



Research article

# Effects of substituting oil palm tree trunk silage for Napier grass silage in total mixed ration on feedlot performance, ruminal fermentation, carcass characteristics and meat quality of crossbred goats

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## Abstract

**Importance of the work:** Commonly, oil palm trunk residues are discarded at the end of the palm's productive life. However, oil palm trunk silage (OPTS) has potential as an additional roughage source for ruminants.

**Objectives:** To evaluate the levels of substitution of conventional Napier grass silage (NGS) with OPTS in the total mixed ration fed to crossbred goats

**Materials & Methods:** The experiment used 32 crossbred (Boer × Anglo-Nubian) male goats (aged 3 mth) with a mean ± SD initial body weight of 16.50 ± 0.5 kg. The experiment was arranged in a completely randomized design. Equal numbers of goats were assigned randomly to four treatment diets (8 goats per treatment) containing different OPTS-to-NGS percentages up to 45% of the total mixed ration diet: 1) 0:45 (NGS); 2) 15:30 (15OPTS); 3) 30:15 (30OPTS); and 4) 45:0 (45OPTS). After being fed the respective diet for 90 d, the animals were slaughtered and evaluated for feedlot performance, ruminal fermentation, blood metabolites, carcass characteristics and meat quality. Data were analyzed using orthogonal polynomial contrasts to test linear, quadratic and cubic responses to roughage levels.

**Results:** Dry matter intake, nutrient intake and average daily gain decreased with increasing OPTS levels ( $p < 0.05$ ). Ruminal pH, ammonia nitrogen (NH<sub>3</sub>-N), short-chain fatty acids, blood urea nitrogen, blood glucose and hematocrit were not affected by the treatments. OPTS substitution had no negative impact on carcass characteristics and meat quality.

**Main finding:** OPTS could be substituted for NGS at inclusion levels below 30% dry matter content of the roughage in the total mixed ration diet.

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## Introduction

The oil palm is the most efficient oil-producing crop globally, with the top-three palm oil-producing countries being Indonesia, Malaysia and Thailand, respectively (FAO, 2022), largely because of their natural topographical advantages. Oil palm has been an economically important crop since ancient times because of its multiple uses (Phitthayaphinant et al., 2012). The growing local demand for biodiesel is likely to drive the rapid expansion of oil palm plantations. Normally, oil palm plantations are replanted with newer cultivars after 25–30 yr because of the decreased oil productivity of old trees (Praneetvatakul and Vijitsrikamol, 2019). Developing suitable diets for ruminants is challenging, particularly in areas with limited availability of land for forage production. The oil palm crop generates multiple feed by-products for animals, derived from the seeds or kernels, which contain a protein-dense meal post-oil extraction (Alimon, 2004). Palm kernel meal used as ruminant feed can be included in concentrate mixtures at 15–45% (Chanjula, 2015). Oil palm fronds, including the leaves, serve as a substitute roughage source for ruminants with no reported toxicity (Tow et al., 2021), while contributing to a good-quality carcass with the meat safe for human consumption (Rasli et al., 2017).

Oil palm trunks (OPTs) represent one of the most important underutilized byproducts of the palm oil industry (Nuryawan et al., 2022). Upon reaching the end of their productive cycle (approximately 25 yr), these monocotyledonous trunks—characterized by a lack of vascular cambium—typically are discarded during replanting. (Sulaiman et al., 2012). However, their structural composition, featuring a dense matrix of vascular bundles and parenchyma, offers a unique chemical profile. Specifically, OPT contains high levels of cellulose (47.5%) and soluble carbohydrates (55.5%), positioning it as a potent, sustainable roughage source for ruminant nutrition (Choowang, 2012).

In integrated palm-goat production systems, leveraging OPT as a primary fiber source could significantly reduce feeding costs while promoting circular agricultural practices. Despite its abundance, the physiological impact remains unexplored of OPT on meat-producing ruminants. Unlike traditional grasses, the specific carbohydrate-to-lignin ratio in OPT may alter ruminal fermentation patterns, which are direct precursors to intramuscular fat deposition and fatty acid profiles. There has been only one *in vitro* study report by Widiawati et al. (2024), which indicated that ensilage increased the crude protein content and digestibility of the OPT, with the top part of the trunk being identified as having the best nutritional value.

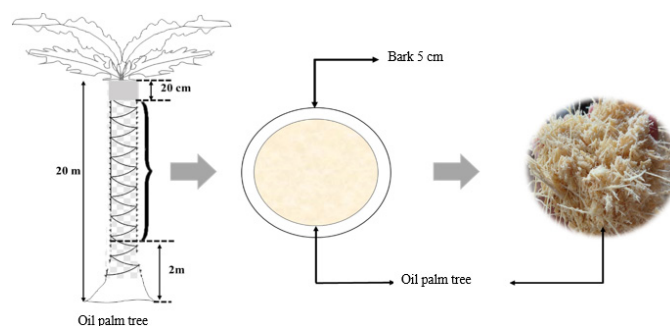
Therefore, the current study sought to justify the transition from conventional Napier grass (NGS) to oil palm trunk silage (OPTS) by evaluating the effects on Boer × Anglo-Nubian crossbred goats. Beyond standard growth performance and ruminal parameters, a primary focus was placed on growth performance, carcass characteristics and meat quality, to determine whether this sustainable roughage source could maintain or enhance the nutritional value of goat meat for the consumer market.

## Materials and Methods

The experimental procedures were conducted at the Ruminant Research Unit, Department of Animal Science, Faculty of Agriculture at Kamphaeng Saen, Kasetsart University, Nakhon Pathom, Thailand. The study received ethical approval from the Animal Usage and Ethics Committee of Kasetsart University, Thailand (ACKU65-AGK-028).

### Silage preparation

The oil palm tree samples were separated into three parts: trunk, bark and cortex (Fig. 1). The stem trunk was the main by-product. Oil palm trunk silage (OPTS) was prepared from oil palm trees aged 25 yr by removing 5 cm of the outer bark, cutting segments 20–30 cm from the top of the trunk and 2 m from the bottom and shredding the remaining middle part (Fig. 1) into pieces (1–2 cm in length). The shredded oil palm trunk was ensiled in 150 L fermentation tanks with 5% molasses and 2.5% urea (Chuchai et al., 2023) and the tanks were tightly sealed with plastic lids. Fermentation lasted 21 d. Napier grass was harvested at day 60 after regrowth and chopped using a forage chopper into pieces (1–2 cm in length) from which additive-free Napier grass silage was prepared. Thereafter, the various experimental forages were sealed hermetically in plastic bags (25 kg per bag). Air was removed from the plastic bags using a vacuum sealer and the contents were allowed to ferment for 21 d.



