GF unit. The unit was calibrated to deliver a drop of 34 ± 2.1 g pellet baits every minute during each animal visit. To reduce its effect on intake composition, the bait was made up of natural rangeland forage as described above. Refused bait was removed from the GF's trough and weighed on each visit to assess individual daily intake quantities. Measurement times were tailored to the feeding behaviour of the animals, with random access to the GF unit being granted in turn at the following times during 7 d: 6:30 h (overnight fast), 10:00 h (immediately after feed intake), 14:00 h (during rumination) and 18:00 h (immediately after feed intake and at sunset) respectively. On the 7th day (last day) of each feeding condition, an additional measurement was performed at 00:00 h (during total rest). The total number of visits amounted to 29 per animal per feeding condition and exceeded the minimum number of 20 visits recommended by Manafiazar et al. (2017). Each animal spent an average of 3 min ± 06s (Min = 2min28s, Max = 4min11s) at the GF unit per visit. The total amount of bait delivered by the GF unit was 34 × 3 = 102 g per animal per visit. The GF unit was automatically calibrated every day (at 4:00 h), with a gas mixture being injected at certified concentrations (CH_4: 509.4 ppm, CO_2: 4,993 ppm, H_2: 10.10 ppm, and O_2: 21.01 ppm; Liquid air, C-Lock, USA). At the beginning and end of each trial (twice a week), a CO_2 recovery test was carried out and the filter was changed (or whenever the airflow fell below 27 L/s). Throughout the study, average values for airflow, recovery rate, and wind direction were 38.8 ± 2.32 L/s (Min = 25.2, Max = 40.6), 97.7 ± 1.2% (Min = 93.0, Max = 99.8) and 141 ± 49.6° (Min = 3.28, Max = 359) respectively.

2.4. Feed and faeces chemical composition

Feed and faeces chemical compositions were estimated using near-infrared spectroscopy (NIRS). NIRS spectra were collected for each sample using a spectrometer (Tango model, Bruker Optik GmbH, Ettlingen, Germany) which captures spectra between 11,536 and 3,952 cm^{-1} with an 8 cm^{-1} step. NIRS models based on 1,890 forage samples were used respectively to predict ash, crude protein (CP), neutral detergent fibre (NDF), acid detergent fibre (ADF), acid detergent lignin (ADL) and gross energy (GE) contents, as well as forage *in vitro* dry matter digestibility (IVDMD) and organic matter digestibility (IVOMD). The NIRS models based on 690 faecal samples and analyses performed with wet chemistry reference methods were used to predict faecal ash, CP, NDF, ADF, ADL and GE contents. Fibres (NDF, ADF, ADL) were analysed following the sequential method described by Van Soest et al. (1991) using an Ankom fibre analyser (Ankom® Tech. Co., Fairport, NY, USA). The NDF and ADF were corrected for ash measured on ADL residue. Ash content was determined by incineration in a muffle furnace for 5 hours at 550 ° C (Hassoun et al. 2022). Total nitrogen content was determined using the Kjeldahl method as in Hassoun et al. (2022) and CP content was calculated as total nitrogen x 6.25. *In vitro* digestibility was determined using the pepsin-cellulase method (Aufrère et al. 2007). Gross energy of offered and refusals was determined by bomb calorimetry (IKA calorimeter model C2000; IKA-Werke GmbH, Staufen, Germany). The chemical composition of feed ingredients and diets is shown in Tables 2 and 3.

2.5. Data processing

2.5.1. Data pre-processing and parameter calculation

Daily individual voluntary diet intake was calculated as the difference between quantities of feed offered and refused. The chemical composition of diet intake and total feed intake (diet + bait) was calculated according to Horvath et al. (2021).

The GF data acquisition file included eCH_4 and CO_2 flow punctual data (g/d) for each visit and each animal ($n = 1{,}359$ punctual data per gas). For each animal, outlier gas data was removed following the approach described by Coppa et al. (2021). This outlier data accounted for 0.29% of the total dataset. Data from each visit was then averaged per animal and per day to produce individual daily values for each gas flow according to Equation 1. Since there were two night-time (00:00 h and 6:30 h) and three daytime (10:00 h, 14:00 h, and 18:00 h) readings, the average was weighted by assigning them equal weight.

$$eCH_4\ [g/d] = 0.5 * [(eCH_4.10{:}00h + eCH_4.14{:}00h + eCH_4.18{:}00h)/3] + 0.5*[(eCH_4.6{:}30h + eCH_4.00{:}00h)/2] \quad (1)$$

with eCH_4.i: average eCH_4 emissions [g/d] for visits over the same i period.

The eCH_4 conversion rate (Ym) was calculated following Equation 2 provided by the [IPCC] Intergovernmental Panel on Climate Change et al. (2019).

$$Ym[\%] = [(eCH_4 * 55.65/1,000)/GEI] * 100 \quad (2)$$

with eCH_4 in [g/d] and GEI in [MJ/d].

GEI per animal per day was calculated from GE of offered and refusals. For each treatment, total DM intake and daily gas emissions (D1 to D7) were averaged to produce a single value per animal.

