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Valorising bamboo leaves for climate-smart livestock production: Nutritional profile, emission reduction, and farmer adoption in Ghana's transitional zones

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ABSTRACT

Bamboo has shown promising potential as a sustainable and nutrient-rich fodder source for livestock, particularly in Ghana's transitional forest zones where traditional forage options are limited. This study evaluated the nutritional composition, *in vitro* rumen fermentation, and digestibility of the leaves of *Oxytenanthera abyssinica* (OA) and *Bambusa vulgaris* (BV) and incorporated them into a basal mix (Bmix) of *Cenchrus purpureus* and *Bridelia ferruginea* for goats. Additionally, a survey was conducted to assess adoption drivers of bamboo as a livestock fodder in the study area. The results show that both bamboo species had similar ($p > 0.05$) dry matter (91.7–92 %), crude protein (12.5–14.5 %), and crude fibre (26.3–28.9 %). OA had higher ($p < 0.05$) ash (12.4 %), Ca (0.48 %), Mg (0.15 %), flavonoids (0.885 mg/l) and oxalates (0.015 %), while BV had more P (0.18 %), K (2.31 %), Fe (65.6 mg/kg), Cu (20.49 mg/kg), Mn (12.9 mg/kg), acid detergent lignin (1.8 %–4.3 %), tannins (0.003 %), saponins (0.28 %) and total antioxidants (96.8 %). In vitro rumen fermentation showed OA+Bmix had the highest gas production (155.1 mL/200 mg DM) and VFAs (89.6 mmol/100 g), followed by BV+Bmix (gas: 146.8 mL/200 mg DM, VFAs: 84.3 mmol/100 g) and control (gas: 145.2 mL/200 mg DM, VFAs: 75.3 mmol/100 g). The OA+Bmix also had the lowest methane (14.1 mL/200 mg DM) and CO_2 (69.0 mL/200 mg DM) compared to BV+Bmix (methane: 16.5 mL/200 mg DM, CO_2: 72.3 mL/200 mg DM) and the control (methane: 24.3 mL/200 mg DM, CO_2: 84.2 mL/200 mg DM). Similarly, OA+Bmix showed the highest nitrogen intake (9.22 g/day), digestibility (8.5 g/day) and retention (88.1 %), along with the highest digestibility for dry matter (58.7 %), crude protein (72.2 %), crude fibre (67.8 %) and ether extract (74.4 %), compared to BV+Bmix (intake: 6.96 g/day, digestibility: 6.47 g/day, retention: 83.2 %, dry matter: 48.3 %, crude protein: 56.8 %, crude fibre: 60.2 %, ether extract: 68.7 %) and the control (intake: 5.54 g/day, digestibility: 4.92 g/day, retention: 59.1 %, dry matter: 33.6 %, crude protein: 41.1 %, crude fibre: 31.6 %, ether extract: 47.2 %). In conclusion, bamboo leaves are nutrient-rich supplements that can improve rumen fermentation, nutrient digestibility and animal health. Their adoption is promising, driven by economic feasibility, accessibility and sustainability. Therefore, prioritising educational and financial support for their adoption is recommended.

1. Introduction

Climate change, driven by the emission of greenhouse gases (GHG) from both natural systems and anthropogenic activities, is having a profound impact on global livestock production (Fawzy et al., 2020). One of the most significant effects is the alteration of rainfall patterns, which affects the availability and quality of feed resources essential for maintaining animal health and productivity (Dumas, 2023). Shifts in

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temperature and precipitation disrupt ecosystems and challenge farmers who rely on rain-fed systems for livestock feed, exacerbating feed shortages and threatening the sustainability of livestock farming (Amissah, 2009; Danquah, 2009).

In Ghana, these climate-induced challenges are particularly evident in the transitional forest zones, which lie between the coastal savannah and the forested regions of the country (Akoto et al., 2018). These zones are ecologically and socio-economically important, hosting a mix of grasslands and forests that support diverse agricultural activities, including livestock production (Duku et al., 2010). However, the region's distinct wet and dry seasons, combined with rising temperatures, affect the growth of traditional fodder crops such as grasses and legumes, leading to significant feed shortages, particularly during the dry season (Duku et al., 2010). As a result, livestock in these areas often suffer from poor nutrition, which negatively impacts their health, productivity and overall well-being (Duku et al., 2010).