**Fig. 1** Stem parts of oil palm tree and its trunk

### *Experimental design, treatments and animal management*

A sample of 32 male Boer × Anglo-Nubian crossbred goats (aged 3 mth, mean body weight  $\pm$  standard deviation = 16.50  $\pm$  0.5 kg) were assigned randomly to one of four treatments in a completely randomized design, with eight animals per treatment. The experimental treatments on a dry matter (DM) basis were: (1) 45% Napier grass silage (NGS); (2) 30% Napier grass silage and 15% oil palm trunk silage (15OPTS); (3) 15% Napier grass silage and 30% oil palm trunk silage (30OPTS); and (4) 45% oil palm trunk silage (45OPTS). The remaining ingredients (55% DM) were identical in all diets and constituted the basal total mixed ration (TMR). All goats were fed the TMR *ad libitum* and the feeding regimen ensured that approximately 5–10% of the offered feed remained uneaten at each feeding. All 32 goats were kept in separate pens (each 1.5 m × 2 m). Animals were fed twice daily at 0730 hours and 1600 hours with *ad libitum* access to fresh water throughout the experiment. The animals were fed the experimental diets daily for 104 d. The first 14 d were allowed for the goats to become accustomed to handling and the corresponding treatments, followed by 90 d for measurement. Each goat was weighed individually upon arrival, just before the morning feeding and at both the beginning and end of the experiment. Throughout the 90 d experimental period, daily records were kept of the amounts of feed offered and refused, allowing for accurate measurement of the total feed intake.

### *Feed and fecal sampling and analysis*

The TMR diets and silage samples were collected once weekly for chemical composition analysis after being ground to pass through a 1 mm sieve. The contents of DM, organic matter (OM), crude protein (CP) and ether extract (EE) were determined according to Association of Official Analysis Chemists (2019). Neutral detergent fiber (NDF), acid detergent fiber (ADF) and acid detergent lignin (ADL) were analyzed according to Association of Official Analysis Chemists (2016).

During the final 3 d of the experiment, 300 g of fresh fecal matter was collected daily from the rectum of each goat just before morning feeding. These samples were immediately stored at -20°C. The daily samples for each goat were pooled and blended, then dried in the hot-air oven at 65°C. Subsequently, the dried samples were ground and passed through a 1 mm screen. The processed fecal samples were analyzed for the contents of DM, CP, EE, NDF, ADF and ash. Acid-insoluble

ash (AIA) was utilized as an internal marker to calculate the apparent digestibility of the nutrients, following the method detailed by Pelegrin-Valls et al. (2021).

### *Growth performance and feed intake*

Each goat was weighed before the morning feeding on day 14 of the pre-feeding period to obtain its initial body weight. Subsequent measurements, used to determine final weights and calculate the average daily gain (ADG), were taken before the morning feeding on days 30, 60 and 90. The amount of feed offered was adjusted weekly, based on the previous week's intake and included a refusal allowance of approximately 10% of the daily intake. The daily feed intake for each animal was calculated by subtracting the amount of feed refused from the amount offered.

### *Blood sampling and analysis*

Blood samples were collected at 0 h (before morning feeding) and 4 h after morning feeding at the end of the experiment (day 90). Approximately 8 mL of blood was obtained from each goat using jugular venipuncture and distributed into two tubes for hematological analysis and serum biochemistry, respectively. Sterile tubes containing ethylenediaminetetraacetic acid were labeled with the corresponding animal identification number, immediately chilled in an ice bath, transported to the laboratory and centrifuged at 3,000 revolutions per minute (rpm) and 4°C for 15 min to determine hematocrit (HCT) or packed cell volume (PCV) amounts. Blood samples without anticoagulant were allowed to coagulate in Kaylite holders at 37°C for serum separation and then centrifuged at 3,000 rpm and 4°C for 15 min. Serum aliquots were stored at -20°C until analysis. Serum blood urea nitrogen (BUN) and blood glucose (BG) concentrations were determined using an automatic chemistry analyzer (PKL PPC 125; Paramedical s.r.l., Salerno, Italy).

### *Ruminal fermentation and analysis*

On day 90, at the end of the experiment, rumen fluid was collected from each goat before feeding and 4 h after feeding using a stomach tube technique based on inserting the tube via the esophagus. The rumen fluid samples were filtered through four layers of cheesecloth and the pH was measured immediately using a pH meter (H19125; Hanna Instruments; Padova, Italy). Aliquots (10 mL) of each rumen fluid sample were stored at -20°C for subsequent

determination of short-chain fatty acids (SCFAs) and  $\text{NH}_3\text{-N}$ . The SCFA concentrations were determined using gas chromatography, as described by Watanabe et al. (2010). The samples were subjected to centrifugation ( $10,000\times g$ , 10 min,  $4^\circ\text{C}$ ). Subsequently, a 100  $\mu\text{L}$  aliquot of the supernatant was treated with 20  $\mu\text{L}$  of 25% metaphosphoric acid and maintained at  $4^\circ\text{C}$  overnight. The resulting mixture was re-centrifuged ( $10,000\times g$ , 10 min,  $4^\circ\text{C}$ ). Next, 50  $\mu\text{L}$  of the supernatant was mixed with 50  $\mu\text{L}$  of crotonic acid. Then, the samples were analyzed using gas chromatography (GC-2010; Shimadzu; Kyoto, Japan). This system utilized an ULBON HR-20M fused silica capillary column (0.53 mm internal diameter  $\times$  30 m length, 3.0  $\mu\text{m}$  film; Shinwa; Kyoto, Japan). A standard curve was constructed using various concentrations of SCFA standard solutions to enable the calculation of the SCFA concentrations in the fermentation broth. Samples were subjected to final centrifugation ( $10,000\times g$ , 15 min,  $4^\circ\text{C}$ ). Subsequently, the supernatant was membrane-filtered, sealed and maintained at  $4^\circ\text{C}$  pending gas chromatography analysis. The injector and detector temperatures for the gas chromatography were both set at  $-20^\circ\text{C}$ . Separately, the ruminal  $\text{NH}_3\text{-N}$  concentration was determined using the indophenol colorimetric method, as described by Weatherburn (1967), using  $(\text{NH}_4)_2\text{SO}_4$  as the standard. The supernatant obtained after centrifuging the rumen fluid samples ( $12,000\times g$ , 20 min,  $4^\circ\text{C}$ ) and the resulting supernatant was reserved for analysis. For colorimetric determination, approximately 40  $\mu\text{L}$  of the sample or standard solution were pipetted into a test tube, with distilled water serving as the control. After adding and thoroughly mixing 2.5 mL of phenol solution, the mixture was incubated in a  $37^\circ\text{C}$  water bath for 30 min. Finally, the absorbance was measured at 650 nm using a spectrophotometer (Multiskan<sup>TM</sup> FC Microplate Photometer; Thermo Fisher Scientific; Vantaa, Finland).