Table 2. Chemical composition of ingredients and diets offered to Sudanese Fulani zebu steers (Exp. 1).

	Ingredients					Diets								
	RF	MaS	SoS	MiS	RiS	RF (100)	RF+All cereal co-products	*p*	RF+MaS (75:25)	RF+SoS (75:25)	RF+MiS (75:25)	RF+RiS (75:25)	SEM	*p*
OM [g/kg]	823	862	872	879	735	$823^{A, ab}$	806^{B}	0.049	801^{bc}	834^{a}	815^{b}	775^{c}	0.378	0.003
CP [g/kg]	26.9	28.1	28.5	30.9	36.4	27.0	29.0	0.062	26.0	31.8	28.4	29.9	0.071	0.075
NDF [g/kg]	689	768	684	748	618	$689^{A,a}$	645^{B}	0.012	668^{b}	644^{c}	638^{cd}	628^{d}	0.411	<0.001
ADF [g/kg]	429	495	393	474	377	$429^{A,a}$	400^{B}	<0.001	415^{b}	395^{c}	396^{c}	393^{c}	0.339	0.011
ADL [g/kg]	80.8	81.4	44.4	81.4	35.6	80.8^{a}	79.9	0.464	80.0^{a}	85.4^{a}	84.5^{a}	69.7^{b}	0.138	0.013
IVDMD	0.265	0.311	0.446	0.291	0.373	0.265^{ab}	0.263	0.114	0.256^{b}	0.247^{b}	0.262^{b}	0.288^{a}	0.038	0.008
IVOMD	0.268	0.269	0.432	0.284	0.347	$0.268^{A,a}$	0.233 B	<0.001	0.240^{ab}	0.232^{bc}	0.209^{c}	0.252^{ab}	0.047	0.001
GE [MJ/kg]	16.5	16.7	16.7	16.7	13.8	16.5	16.2	0.198	15.5	16.7	16.9	15.9	0.137	0.129

OM: organic matter, DM: dry matter, NDF: neutral detergent fibre, ADF: acid detergent fibre, ADL: pickling lignin, IVDMD: in vitro dry matter digestibility, IVOMD: in vitro organic matter digestibility, GE: gross energy.
RF: dry rangeland forage harvested in hot dry season, MaS: maize straw, SoS: sorghum straw, MiS: millet straw, RiS: rice straw.
^{A,B}Values with different superscripts within the same row differ significantly at $p < 0.05$: comparison between control diet and combined experimental diets.
^{a,b,c}Values with different superscripts within the same row differ significantly at $p < 0.05$: comparison between all individual diets per experiment.

Table 3. Chemical composition of ingredients and diets offered to Sudanese Fulani zebu steers (Exp. 2).

	Ingredients			Diets						
	Pmax	CoH	PeH	Pmax (100)	Pmax+All legume co-products	*p*	Pmax +CoH (75:25)	Pmax +PeH (75:25)	SEM	*p*
OM [g/kg]	827	879	839	827	817	0.296	840	830	0.242	0.208
CP [g/kg]	37	126	131	$37^{B,c}$	61^{A}	<0.001	66^{a}	59^{b}	0.312	<0.001
NDF [g/kg]	670	380	396	$670^{A,a}$	598^{B}	<0.001	609^{b}	614^{b}	0.728	0.001
ADF [g/kg]	408	265	268	408^{A}	386^{B}	0.024	392	398	0.281	0.088
ADL [g/kg]	65.2	68.5	82.7	65.3^{B}	83.3^{A}	<0.001	80.9	89.4	0.250	<0.001
IVDMD	0.350	0.731	0.722	$0.350^{B,b}$	0.399^{A}	<0.001	0.397^{a}	0.401^{a}	0.066	0.005
IVOMD	0.319	0.723	0.714	$0.319^{B,b}$	0.362^{A}	<0.001	0.361^{a}	0.363^{a}	0.063	0.005
GE [MJ/kg]	16.6	16.9	16.4	16.7	16.5	0.443	16.8	16.9	0.078	0.072

OM: organic matter, DM: dry matter, NDF: neutral detergent fibre, ADF: acid detergent fibre, ADL: pickling lignin, IVDMD: in vitro dry matter digestibility, IVOMD: in vitro organic matter digestibility, GE: gross energy.
Pmax: Panicum maximum C1 hay harvested at maturity stage, CoH: cowpea haulm, PeH: peanut haulm.
^{A,B}Values with different superscripts within the same row differ significantly at $p < 0.05$: comparison between control diet and combined experimental diets.
^{a,b,c}Values with different superscripts within the same row differ significantly at $p < 0.05$: comparison between all individual diets per experiment.