Smallholder farmers in the transitional zones of Ghana, who rely on indigenous knowledge and locally available resources to manage their livestock, face further difficulties due to financial constraints. These farmers often lack access to commercial feed alternatives, making them vulnerable to the effects of climate change (Adams and Ohene-Yankyera, 2015). This situation creates a vicious cycle of declining livestock health and productivity, threatening the livelihoods of farmers. Therefore, there is an urgent need for sustainable, climate-resilient feed alternatives capable of withstanding the challenges posed by changing environmental conditions.

Bamboo, often referred to as the 'world's giant grass,' has emerged as a potential solution to feed shortages in Ghana's transitional zones. Known for its rapid growth, drought tolerance, high biomass production and adaptability to diverse soil types and climates, bamboo presents a promising alternative to conventional livestock feed (INBAR, 2019). Its ability to thrive in a range of climatic conditions makes it an ideal candidate for mitigating the feed shortages exacerbated by climate change in these regions.

Bamboo leaves are rich in protein, fibre and essential minerals, and studies have shown that they can improve livestock health and productivity (Sahoo et al., 2010; Akoto et al., 2020; Altamirano-Gutiérrez et al., 2023; Zali, 2024). Additionally, feeding bamboo leaves has the potential to reduce methane emissions from ruminants, contributing to more sustainable and climate-resilient livestock farming practices (Andriarimalala et al., 2019; Halvorson et al., 2011).

Bamboo species are already integrated into agroecosystems in Ghana's highland and coastal areas for environmental conservation and industrial purposes (Adu-Poku et al., 2023). Despite bamboo's well-documented environmental benefits, including its role in carbon sequestration and soil conservation (Halvorson et al., 2011), its potential as a sustainable feed resource has not been adequately explored in Ghana's transitional zones. While the potential of bamboo as livestock fodder has been studied in other regions, particularly in Asia (Asaolu et al., 2009), there is limited research on its application within the Ghanaian context. The few studies on bamboo as livestock fodder, including those by Antwi-Boasiko et al. (2011), Sasu et al. (2023), and Antwi et al. (2023) highlight the urgent need for further research into its practical applications in Ghana transitional forest zones. Additionally, socio-economic and cultural barriers to bamboo adoption by farmers in these zones remain poorly understood, further highlighting the need for a comprehensive study on its potential as a climate-smart livestock feed.

Therefore, we aimed to assess the nutritional benefits of bamboo leaves by evaluating their protein, fibre, mineral content, total antioxidant capacity, nutrient digestibility and blood profile for livestock feed suitability. We also sought to examine their greenhouse gas reduction potential for climate-smart livestock farming, while investigating the drivers and barriers to their widespread adoption as viable fodder in Ghana's agroecosystems.

2. Materials and methods

2.1. Experimental design and study locations

This study utilised a four-phased experimental design to evaluate bamboo leaves as livestock fodder in Ghana, integrating nutritional assessments with a community-based survey to explore adoption drivers. The study commenced with Phase 1, which focused on nutritional evaluations, including chemical composition and bioactive compound analyses. Phase 2 involved *in vitro* rumen fermentation while Phase 3 assessed *in vivo* nutrient digestibility and health parameter trials. These phases were conducted from mid-April to mid-July 2023 at the Livestock Section of the Department of Animal Science, Kwame Nkrumah University of Science and Technology (KNUST), located in Ghana's semi-deciduous humid forest zone. The study area features a bimodal rainfall pattern (1300 mm annually), daily temperatures ranging from 20 °C to 35 °C (average 26 °C), and relative humidity fluctuating between 67 % and 97 % (unpublished meteorological data, Department of Animal Science, KNUST, 2024)

Phase 4 involved a field survey conducted in the Ejura-Sekyeredumase District of the Ashanti Region, Ghana (Fig. 1), from August to September 2023, assessing the adoption potential of bamboo leaves as livestock feed. The study area falls within the transitional forest zone of Ghana, characterised by mixed savannah and forest vegetation. This ethnically diverse region spans 1327 km^2 and experiences a bimodal rainfall pattern (1200–1500 mm annually) with alternating wet and dry seasons. Smallholder farmers dominate the economy, cultivating staple crops such as maize, cassava and millet alongside cash crops such as cashews, mangoes and teak. Livestock production includes cattle, goats, sheep, chickens and non-traditional livestock such as bees and grasscutters (cane rats), typically managed under semi-intensive systems (Duku et al., 2010). The district's diverse agricultural activities and conducive environment for plant growth highlight its relevance to evaluating bamboo's potential as an accessible and sustainable feed resource.