#### Carcass characteristics and meat quality measurement

A subsample of 20 goats (five goats randomly selected from each treatment) was slaughtered on the day after the end of the experiment. These goats were fasted for 24 h before being loaded and transported approximately 0.8 km to a slaughterhouse. Before slaughter, the final body weight of each goat was recorded to determine the dressing percentage. These goats were slaughtered according to standard commercial procedures and bled by severing the carotid arteries and jugular vein in a single cut, in accordance with Halal practice (Safari

et al., 2011). Carcass characteristics were recorded immediately post-dressing to determine the hot carcass weight (HCW). Subsequently, the warm dressing percentage was calculated using the Equation 1:

$$\text{Warm dressing percentage} = (\text{HCW} / \text{Slaughter weight}) \times 100 \quad (1)$$

Carcasses were chilled at  $2^\circ\text{C}$  for 24 h. Following chilling, the left and right *longissimus lumborum* (LM) muscles were excised for the assessment of meat quality traits. The meat pH was measured at 1 hr and 24 hr *postmortem* using a pH meter (D-51; Horiba; Kyoto, Japan). Meat color was determined using a colorimeter (Opto-Star; Matthäus, NobitzKlaus, Germany). The LM area was determined by tracing the muscle's cross-section between the 12<sup>th</sup> and 13<sup>th</sup> ribs onto paper. Subsequently, this traced area was analyzed using a leaf area meter (LH-3100C; Li-COR Bioscience; Lincoln, NE, USA), following the methodology described by Cacere et al. (2014). The color measurement was performed on sliced LM samples (200 g, 2.5 cm thick) after 30 min of exposure to the air at  $4^\circ\text{C}$  using a color meter (CR 310 Chroma Meter; Minolta; Osaka, Japan). The parameters  $L^*$  (lightness),  $a^*$  (redness) and  $b^*$  (yellowness) values were recorded at six positions per sample and the average was calculated (Francozo et al., 2013). Shear force was determined using a material testing machine (LR 5K; Lloyd Instruments Ltd; Bognor Regis, UK).

#### Statistical analysis

Statistical analyses were performed using R software, version 4.1.1 (R Core Team, 2024). Treatment means were analyzed using orthogonal polynomial contrasts to assess the linear, quadratic and cubic effects of roughage inclusion. The marbling score was analyzed non-parametrically using the Kruskal-Wallis test. The data were fitted to Equation 2:

$$Y_{ij} = \mu + T_i + \varepsilon_{ij} \quad (2)$$

where  $Y_{ij}$  is the dependent variable,  $\mu$  is the overall mean,  $T_i$  is the treatment effect  $i$  and  $\varepsilon_{ij}$  is the random residual error. Statistical significance was determined at  $p < 0.05$ .

## Results

### Chemical composition of diets

The chemical composition of the experimental diets is presented in Table 1. The OPT contained CP, EE, NDF, ADF and ADL contents on a DM basis of 1.48%, 0.92%, 64.71%, 35.35% and 4.76%, respectively. The OPTS had higher CP (9.27% DM) and NDF (39.54% DM) contents than the OPT. The NGS contained CP, EE, NDF, ADF and ADL contents on a DM basis of 6.82%, 1.91%, 54.92%, 25.42% and 5.46%, respectively. The TMR diets were formulated with 55% concentrate and 45% roughage. The OPTS was substituted for NGS at four inclusion levels (0%, 15%, 30%, 45%), with the resultant TMRs having CP contents on a DM basis of 15.96%, 16.90%, 16.50% and 16.68%, respectively. The NDF, ADF and ADL contents of

the TMRs in the ranges 42.64–47.83%, 21.47–28.07% and 1.47–3.74%, respectively. Crucially, the fiber contents increased as the level of OPTS rose in the TMR. This increase was directly attributed to the higher inherent NDF content of the OPTS itself.

### Growth performance

Feedlot performance and apparent nutrient digestibility are presented in Table 2. The TMR intake and ADG both decreased linearly as the level of OPTS in the TMR increased ( $p < 0.05$ ). The intakes of CP, NDF and nitrogen-free extract (NFE) all showed a significant linear decrease as the level of OPTS in the TMRs increased. This reduction in nutrient intake was a direct consequence of the observed decrease in the overall TMR intake. In contrast, the apparent digestibility of the CP, NDF and ADF was not significantly affected by the different levels of OPTS substitution.