2.6. Statistical analysis

Statistical analyses were performed using R software version 4.1.2 (R Core Team 2021). The effect of supplementation was studied in each experiment by comparing the control diet with the pool of experimental diets using a student's test (t.test). The distinctive effect of each co-product was then tested using analysis of variance (ANOVA). This analysis enabled to test the differences in intake, digestibility, and eCH_4 emissions in each experiment. The data was analysed using a mixed model. Least squares means for all parameters responses variables analysed were generated and compared with the Duncan test (duncan.test) via the agricolae package (de Mendiburu 2023) when $p < 0.05$. The chemical composition of feed intake and refusals was also compared in each experiment using the student's test (t.test). The following statistical model was used for ANOVA data analysis:

$$Y_a = \mu + f_a + \varepsilon_a$$

where Y_a = variable to be defined (feed offered content, intake, digestibility, eCH_4);
μ = overall average;
f_a=a^{th} feed (co-product) effect;
ε_a = random error.

3. Results

3.1. Chemical composition of diets

Both basic forages (RF and Pmax) had similar chemical compositions, but with a higher CP content and *in vitro* digestibility for Pmax (Tables 2 and 3). In Exp. 1, the NDF content was lower in the experimental diets ($p < 0.001$), except for RF+MaS. In Exp. 2, both experimental diets had higher CP content ($p < 0.001$) than the Pmax diet. The NDF and ADF contents were different in the experimental diets, with NDF contents lower ($p = 0.001$) than in Pmax. *In vitro* digestibility was higher in the experimental haulm diets ($p < 0.05$).

3.2. Diet intake and digestibility

In Exp. 1 (Table 4), the highest intake (DMI, OMI, GEI in g/kg LW per day) was achieved with the RF+RiS diet, which was the only experimental diet with a higher intake compared with the RF diet. The average daily bait intake was 330 g DM per animal (Min = 16 g; Max = 380 g). Feed refusals were richer in fibre than intakes (Table 5). The refusals were >50% in the case of RF, RF+MaS and RF+MiS diets, and <50% for RF+SoS and RF+RiS ($p < 0.001$). The CPI was higher in the supplemented treatments ($p = 0.001$). The OMd was significantly higher for the RF+SoS diet and lower for RF+MaS one (Table 6).

In Exp. 2, a significant difference was noted for DMI, with a maximum value for Pmax +PeH ($p = 0.004$) (Table 7). The experimental diets showed a higher CPI than the Pmax diet ($p < 0.001$). Average daily bait intake was 300 g DM per animal (Min = 9 g; Max = 380 g). The CP content was lower in refusals than in the intake of experimental diets ($p < 0.001$) (Table 8). Refusals amounted to 39%, 31% and 25% of feed offered for Pmax, Pmax+CoH and Pmax+PeH respectively. The OMd was significantly higher for the Pmax+PeH diet (Table 9). The experimental diets displayed significantly different CPd values (Table 9).

3.3. Enteric methane emissions

In Exp. 1, all supplemented diets showed a reduction of eCH_4 [g/d] from −8.0% to −28.8% compared with RF (Table 10). The eCH_4 yields [g/kg DMI] also

Table 4. Daily intake by Sudanese Fulani zebu steers for each diet (including bait distributed by GF) (Exp. 1).

Intake	RF	RF+All cereal co-products		RF +MaS	RF+SoS	RF+MiS	RF+RiS		
N animals	10	20	*p*	5	5	5	5	SEM	*p*
DMI [kg]	2.41^{ab}	2.47	0.665	2.21^{b}	2.49^{ab}	2.35^{ab}	2.86^{a}	0.072	0.042
DMI [g/kg BW]	16.4^{b}	18.0	0.112	15.9^{b}	17.7^{b}	17.0^{b}	21.5^{a}	0.487	0.025
OMI [kg/d]	2.18	2.17	0.986	1.93	2.23	2.10	2.43	0.06	0.365
OMI [g/kg BW]	14.8^{b}	15.8	0.218	13.9^{b}	15.9^{b}	15.2^{b}	18.3^{a}	0.388	0.032
CPI [kg]	$0.061^{B,\ c}$	0.083^{A}	0.001	0.061^{c}	0.102^{ab}	0.083^{b}	0.102^{a}	0.003	0.001
CPI [g/kg BW]	$0.463^{B,\ c}$	0.642^{A}	<0.001	0.463^{c}	0.705^{a}	0.612^{b}	0.781^{a}	0.026	<0.001
NDFI [kg]	1.78	1.56	0.061	1.49	1.49	1.42	1.85	0.05	0.062
NDFI [g/kg BW]	12.1^{b}	11.4	0.327	10.7^{b}	10.6^{b}	10.3^{b}	13.9^{a}	0.334	0.015
ADFI [kg]	$1.12^{A,\ a}$	0.93^{B}	0.019	0.90^{ab}	0.88^{ab}	0.82^{b}	1.14^{a}	0.030	0.018
ADFI [g/kg BW]	7.58^{ab}	6.83	0.118	6.50^{bc}	6.30^{bc}	5.94^{c}	8.58^{a}	0.226	0.003
GEI [MJ]	44.2^{ab}	43.6	0.832	36.5^{b}	44.6^{ab}	43.3^{ab}	49.9^{a}	1.34	0.183
GEI [MJ/kg BW]	0.291^{b}	0.313	0.362	0.261^{b}	0.314^{b}	0.312^{b}	0.374^{a}	0.008	0.019

RF: dry rangeland forage harvested in hot dry season, MaS: maize straw, SoS: sorghum straw, MiS: millet straw, RiS: rice straw.
DMI: dry matter intake, OMI: organic matter intake, CPI: crude protein intake, NDFI: neutral detergent fibre intake, ADFI: acid detergent fibre intake, GEI: gross energy intake, BW: body weight.
[A,B]Values with different superscripts within the same row differ significantly at $p < 0.05$: comparison between control diet and combined experimental diets.
[a,b,c]Values with different superscripts within the same row differ significantly at $p < 0.05$: comparison between all individual diets per experiment.

Table 5. Chemical composition of daily intake and refusal of cereal co-product diets (without bait) in Sudanese Fulani zebu steers (Exp. 1).

Diets		OM [g/kg]	CP [g/kg]	NDF [g/kg]	ADF [g/kg]	ADL [g/kg]	GE [MJ/kg]
RF	Intake	859^{a}	26.6	734^{a}	462^{a}	74.6^{b}	17.5^{a}
	Refusal	796^{b}	27.1	658^{b}	406^{b}	84.9^{a}	15.8^{b}
	SEM	7.49	0.33	8.99	6.63	1.34	0.21
	p	<0.001	0.547	<0.001	<0.001	<0.001	<0.001
RF+All cereal co-products	Intake	809	34.0^{a}	589^{b}	351^{b}	73.6^{b}	16.2
	Refusal	806	23.8^{b}	693^{a}	442^{a}	87.3^{a}	16.3
	SEM	0.97	5.98	9.27	8.09	1.92	0.27
	p	0.633	<0.001	<0.001	<0.001	0.001	0.772
RF+MaS	Intake	800	27.5	632^{b}	381^{b}	83.6^{a}	15.0
	Refusal	800	24.6	686^{a}	433^{a}	78.1^{b}	15.8
	SEM	5.13	0.84	11.2	10.3	1.44	0.202
	p	0.215	0.485	<0.001	<0.001	<0.001	0.226
RF+SoS	Intake	841^{a}	40.2^{a}	564^{b}	332^{b}	86	16.8
	Refusal	829^{b}	24.7^{b}	709^{a}	447^{a}	85.0	16.5
	SEM	4.13	2.62	24.2	19.3	0.31	0.107
	p	0.045	<0.001	<0.001	<0.001	0.322	0.342
RF+MiS	Intake	827^{a}	34.3^{a}	564^{b}	324^{b}	68.4^{b}	17.1
	Refusal	810^{b}	23.1^{b}	701^{a}	456^{a}	97.9^{a}	16.8
	SEM	4.19	1.92	22.9	22.2	4.95	0.095
	p	0.048	<0.001	<0.001	<0.001	<0.001	0.228
RF+RiS	Intake	769^{b}	34.1^{a}	595^{b}	367^{b}	56.8^{b}	15.8
	Refusal	786^{a}	23.1^{b}	676^{a}	432^{a}	88.1^{a}	16.0
	SEM	3.48	1.88	13.6	11.0	5.35	0.053
	p	0.022	<0.001	<0.001	<0.001	<0.001	0.284

RF: dry rangeland forage harvested in hot dry season, MaS: maize straw, SoS: sorghum straw, MiS: millet straw, RiS: rice straw.
OM: organic matter, CP: crude protein, NDF: neutral detergent fibre, ADF: acid detergent fibre, ADL: acid detergent lignin, GE: gross energy.
^{a,b}Values with different superscripts within the same row differ significantly at $p < 0.05$: comparison between all individual diets per experiment.

Table 6. Apparent digestibility of diet intake (including bait distributed by GF) by Sudanese Fulani zebu steers (Exp. 1).

Digestibility	RF	RF+All cereal co-products		RF+MaS	RF+SoS	RF+MiS	RF+RiS		
N animals	10	20	*p*	5	5	5	5	SEM	*p*
DM	0.460	0.480	0.140	0.467	0.511	0.486	0.459	0.006	0.234
OM	0.500^{ab}	0.518	0.187	0.480^{b}	0.546^{a}	0.520^{ab}	0.529^{ab}	0.006	0.047
CP	0.001$^{B, b}$	0.177^{A}	0.044	0.129^{a}	0.002^{b}	0.282^{a}	0.295^{a}	0.045	0.040
NDF	0.592$^{A, a}$	0.550^{B}	0.018	0.554^{ab}	0.549^{ab}	0.527^{b}	0.600^{a}	0.007	0.004
ADF	0.559$^{A, ab}$	0.526^{B}	0.041	0.515^{bc}	0.508^{bc}	0.479^{c}	0.604^{a}	0.009	0.002
GE	0.508^{b}	0.529	0.210	0.462^{c}	0.555^{ab}	0.517^{b}	0.585^{a}	0.009	<0.001

RF: dry rangeland forage harvested in hot dry season, MaS: maize straw, SoS: sorghum straw, MiS: millet straw, RiS: rice straw.
DM: dry matter, OM: organic matter, CP: crude protein, NDF: neutral detergent fibre, GE: gross energy.
^{A,B}Values with different superscripts within the same row differ significantly at $p < 0.05$: comparison between control diet and combined experimental diets.
^{a,b,c}Values with different superscripts within the same row differ significantly at $p < 0.05$: comparison between all individual diets per experiment.

decreased overall with supplementation: 24.8 g on average for the experimental treatments compared with 30.6 g for RF treatment ($p = 0.047$). MaS, SoS, MiS, and RiS generated a drop of −5.60%, −20.9%, −25.8%, and −23.2% respectively. The

Table 7. Daily intake by Sudanese Fulani zebu steers for each diet (including bait distributed by GF) (Exp. 1).