**Table 1** Ingredients and nutrient composition of oil palm tree trunk silage, Napier grass silage and total mixed rations, with oil palm trunk silage substituted for Napier grass silage at different levels.

| Chemical component<br>(%DM)              | OPTS in total mixed ration (%DM) |        |        |        | OPT   | OPTS  | Napier grass silage |
|------------------------------------------|----------------------------------|--------|--------|--------|-------|-------|---------------------|
|                                          | NGS                              | 15OPTS | 30OPTS | 45OPTS |       |       |                     |
| 1. Ingredient                            |                                  |        |        |        |       |       |                     |
| Palm kernel meal                         | 22.00                            | 22.00  | 22.00  | 22.00  |       |       |                     |
| Cassava chip                             | 6.60                             | 6.60   | 6.60   | 6.60   |       |       |                     |
| Ground corn                              | 4.40                             | 4.40   | 4.40   | 4.40   |       |       |                     |
| Soybean meal                             | 12.65                            | 12.65  | 12.65  | 12.65  |       |       |                     |
| Fish meal                                | 6.05                             | 6.05   | 6.05   | 6.05   |       |       |                     |
| Molasses                                 | 1.10                             | 1.10   | 1.10   | 1.10   |       |       |                     |
| Di-calcium                               | 0.55                             | 0.55   | 0.55   | 0.55   |       |       |                     |
| Salt                                     | 1.10                             | 1.10   | 1.10   | 1.10   |       |       |                     |
| Premix                                   | 0.55                             | 0.55   | 0.55   | 0.55   |       |       |                     |
| Napier grass silage                      | 45.00                            | 30.00  | 15.00  | 0.00   |       |       |                     |
| Oil palm trunk silage                    | 0.00                             | 15.00  | 30.00  | 45.00  |       |       |                     |
| 2. Nutrient composition                  |                                  |        |        |        |       |       |                     |
| Dry matter (%)                           | 59.27                            | 51.92  | 51.72  | 55.80  | 42.40 | 29.88 | 21.80               |
| Organic matter (%)                       | 91.06                            | 90.34  | 88.99  | 84.99  | 94.43 | 94.49 | 95.76               |
| Crude protein                            | 15.96                            | 16.90  | 16.50  | 16.68  | 1.48  | 9.27  | 6.82                |
| Ether extract                            | 4.76                             | 4.48   | 4.13   | 2.96   | 0.92  | 0.98  | 1.91                |
| Ash                                      | 8.94                             | 9.66   | 11.01  | 15.01  | 5.57  | 5.51  | 4.24                |
| Neutral detergent fiber                  | 42.64                            | 43.35  | 45.24  | 47.83  | 64.71 | 65.81 | 54.92               |
| Acid detergent fiber                     | 21.47                            | 23.56  | 25.51  | 28.07  | 35.35 | 39.54 | 25.42               |
| Acid detergent lignin                    | 1.47                             | 2.36   | 2.63   | 3.74   | 4.76  | 2.63  | 5.46                |
| Nonstructural carbohydrate <sup>2/</sup> | 27.70                            | 25.61  | 23.12  | 17.52  | 27.32 | 18.43 | 32.11               |
| Hemicellulose                            | 21.17                            | 19.79  | 19.73  | 19.76  | 29.36 | 26.27 | 29.50               |
| Cellulose                                | 20.00                            | 21.20  | 22.88  | 24.33  | 30.59 | 36.91 | 19.96               |

DM = dry matter; TMR = total mixed ration; OPT = oil palm trunk; OPTS = oil palm trunk silage; The experimental diets (TMR) including: 1) Napier grass silage 45% + Oil palm trunk silage 0% (NGS), 2) Napier grass silage 30% + Oil palm trunk silage 15% (15OPTS), 3) Napier grass silage 15% + Oil palm trunk silage 30% (30OPTS) and 4) Napier grass silage 0% + Oil palm trunk silage 45% (45OPTS).

Premix compound = Vitamin (Vit.) A = 220,000 international units (IU), Vit. D3 = 44,000 IU, Vit. E = 440 IU, Ca = 96.25 g, P = 52.25 g, S = 22.55 g, Mg = 5.50 g, Co = 1.65 g, Se = 605 mg, Fe = 770 mg, Zn = 495 mg, Mn = 385 mg, I = 55 mg, Se = 0.6 mg.

Non structural carbohydrate =  $100 - (\% \text{Crude protein} + \% \text{Neutral detergent fiber} + \% \text{Ether extract} + \% \text{Ash})$ ; Hemicellulose = Neutral detergent fiber - Acid detergent fiber; Cellulose = Acid detergent fiber - Acid detergent lignin.

**Table 2** Effects of substituting oil palm trunk silage for Napier grass silage in total mixed ration on feedlot performance, nutrient intake and apparent nutrient digestibility in feedlot goats during 90 d.

| Item                                | OPTS in total mixed ration (%DM) |                             |                              |                            | SEM    | <i>p</i> Value |      |      |
|-------------------------------------|----------------------------------|-----------------------------|------------------------------|----------------------------|--------|----------------|------|------|
|                                     | NGS                              | 15OPTS                      | 30OPTS                       | 45OPTS                     |        | L              | Q    | C    |
| Initial weight (kg)                 | 16.47±0.64                       | 16.57±0.35                  | 16.02±0.64                   | 16.50±0.80                 | 0.75   | 0.10           | 0.93 | 0.17 |
| Final weight (kg)                   | 33.54±2.84 <sup>a</sup>          | 30.37±2.49 <sup>ab</sup>    | 29.57±1.45 <sup>b</sup>      | 27.80±2.36 <sup>b</sup>    | 2.34   | 0.01           | 0.42 | 0.85 |
| Weight gain (kg)                    | 17.06±2.37 <sup>a</sup>          | 13.80±2.83 <sup>ab</sup>    | 13.55±2.47 <sup>ab</sup>     | 11.30±3.16 <sup>b</sup>    | 2.72   | 0.01           | 0.60 | 0.88 |
| Average daily gain (g/d)            | 170.83±23.92 <sup>a</sup>        | 153.33±28.43 <sup>ab</sup>  | 150.55±25.49 <sup>ab</sup>   | 125.55±31.52 <sup>b</sup>  | 26.29  | 0.01           | 0.77 | 0.25 |
| TMR intake (g DM/d)                 | 1302.40±142.95 <sup>a</sup>      | 1232.52±122.60 <sup>a</sup> | 1088.91±123.74 <sup>ab</sup> | 944.82±139.14 <sup>b</sup> | 212.76 | 0.01           | 0.97 | 0.15 |
| Feed conversion ratio               | 7.63±1.74                        | 8.05±2.29                   | 7.23±1.39                    | 7.53±2.60                  | 2.05   | 0.32           | 0.99 | 0.39 |
| Nutrient intake (g DM/d)            |                                  |                             |                              |                            |        |                |      |      |
| Crude protein                       | 207.86±22.82 <sup>a</sup>        | 208.30±20.72 <sup>a</sup>   | 179.67±20.45 <sup>ab</sup>   | 157.60±23.20 <sup>b</sup>  | 33.64  | 0.04           | 0.63 | 0.82 |
| Neutral detergent fiber             | 555.38±60.96 <sup>a</sup>        | 534.30±53.15 <sup>a</sup>   | 492.64±56.00 <sup>ab</sup>   | 451.91±66.55 <sup>b</sup>  | 53.91  | 0.05           | 0.93 | 0.46 |
| Acid detergent fiber                | 279.63±30.69                     | 290.38±28.89                | 277.87±31.58                 | 265.21±39.05               | 30.11  | 0.07           | 0.76 | 0.77 |
| Nitrogen-free extract               | 722.78±79.33 <sup>a</sup>        | 640.30±63.68 <sup>ab</sup>  | 576.80±65.65 <sup>b</sup>    | 434.05±63.90 <sup>c</sup>  | 63.32  | 0.01           | 0.93 | 0.31 |
| Apparent digestibility nutrient (%) |                                  |                             |                              |                            |        |                |      |      |
| Crude protein                       | 75.93±0.48                       | 75.84±1.54                  | 76.51±0.76                   | 76.34±0.32                 | 9.88   | 0.76           | 0.93 | 0.88 |
| Neutral detergent fiber             | 56.55±9.07                       | 55.14±12.96                 | 56.79±5.57                   | 53.25±3.42                 | 4.95   | 0.61           | 0.61 | 0.46 |
| Acid detergent fiber                | 42.91±2.68                       | 42.93±2.44                  | 41.76±1.10                   | 40.40±4.25                 | 3.33   | 0.52           | 0.93 | 0.30 |