Intake	Pmax	Pmax + All legume co-products		Pmax+CoH	Pmax+PeH		
n	10	10	*p*	5	5	SEM	*p*
DMI [kg]	3.36	3.60	0.209	3.45	3.76	0.094	0.226
DMI [g/kg BW]	21.7$^{B, c}$	25.5^{A}	0.001	24.2^{b}	26.8^{a}	0.649	0.004
OMI [kg/d]	3.03	3.25	0.206	3.13	3.37	0.083	0.261
OMI [g/kg BW]	19.6$^{B, c}$	23.0^{A}	<0.001	21.9^{b}	24.1^{a}	0.6	0.004
CPI [kg]	0.13$^{B, b}$	0.25^{A}	<0.001	0.26^{a}	0.25^{a}	0.015	<0.001
CPI [g/kg BW]	0.84$^{B, b}$	1.80^{A}	<0.001	1.82^{a}	1.79^{a}	0.113	<0.001
NDFI [kg]	2.40	2.29	0.247	2.17	2.41	0.06	0.169
NDFI [g/kg BW]	15.5^{b}	16.2	0.292	15.2^{b}	17.2^{a}	0.341	0.029
ADFI [kg]	1.46	1.48	0.813	1.40	1.56	0.04	0.360
ADFI [g/kg BW]	9.5$^{B, b}$	10.5 ^{A}	0.026	9.8^{b}	11.2^{a}	0.2	0.008
GEI [MJ]	61.7	66.1	0.202	63.0	69.2	1.70	0.201
GEI [MJ/kg BW]	0.391$^{B, c}$	0.462^{A}	<0.001	0.441^{b}	0.493^{a}	0.011	0.002

Pmax: Panicum maximum C1 hay harvested at maturity stage, CoH: cowpea haulm, PeH: peanut haulm.
DMI: dry matter intake, OMI: organic matter intake, CPI: crude protein intake, NDFI: neutral detergent fibre intake, ADFI: acid detergent fibre intake, GEI: gross energy intake, BW: body weight.
^{A,B}Values with different superscripts within the same row differ significantly at $p < 0.05$: comparison between control diet and combined experimental diets.
^{a,b}Values with different superscripts within the same row differ significantly at $p < 0.05$: comparison between all individual diets per experiment.

Table 8. Chemical composition of daily intake and refusal of legume co-product diets (without bait) in Sudanese Fulani zebu steers (Exp. 2).

Diets		OM [g/kg]	CP [g/kg]	NDF [g/kg]	ADF [g/kg]	ADL [g/kg]	GE [MJ/kg]
Pmax	Intake	851^{a}	37.8	692^{a}	423^{a}	64.8	17.3^{a}
	Refusal	793^{b}	35.5	640^{b}	387^{b}	66.0	15.6^{b}
	SEM	7.25	0.518	6.64	4.90	0.70	0.214
	p	0.025	0.236	<0.001	<0.001	0.287	<0.001
Pmax+All legume co-products	Intake	830^{a}	69.1^{a}	590^{b}	384	83.6	16.9^{a}
	Refusal	781^{b}	42.1^{b}	616^{a}	391	83.9	15.3^{b}
	SEM	6.38	3.37	3.04	5.19	3.38	0.259
	p	<0.001	<0.001	0.008	0.320	0.898	<0.001
Pmax+CoH	Intake	827^{a}	72.7^{a}	576^{b}	375^{b}	78.4	16.7^{a}
	Refusal	780^{b}	45.2^{b}	614^{a}	388^{a}	79.7	15.3^{b}
	SEM	7.88	4.79	7.97	3.82	1.02	0.237
	p	<0.001	<0.001	<0.001	<0.001	0.351	<0.001
Pmax+PeH	Intake	833^{a}	65.3^{a}	604^{b}	394	88.9	17.2^{a}
	Refusal	782^{b}	38.9^{b}	617^{a}	394	88.2	15.3^{b}
	SEM	10.0	4.64	7.06	5.76	1.53	0.349
	p	<0.001	<0.001	<0.001	0.356	0.355	<0.001

Pmax: Panicum maximum C1 hay harvested at maturity stage, CoH: cowpea haulm, PeH: peanut haulm.
OM: organic matter, CP: crude protein, NDF: neutral detergent fibre, ADF: acid detergent fibre, ADL: acid detergent lignin, GE: gross energy.
^{a,b}Values with different superscripts within the same row differ significantly at $p < 0.05$: comparison between all individual diets per experiment.

eCH_4 emissions in g/kg LW, g/kg DMI, g/kg OMI, g/kg dDMI or g/kg dOMI followed the same patterns.