SEM = standard error of mean ( $n = 8$ ); L = linear effect; Q = quadratic effect; C = cubic effect.

DM = dry matter; OPTS = oil palm trunk silage; with OPTS-to-Napier grass silage percentages for a total 45% of the total mixed ration diet: 1) 0:45 (NGS); 2) 15:30 (15OPTS); 3) 30:15 (30OPTS); and 4) 45:0 (45OPTS). The experimental diets (TMR) including: 1) Napier grass silage 45% + Oil palm trunk silage 0% (NGS), 2) Napier grass silage 30% + Oil palm trunk silage 15% (15OPTS), 3) Napier grass silage 15% + Oil palm trunk silage 30% (30OPTS) and 4) Napier grass silage 0% + Oil palm trunk silage 45% (45OPTS).

Mean ± standard deviation (SD) within the same row followed by different lowercase superscripts are significantly different ( $p < 0.05$ ).

### Blood metabolites and rumen fermentation

The blood metabolites and fermentation characteristics in the rumen are presented in Tables 3 and 4, respectively. Despite the different inclusion levels of OPTS in the different TMR diets, the key indicators of health and fermentation (ruminal pH, ruminal  $\text{NH}_3\text{-N}$ , BUN, BG, PCV) remained stable across all

treatment groups throughout the 90 d trial. The measurements taken at 0 hr (pre-feeding) and 4 hr (post-feeding) were not significantly different. However, the BUN level measured pre-feeding (0 hr) exhibited a significant linear increase as the level of OPTS in the TMR increased. Furthermore, the BUN level measured 4 hr post-feeding increased with higher OPTS inclusion, following a significant quadratic trend.

**Table 3** Effects of substituting oil palm trunk silage for Napier grass silage in total mixed ration on blood metabolites in feedlot goats after 90 d.

| Item        | OPTS in total mixed ration (%DM) |            |            |            | SEM  | <i>p</i> value |      |      |
|-------------|----------------------------------|------------|------------|------------|------|----------------|------|------|
|             | NGS                              | 15OPTS     | 30OPTS     | 45OPTS     |      | L              | Q    | C    |
| BUN (mg/dL) |                                  |            |            |            |      |                |      |      |
| 0 hr        | 22.00±1.63                       | 22.00±1.63 | 24.00±2.04 | 25.00±1.83 | 1.79 | 0.10           | 0.58 | 0.46 |
| 4 hr        | 22.50±1.73                       | 27.25±2.48 | 26.00±2.20 | 25.50±2.89 | 2.36 | 0.18           | 0.03 | 0.18 |
| BG (mg/dL)  |                                  |            |            |            |      |                |      |      |
| 0 hr        | 61.50±2.64                       | 62.50±4.20 | 61.00±2.45 | 59.25±4.92 | 4.66 | 0.44           | 0.56 | 0.83 |
| 4 hr        | 67.50±2.38                       | 67.00±3.76 | 65.00±5.77 | 65.50±6.42 | 0.86 | 0.47           | 0.84 | 0.79 |
| PCV (%)     |                                  |            |            |            |      |                |      |      |
| 0 hr        | 29.95±1.29                       | 30.05±2.08 | 29.00±1.15 | 30.00±1.63 | 1.58 | 1.00           | 1.00 | 0.18 |
| 4 hr        | 30.00±3.27                       | 30.00±1.63 | 33.00±1.83 | 30.00±0.82 | 2.08 | 0.53           | 0.17 | 0.07 |

SEM = standard error of mean ( $n = 8$ ); L = linear effect; Q = quadratic effect; C = cubic effect.

DM = dry matter; OPTS = oil palm trunk silage; The experimental diets (TMR) including: 1) Napier grass silage 45% + Oil palm trunk silage 0% (NGS), 2) Napier grass silage 30% + Oil palm trunk silage 15% (15OPTS), 3) Napier grass silage 15% + Oil palm trunk silage 30% (30OPTS) and 4) Napier grass silage 0% + Oil palm trunk silage 45% (45OPTS). BUN = blood urea nitrogen, BG = blood glucose; PCV = packed cell volume.

Values = mean ± standard deviation (SD).