In Exp. 2, eCH_4 emissions [g/d] were also lower (−14% on average, $p = 0.055$) in LC treatments ($N = 10$) compared with Pmax treatment (Table 11). This drop amounted to 19% and 10% respectively for Pmax+CoH and Pmax+PeH compared with Pmax ($p =$

Table 9. Apparent digestibility of diet intake (including bait distributed by GF) by Sudanese Fulani zebu steers (Exp. 2).

Digestibility	Pmax	Pmax + All legume co-products		Pmax+CoH	Pmax+PeH		
N animals	10	10	*p*	5	5	SEM	*p*
DM	0.487	0.497	0.795	0.486	0.509	0.010	0.337
OM	0.523^{b}	0.527	0.811	0.515^{b}	0.540^{a}	0.009	0.035
CP	0.232$^{A, a}$	0.121^{B}	0.031	0.140^{b}	0.102^{c}	0.049	<0.001
NDF	0.582$^{A, a}$	0.545^{B}	0.042	0.528^{c}	0.562^{b}	0.009	0.003
ADF	0.562^{a}	0.526	0.064	0.509^{b}	0.544^{a}	0.009	0.005
GE	0.519^{b}	0.518	0.962	0.507^{b}	0.530^{a}	0.009	0.018

Pmax: Panicum maximum C1 hay harvested at maturity stage, CoH: cowpea haulm, PeH: peanut haulm.
DM: dry matter, OM: organic matter, CP: crude protein, NDF: neutral detergent fibre, GE: gross energy.
^{A,B}Values with different superscripts within the same row differ significantly at $p < 0.05$: comparison between control diet and combined experimental diets.
^{a,b,c}Values with different superscripts within the same row differ significantly at $p < 0.05$: comparison between all individual diets per experiment.

Table 10. Daily enteric methane emissions by Sudanese Fulani zebu steers (Exp. 1).

Diets	RF	RF+All co-products		RF+MaS	RF+SoS	RF+MiS	RF+RiS		
N animals	10	20	*p*	5	5	5	5	SEM	*p*
eCH_4 [g/d]	73.2^{A}	60.1^{B}	0.030	61.1	59.7	52.2	67.4	2.909	0.232
eCH_4 [g/kg BW]	0.500	0.442	0.155	0.441	0.432	0.391	0.503	0.019	0.478
eCH_4 [g/kg DMI]	30.6^{A}	24.8^{B}	0.038	28.8	24.2	22.7	23.5	1.34	0.254
eCH_4 [g/kg dDMI]	66.3^{A}	52.0^{B}	0.023	62.1	47.4	46.9	51.8	3.03	0.132
eCH_4 [g/kg OMI]	33.9^{A}	28.2^{B}	0.049	33.0	27.0	25.4	27.6	1.49	0.323
eCH_4 [g/kg dOMI]	67.5^{A}	55.0^{B}	0.041	68.9	49.8	49.1	52.3	3.16	0.151
Ym [% GEI]	9.32	7.93	0.134	9.78	7.54	6.88	7.52	0.434	0.270

RF: dry rangeland forage harvested in hot dry season, MaS: maize straw, SoS: sorghum straw, MiS: millet straw, RiS: rice straw.
eCH_4: enteric methane, BW: body weight, DMI: dry matter intake, dDMI: digestible dry matter intake, OMI: organic matter intake, dOMI: digestible organic matter intake, GEI: gross energy intake.
^{A,B}Values with different superscripts within the same row differ significantly at $p < 0.05$: comparison between control diet and combined experimental diets.

Table 11. Daily enteric methane emissions by Sudanese Fulani zebu steers (Exp. 2).

Diets	Pmax	Pmax+All legume co-products		Pmax+CoH	Pmax+PeH		
N animals	10	10	*p*	5	5	SEM	*p*
eCH_4 [g/d]	93.6	79.9	0.055	75.6	84.3	3.60	0.151
eCH_4 [g/kg BW]	0.601	0.567	0.460	0.531	0.604	0.021	0.288
eCH_4 [g/kg DMI]	28.0$^{A, a}$	22.3^{B}	0.007	22.0^{b}	22.6^{b}	1.11	0.020
eCH_4 [g/kg dDMI]	58.3$^{A, a}$	44.9^{B}	0.006	45.2^{b}	44.6^{b}	2.93	0.030
eCH_4 [g/kg OMI]	30.9$^{A, a}$	24.8^{B}	0.007	24.2^{b}	25.3^{b}	1.22	0.019
eCH_4 [g/kg dOMI]	59.9$^{A, a}$	46.9^{B}	0.008	47.0^{b}	46.8^{b}	2.81	0.036
Ym [% GEI]	8.48$^{A, a}$	6.77^{B}	0.006	6.70^{b}	6.85^{b}	0.333	0.047

Pmax: Panicum maximum C1 hay harvested at maturity stage, CoH: cowpea haulm, PeH: peanut haulm.
eCH4: enteric methane, BW: body weight, DMI: dry matter intake, dDMI: digestible dry matter intake, OMI: organic matter intake, dOMI: digestible organic matter intake, GEI: gross energy intake.
^{A,B}Values with different superscripts within the same row differ significantly at $p < 0.05$: comparison between control diet and combined experimental diets.
^{a,b}Values with different superscripts within the same row differ significantly at $p < 0.05$: comparison between all individual diets per experiment.