**Table 4** Effects of substituting oil palm trunk silage for Napier grass silage in a total mixed ration on ruminal fermentation in feedlot goats after 90 days

| Item                                                        | OPTS in total mixed ration (%DM) |                         |                         |                        | SEM  | p value |      |      |
|-------------------------------------------------------------|----------------------------------|-------------------------|-------------------------|------------------------|------|---------|------|------|
|                                                             | NGS                              | 15OPTS                  | 30OPTS                  | 45OPTS                 |      | L       | Q    | C    |
| Ruminal (pH)                                                |                                  |                         |                         |                        |      |         |      |      |
| 0 hr                                                        | 6.20±0.05                        | 6.26±0.08               | 6.19±0.07               | 6.23±0.04              | 0.35 | 0.91    | 0.89 | 0.08 |
| 4 hr                                                        | 6.70±0.22                        | 6.68±0.08               | 6.75±0.14               | 6.55±0.45              | 0.73 | 0.51    | 0.50 | 0.56 |
| Ammonia nitrogen (mg/dL)                                    |                                  |                         |                         |                        |      |         |      |      |
| 0 hr                                                        | 9.70±0.04                        | 9.93±0.08               | 9.73±0.06               | 9.87±0.16              | 0.12 | 0.74    | 0.87 | 0.20 |
| 4 hr                                                        | 9.75±0.19                        | 9.88±0.16               | 9.88±0.35               | 9.84±0.13              | 0.15 | 0.60    | 0.46 | 0.84 |
| Total SCFAs (mmol/L)                                        |                                  |                         |                         |                        |      |         |      |      |
| 0 hr                                                        | 92.92±4.30                       | 93.18±1.24              | 91.06±3.70              | 89.88±5.92             | 4.14 | 0.24    | 0.71 | 0.73 |
| 4 hr                                                        | 98.65±0.28                       | 94.57±5.53              | 98.55±0.88              | 94.45±4.08             | 3.46 | 0.29    | 0.99 | 0.05 |
| Proportion of acetic acid per total SCFAs (%)               |                                  |                         |                         |                        |      |         |      |      |
| 0 hr                                                        | 66.30±1.29                       | 65.75±2.08              | 65.20±1.15              | 63.66±1.63             | 2.71 | 0.18    | 0.72 | 0.87 |
| 4 hr                                                        | 68.70±3.27                       | 64.69±1.63              | 67.80±1.83              | 66.13±0.82             | 2.40 | 0.41    | 0.39 | 0.06 |
| Proportion of propionic acid per total SCFAs (%)            |                                  |                         |                         |                        |      |         |      |      |
| 0 hr                                                        | 15.97±1.26                       | 16.02±0.57              | 14.97±1.12              | 15.49±1.66             | 1.21 | 0.37    | 0.77 | 0.34 |
| 4 hr                                                        | 16.52±0.25                       | 16.73±0.69              | 16.69±0.61              | 16.52±0.64             | 0.57 | 0.81    | 0.26 | 0.61 |
| Proportion of butyric acid per total SCFAs (%)              |                                  |                         |                         |                        |      |         |      |      |
| 0 hr                                                        | 5.97±0.50                        | 5.93±0.09               | 5.36±0.46               | 5.93±0.16              | 0.33 | 0.39    | 0.10 | 0.05 |
| 4 hr                                                        | 7.54±0.32                        | 7.49±0.77               | 8.46±1.03               | 7.10±0.61              | 0.73 | 0.75    | 0.09 | 0.05 |
| Proportion of other SCFAs per total SCFAs (%) <sup>3/</sup> |                                  |                         |                         |                        |      |         |      |      |
| 0 hr                                                        | 4.66±0.02                        | 5.42±0.40               | 5.51±0.30               | 4.78±0.10              | 0.79 | 0.98    | 0.05 | 0.88 |
| 4 hr                                                        | 5.87±0.03                        | 5.38±0.04               | 5.32±0.02               | 4.68±0.02              | 0.99 | 0.11    | 0.77 | 0.69 |
| Acetate:propionate ratio                                    |                                  |                         |                         |                        |      |         |      |      |
| 0 hr                                                        | 4.16±0.15                        | 4.10±0.10               | 4.36±0.27               | 4.12±0.21              | 0.19 | 0.73    | 0.34 | 0.08 |
| 4 hr                                                        | 4.16±0.03 <sup>a</sup>           | 4.00±1.24 <sup>ab</sup> | 4.00±3.70 <sup>ab</sup> | 3.88±5.92 <sup>b</sup> | 0.10 | 0.13    | 0.01 | 0.04 |

SEM = standard error of mean ( $n = 8$ ); L = linear effect; Q = quadratic effect; C = cubic effect.

DM = dry matter; OPTS = oil palm trunk silage; The experimental diets (TMR) including: 1) Napier grass silage 45% + Oil palm trunk silage 0% (NGS, 2) Napier grass silage 30% + Oil palm trunk silage 15% (15OPTS), 3) Napier grass silage 15% + Oil palm trunk silage 30% (30OPTS) and 4) Napier grass silage 0% + Oil palm trunk silage 45% (45OPTS).; BUN = blood urea nitrogen, BG = blood glucose; PCV = *packed cell volume*.

SCFA = short-chain fatty acids; Other SCFAs = valeric acid, iso-valeric acid and iso-butyric acid.

Mean ± standard deviation (SD) within the same row followed by different lowercase superscripts are significantly different ( $p < 0.05$ ).

The SCFAs profile is shown in Table 4. The total SCFAs measured in the ruminal digesta pre-feeding (0 hr) were not significantly different among the treatment groups. However, the total SCFAs measured 4 hr post-feeding were significantly affected by increasing levels of OPTS, showing both a linear and a quadratic response. The major individual SCFAs molar proportions for acetate, propionate, butyrate, other SCFAs and the acetate-to-propionate (A:P) ratio—measured at both 0 hr (pre-feeding) and 4 hr (post-feeding)—were not significantly different among the treatment groups. However, two exceptions were observed at 4 hr post-feeding: 1) the molar proportion of butyrate was the highest in the 30OPTS group, 2) the A:P ratio was the lowest in the 45OPTS group, with both exhibiting significant quadratic and cubic effects.

### Carcass traits and meat quality

Carcass characteristics and meat quality are presented in Table 5. Increasing the level of OPTS significantly reduced both the live body weight (LBW) and the hot carcass weight (HCW). The reduction in LBW followed a quadratic trend ( $p < 0.05$ ), while the decline in HCW displayed a steady linear effect ( $p < 0.05$ ). Several carcass and meat quality characteristics were significantly affected by the OPTS in the TMR. Warm dressing percentage and carcass length showed complex responses, with significant linear and cubic effects to increasing OPTS. Notably, the 45OPTS group had lower values for both parameters compared to the other groups. The decline in muscle pH measured at 1 hr *postmortem* displayed a significant quadratic effect with increasing OPTS. The meat (LM) lightness ( $L^*$  value) decreased linearly with increasing OPTS levels ( $p < 0.05$ ). Conversely, the following characteristics were not significantly different among the treatment groups: shear force, LM area and the redness ( $a^*$ ) and yellowness ( $b^*$ ) values of LM color.

**Table 5** Effects of substituting oil palm trunk silage for Napier grass silage in a total mixed ration on carcass characteristics and meat quality in feedlot goats at 90 d

| Item                              | OPTS in total mixed ration (%DM) |                         |                          |                         | SEM  | <i>p</i> value |       |      |
|-----------------------------------|----------------------------------|-------------------------|--------------------------|-------------------------|------|----------------|-------|------|
|                                   | NGS                              | 15OPTS                  | 30OPTS                   | 45OPTS                  |      | L              | Q     | C    |
| Live body weight (kg)             | 32.73±2.84 <sup>a</sup>          | 31.45±2.49 <sup>a</sup> | 32.20±1.45 <sup>a</sup>  | 29.56±2.36 <sup>b</sup> | 0.64 | 0.88           | 0.01  | 0.81 |
| Hot carcass weight (kg)           | 20.50±0.58 <sup>a</sup>          | 18.63±0.96 <sup>a</sup> | 17.87±0.52 <sup>ab</sup> | 15.70±0.96 <sup>b</sup> | 0.78 | <0.01          | 0.48  | 0.91 |
| Warm dressing (%)                 | 63.21±1.45 <sup>a</sup>          | 59.30±0.93 <sup>b</sup> | 55.75±0.43 <sup>c</sup>  | 53.85±1.00 <sup>d</sup> | 1.02 | <0.01          | <0.01 | 0.24 |
| Carcass length (cm)               | 0.11±0.02 <sup>a</sup>           | 0.14±0.02 <sup>a</sup>  | 0.12±0.01 <sup>a</sup>   | 0.09±0.01 <sup>b</sup>  | 0.01 | <0.01          | 0.02  | 0.47 |
| LM area (cm <sup>2</sup> )        | 6.27±0.22                        | 6.32±0.02               | 6.35±0.03                | 6.30±0.20               | 0.07 | 0.54           | 0.19  | 0.57 |
| Shear force (kg/cm <sup>2</sup> ) | 3.22±0.23                        | 3.39±0.33               | 3.14±0.10                | 3.46±0.20               | 0.23 | 0.31           | 0.47  | 0.08 |
| pH at 1 hr                        | 6.06±0.06                        | 6.14±0.03               | 6.13±0.03                | 6.08±0.04               | 0.04 | 0.59           | <0.01 | 0.59 |
| pH at 24 hr                       | 5.40±0.04                        | 5.45±0.00               | 5.42±0.07                | 5.44±0.05               | 0.05 | 0.48           | 0.58  | 0.27 |
| Meat color of LM                  |                                  |                         |                          |                         |      |                |       |      |
| <i>L</i> *                        | 37.37±0.56 <sup>a</sup>          | 36.00±1.05 <sup>a</sup> | 34.92±1.91 <sup>ab</sup> | 32.37±2.93 <sup>b</sup> | 1.18 | 0.01           | 0.88  | 0.52 |
| <i>a</i> *                        | 10.69±0.61                       | 10.75±0.57              | 11.24±0.92               | 10.65±0.38              | 0.64 | 0.81           | 0.33  | 0.31 |
| <i>b</i> *                        | 8.58±0.50                        | 8.03±0.63               | 7.90±0.53                | 7.88±0.25               | 0.50 | 0.06           | 0.31  | 0.77 |

SEM = standard error of mean ( $n = 8$ ); L = linear effect; Q = quadratic effect; C = cubic effect.

DM = dry matter; OPTS = oil palm trunk silage; The experimental diets (TMR) including: 1) Napier grass silage 45% + Oil palm trunk silage 0% (NGS), 2) Napier grass silage 30% + Oil palm trunk silage 15% (15OPTS), 3) Napier grass silage 15% + Oil palm trunk silage 30% (30OPTS) and 4) Napier grass silage 0% + Oil palm trunk silage 45% (45OPTS). LM = *longissimus lumborum* muscles; *L*\* = lightness measured on a scale 0–100, where 100 represents pure white; *a*\* = color axis ranging from extreme green ( $-a^*$ ) to extreme red ( $+a^*$ ); *b*\* = color axis ranging from extreme blue ( $-b^*$ ) to extreme yellow ( $+b^*$ ).

Mean ± standard deviation (SD) within the same row followed by different lowercase superscripts are significantly different ( $p < 0.05$ ).

## Discussion

Napier grass is a highly productive tropical forage characterized by rapid growth and a strong response to intensive management (Singh et al., 2013). In the current study, the chemical profile of raw Napier grass—specifically its crude protein (CP) and fiber fractions (NDF and ADF)—remained relatively stable post-fermentation. In contrast, raw oil palm trunk (OPT) had a significantly lower CP content (approximately 1.5% DM) and higher fiber concentrations, mirroring the nutritional limitations of other lignocellulosic byproducts such as sugarcane bagasse (Almeida et al., 2018).

To overcome these nutritional constraints, the OPT was treated with 2.5% urea and 5% molasses. This supplementation successfully elevated the CP content to 9.27% DM and softened the recalcitrant fiber matrix, likely improving digestive efficiency in goats. These findings aligned with other research on rice straw (Mgheni et al., 1993; Wanapat et al., 2009; Gunun et al. 2013), where urea treatment served to enhance protein levels. Furthermore, the reduction in fiber content observed here supports the findings of Lunsin et al. (2018), who attributed such changes to the alkaline effect of urea on the structural carbohydrates of roughage.

The variation in CP concentrations across the total mixed ration diets was driven primarily by the superior protein content of the treated OPTS relative to the Napier grass

silage. Additionally, there was a linear increase in the TMR fiber levels as the inclusion rate of OPTS rose, reflecting the inherently fibrous nature of the palm trunk.