0.151). CoH and PeH led to a significant drop of 21% and 19% [g/kg DMI] respectively. The eCH_4 emissions in g/kg OMI, g/kg dDMI or g/kg dOMI also followed the same patterns.

4. Discussion

4.1. Composition and nutritional quality

This study investigated the effects of feeding strategies based on typical co-products in Sub-Saharan Africa on dry matter intake, digestibility and enteric methane emissions in steers. The crop co-products tested in this study are among the most widely available in West Africa ([FAO] Food and Agriculture Organization 2014) and the most commonly used by livestock farmers in the field (Jarial et al. 2020). The LC offer high nutritional quality compared with CC, as reported by Savadogo et al. (1999) in Burkina Faso and Jarial et al. (2020) in Niger. The CP content values found in this study for CC are consistent with those of Savadogo et al. (1999). Among CC, only RiS was richer in CP than RF. The CP content of CoH is consistent with those obtained by Savadogo et al. (1999) and Jarial et al. (2020), although these authors reported a lower CP content for PeH than the current study.

Comparison of both control diets revealed that Pmax was richer in CP, lower in ADL and more digestible *in vitro* than RF. However, Pmax had lower nutritional value than Pmax hay (CL Orstom variety) in the early flowering stage in the dry tropics ([INRA] Institut National de la Recherche Agronomique 2018), probably because it was harvested at a later stage. With LC supplementation, CP content [g/kg DM] rose from less than 40 for the unsupplemented Pmax diet to 60–70. A reduction in both NDF and ADF contents was also recorded. Although not all CC led to an improvement in CP contents, some, namely SoS, MiS and RiS, reduced the NDF content of the diets. This shows that CC have no adverse effects on nutritional value (Obeidat et al. 2022). These findings thus confirm the supremacy of LC over CC as supplements to nutritionally poor diets (Mahesh and Mohini 2014).

4.2. Diet intake and digestibility

Steers showed different levels of motivation to feed under the various experimental diets, and this is reflected in the different DMI values [g/kg LW] recorded. Several studies have documented the effect of crop co-products on voluntary feed intake (Sun et al. 2018; Obeidat et al. 2022). Feed intake is regulated by a set of mechanisms involving feeding behaviour constraints, satiation mechanisms and physiological regulation of the motivation to feed (Faverdin et al. 1997). Despite the highest CP content (and lowest fibre contents) of RF+SoS and RF+RiS diets, only RiS supplementation leads to an increase in DMI. This can be attributed to the selection made by the animals during intake, whereby sorghum stalks were left aside (Savadogo et al. 2000) as they are heavier and richer in fibre than leaves. Santander et al. (2023) reported that reducing fibre content in a diet significantly increases its intake. The similar DMI values across all diets (absence of a significant difference) in the current study could be explained by the lack of nutritional improvement in experimental diets and the significant amounts of offered feed which resulted in remarkable selection. These results are consistent with those of Sun et al. (2018) who found no effect on DMI when supplementing 30% of a poor diet with maize stalks. The low DMI value recorded for Exp. 1 diets reflected in the high refusal rate (>50%), is probably due to the low quality of the RF, which is a hot dry season forage (Müller et al. 2019) and to the presence of stalks in CC.

In Exp. 2, the experimental diets led to an increase in DMI of 11–23% [g/kg LW]. This DMI value is consistent with that of Ngwa and Tawah (2002). Azoutane et al. (2023) also reported an increase in DMI after including up to 30% cowpea haulms in a *Brachiaria deflexa* ration. Improved DMI, which is reflected in the low refusal rate (<33%) compared with Exp. 1, is attributable to Pmax, which is a better basic forage (CP-rich), and to supplementation with LC, which are also richer in CP than CC. Results from this study show that, besides concentrates that are difficult to procure, co-products such as RiS, CoH and PeH can be effective in improving intake of poor-quality feed in ruminants. In addition, co-products such as MaS, MiS and SoS can help to maintain feed intake levels in ruminants.

The RF diet is of low nutritional quality and both control diets have similar nutritional qualities, save for a few parameters. Although Pmax had better chemical composition and *in vitro* digestibility than RF, its supplementation with co-products had little impact on diet DM digestibility. The recorded diets' DM digestibility values in this study broadly corroborate those reported by Santander et al. (2023) for diets that they described as "higher in fibre". Crop co-products would be provided to animals in small quantities preventing improvement in DMd. The CC experimental diets generally showed lower digestibility than LC experimental ones due to the development of strong physical and/or chemical bonds between lignin and structural polysaccharides (cellulose and hemicellulose) (Mahesh and Mohini 2014). The slight improvement in OMd and GEd reported in RF+SoS and RF+RiS respectively may be linked to their slightly higher CP content. The point was emphasised for Pmax+PeH because of its high CP content. However, this pattern is not observed in Pmax+CoH. The quality of the protein content provided to the Pmax+CoH diet by CoH may account for this difference (Duodu et al. 2003). Additionally, there is an interaction between nutrients in the various feedstuffs making up each diet, which determines its digestibility (Cao et al. 2023). Diets in Exp. 1 were of extremely poor quality. The nil CPd values recorded in some treatments could be due to mobilisation of body protein, with increased faecal N thanks to urea recycling through saliva and incorporation in microbial and endogenous protein. The LC experimental diets show low CPd values despite being of better nutritional quality than Pmax. The CoH and PeH are known to contain tannins (Mohatla et al. 2016) which have a negative effect on CPd (Besharati et al. 2022). The NDFd and ADFd values are lower in the experimental diets than in their respective control diets. This could be due to the increase in CP content in diets (Norris et al. 2021) which, while undoubtedly altering fermentation, would increase digestive transit and cause some of the fibre to be excreted.

4.3. Enteric methane emissions

One of the innovative aspects of this study is that it demonstrates the possibility of reducing eCH_4 emissions through farmers' feeding practices in a real environment, in particular through the use of crop co-products with low nutritional value. The eCH_4 yield recorded across all experimental diets (24.0 g/kg DMI on average) is in line with that provided by [IPCC] Intergovernmental Panel on Climate Change et al. (2019) with Tier 2 (23.3 g/kg DMI). The eCH_4 values of the control diets (29.3 g/kg DMI) were higher. This is probably due to the fact that the average IPCC yield is meant for many cattle categories and does not take account for the diversity of feed resources. Supplementation with crop co-products led to a reduction in eCH_4 production, yield and intensity [g/kg LW]. In both experiments, experimental diets (LC and CC) were more nutritious than control diets. These differences resulted in a direct improvement in DMI and a reduction in eCH_4 yield. Overall, CC lowered eCH_4 yield by 19% and LC by 20%. The accentuated effect of LC experimental diets on eCH_4 emissions is certainly due to their higher CP content, lower NDF content (Gaviria-Uribe et al. 2020), and higher tannin content. It is known that supplementation with plants containing tannin mitigates eCH_4 (Archimède et al. 2016). This compound is present in the CL used in the current study and the mitigation observed can partly be linked to this compound. It is revealed that some sorghum and millet genus contain tannin (Dykes and Rooney 2006) but there is no information on cereal straws tannin content. The latter was not measured in this study. By differentiating experimental diets to see if any difference could be identified between co-products, the RF+MaS diet did not lead to a reduction in emissions. Greater reductions than those achieved in this study were recorded by Gaviria-Uribe et al. (2020) in Colombia with the addition of a shrub legume (*Leucaena leucocephala*) to a diet of *Urochloa hybrid cv Cayman*. The forage used by these authors was not only harvested green, it was also slightly more nutritious than the feed resources tested in this study. The reduction rate (/kg digestible matter) seen in Exp. 2 is higher than that reported by Soltan et al. (2013) following supplementation with *Leucaena leucocephala*. The Ym values achieved for both RF and RF+MaS diets with high NDF and ADF contents were higher than those suggested by the IPCC Tier 2 model ([IPCC] Intergovernmental Panel on Climate Change et al. 2019). However, all the other diets in this study produced similar Ym values to those of this model. This study demonstrates the importance of quantifying eCH_4 emissions induced by local ruminant feed resources on the one hand, and highlights the capacity of local resources to contribute to eCH_4 mitigation in ruminants on the other.

5. Conclusion

Feeding strategies based on crop co-products improve diet quality. The nutritional quality of feed offered to ruminants directly influences voluntary intake and eCH_4 emissions. A supplementation of the basal diet with legume co-products led to an increase in feed intake. Among the cereal co-products tested, only rice straw led to an improvement in diet intake. All feeding strategies, except the inclusion of maize straw, resulted in significant eCH_4 yield reduction. Raising awareness among agro-pastoralists about the use of crop co-products offers real prospects for eCH_4 emissions mitigation in ruminants from the Sahel region.

Acknowledgments

The authors wish to thank Florentin SANOU, Wilfrid HOUNGUE and Saïdou BOLI (CIRDES, Burkina Faso) for their support during data collection; Yvanne ROCHETTE (INRAE, France) and Michel OROUNLADJI (CIRDES, Burkina Faso) respectively for assistance with data cleansing and analysis; and Donato Andueza (INRAE, France) for advice on spectral data.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This study was made possible through the support of the "Carbon Sequestration and greenhouse gas emissions in (agro) Sylvopastoral Ecosystems in the sahelian CILSS States" (CaSSECS) regional project funded by the European Union (European DeSIRA programme, under grant agreement No. [FOOD/2019/410-169]).

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