Generally, the feed intake of a ruminant increases until the animal's energy requirement is met (National Research Council, 2007). In the current experiment, TMR intake decreased as the level of OPTS increased, which was likely associated with the higher NDF and lignin contents of the diet. This agreed with Lammers et al. (1996), who reported that increasing dietary fiber reduced feed intake and that the voluntary intake of goats was influenced by the size and the physical form of the diet. In addition, other factors may have affected intake such as animal species, the origin and type of feedstuffs and the structural characteristics of the diet. Furthermore, the odor of urea at the higher OPTS inclusion levels may have contributed to reductions in feed intake, CP intake and ADG. However, the OPTS level did not affect the feed conversion ratio.

Ruminal pH and NH<sub>3</sub>-N were not affected by the OPTS level and remained within the normal range (pH 6.0–7.0) considered optimal for microbial growth and fiber digestion (Van Soest, 1994). Furthermore, the concentrations of both ruminal NH<sub>3</sub>-N and BUN in the current study were near the normal levels suggested by Preston and Leng (1987), who proposed that ruminal NH<sub>3</sub>-N concentrations in the range 5–26 mg/dL were adequate for microbial growth, with microbial activity becoming more efficient when the NH<sub>3</sub>-N supply was continuous and concentrations were

at the higher end of this range. Roseler et al. (1993) reported that balanced energy and protein diets for lactating dairy cows were associated with average BUN concentrations of 15 mg/dL, whereas Lloyd (1982) reported BUN values in goats in the range 11.2–27.7 mg/dL. Normal BUN concentrations vary with age, diet, protein intake and particularly with ruminal  $\text{NH}_3\text{-N}$  concentration (Vaghar Seyedin et al., 2024). Therefore, the increase in BUN with increasing OPTS inclusion reflected the increase in the  $\text{NH}_3\text{-N}$  concentration in the rumen, which was consistent with Preston et al. (1965), who reported that BUN values were highly correlated with protein intake, as well as with Kung and Huber (1983), who described the relationship between BUN and ammonia production in the rumen.

OPTS inclusion in the TMR had no significant effect on PCV or BG in the feedlot goats at 90 d; in addition, the PCV and BG values at 0 hr before feeding and 4 hr after feeding were consistent across treatments. These PCV values were within the normal range for goats (22–38%) reported by Jain (1993). PCV is an important indicator of red blood cell status; values below the normal range indicate anemia, whereas abnormally high values indicate polycythemia (Johns and Heller, 2021). Therefore, all the goats fed any of the four experimental diets for 90 d in the current study were in normal health, with no evidence of anemia. Although the molar proportions of SCFAs, particularly acetic acid and butyric acid, were not affected by the dietary treatments at any sampling time, total SCFAs and the proportions of acetic acid, propionic acid and butyric acid at 0 hr and 4 hr post-feeding were within relatively narrow ranges and did not differ markedly from the control group. These values were consistent with those reported by Chanjula et al. (2007a, 2007b), who found that the total SCFAs concentrations in male Thai native hybrid goats were in the range 75–86.57 mmol/L. France and Siddons (1993) reported that total SCFAs concentrations in the normal rumen were in the range 70–130 mmol/L and these were correlated with the extent of fermentation and the digestibility coefficient of organic matter (Dijkstra et al., 2005).

In the current study, substituting OPTS for Napier grass silage in the diet affected carcass traits of the fattening goats. Fasted live weight, hot carcass weight and warm dressing percentage decreased as the level of OPTS increased, which was consistent with the reduced feed intake observed at higher levels of OPTS inclusion. The physical characteristics of meat, evaluated using the LM of fattening goats at 1 hr and 24 hr *postmortem*, had pH values in the ranges 6.06–6.14 and 5.40–5.45, respectively, with both these being within the normal range of 5.9–6.5 reported by Pi et al. (2005).

Including OPTS silage in the TMR for 90 d did not affect the LM color compared to the control group. In the current study, the  $L^*$  values were close to those reported by Chanjula et al. (2014) for goat meat (39.81–43.57, 9.34–9.89 and 11.09–12.45 for  $L^*$ ,  $a^*$  and  $b^*$ , respectively) but were lower than the  $L^*$  values reported by Solaiman et al. (2011). Solaiman et al. (2011) reported that the CIELAB color coordinates ( $L^*$ ,  $a^*$ ,  $b^*$ ) for the loin muscle of Boer crossbred goats versus sheep were 38.05 vs. 39.91, 16.21 vs. 17.35, and 15.44 vs. 16.82, respectively. Muscle color is influenced by many factors, including breed, age, sex, diet and muscle type, which differ in myoglobin content (Goetsch et al., 2011).

Therefore, OPT shows promise as a viable roughage source for goats when it is fermented with urea and molasses. This fermentation process is essential as it effectively increases the protein content and enhances the utilization of the fiber within the OPT. Based on the study results, the inclusion of OPTS in the TMR for goats should be limited to a maximum of 30% DM of the diet to avoid adverse effects.

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## Conclusion

This study demonstrated that OPTS was a viable alternative roughage source for Boer × Anglo-Nubian crossbred goats, supporting the integration of oil palm byproducts into sustainable ruminant production. While increasing inclusion levels of OPTS led to a reduction in dry matter intake, final body weight and ADG—likely due to the physical limitations of the fiber matrix—the substitution of 30% OPTS in the TMR was the optimal threshold for maintaining acceptable growth performance.

Notably, the inclusion of OPTS had no adverse effect on the measured ruminal fermentation parameters, short-chain fatty acid profiles, carcass characteristics, or meat quality, suggesting that the physiological and metabolic health of the animals remained robust even when traditional forages had been replaced partially by palm-based biomass.

Moving forward, the successful adoption of OPT in feedlot systems will require a clearer distinction between the inherent physical characteristics of the trunk and the biochemical effects of urea treatment on palatability and nitrogen kinetics. Future research should prioritize the optimization of silage processing—specifically through the use of microbial inoculants and refined urea concentrations—to mitigate intake limitations and further enhance the nutritional value of this abundant agricultural byproduct.

## Conflict of interest

The authors declare that there are no conflicts of interest.

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