2.2. Experimental phase 1

2.2.1. Sources of plant species and leaf sampling procedure

Fresh leaves from *Oxytenanthera abyssinica* (A.Rich.) Munro, *Bambusa vulgaris* Schrad. ex J.C.Wendl., *Cenchrus purpureus* (Schumach.) Morrone and *Bridelia ferruginea* Benth. were collected from naturally growing stands within a 1-km radius of the KNUST Botanical Garden, situated near the study area. The garden, located in Ghana's transitional ecological zone, features a mix of savannah and forest vegetation, which supports the growth of a diverse range of plant species, including those selected for this study. Two bamboo species, *Oxytenanthera abyssinica* (Lowland bamboo) and *Bambusa vulgaris* (Golden bamboo) were selected alongside *Cenchrus purpureus* (Napier grass), and *Bridelia ferruginea* (a multipurpose tree, MPT) due to their adaptability, prevalence in most agroecosystems of Ghana, and significance as cost-effective feed resources for smallholder livestock farmers. The bamboo species were chosen for their ecological and socio-economic value in tropical and subtropical climates (Philips, 1995; Kumar et al., 2012), while *Cenchrus purpureus*, a vital tropical grass forage in cut-and-carry systems (Farrell et al., 2002), and *Bridelia ferruginea*, a fodder plant with pharmacological and traditional medicinal properties (Adebayo and Ishola, 2009; Ngueyem et al., 2009) added diversity to the evaluation. The bamboo leaves were harvested at their optimal growth stage, as determined by their physical characteristics, including the size and number of culms, the presence of mature branches, and the thickness of the culms. The *Cenchrus purpureus* and *B. ferruginea* were sampled during their vegetative growth stage, identifiable by their healthy and fully developed leaves. A mixed sampling approach was employed to capture the variation in the plant species. For the bamboos and *B. ferruginea*, line-intercept sampling was utilised. A 100 m transect line was

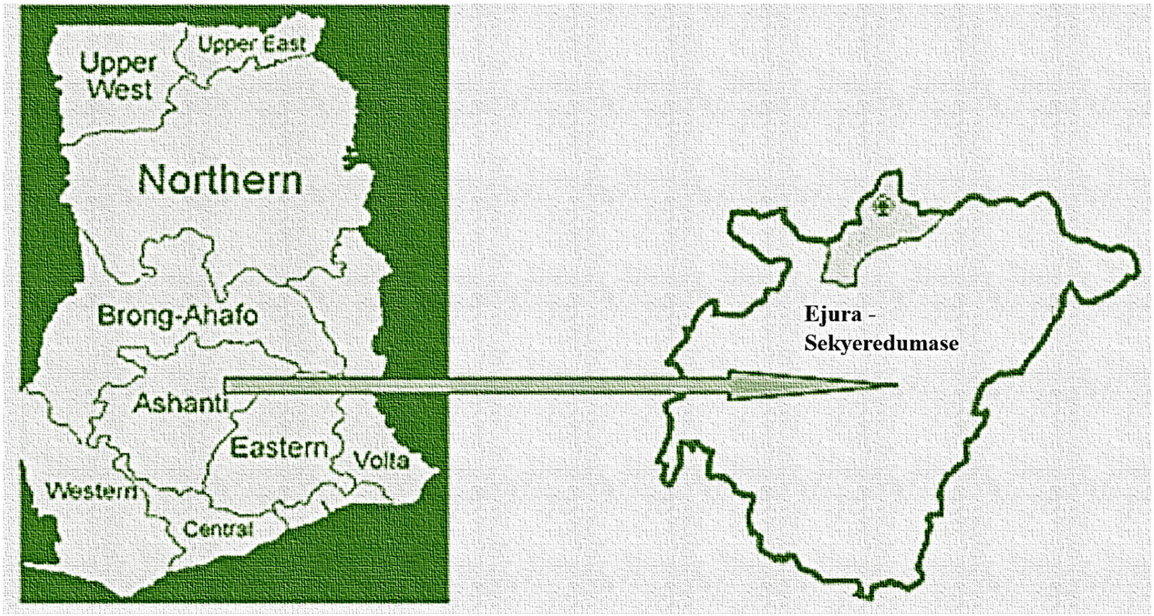

Fig. 1. Ejura-Sekyedumase district of the Ashanti region of Ghana.

randomly laid across the field, and plants that intersected the line at regular intervals were selected for leaf collection. This procedure was repeated at three different locations to ensure a representative sample and account for environmental variations. For *C. purpureus*, a quadrant sampling method was used. A 10 m × 10 m quadrant was established in three distinct locations on the field. Within each quadrant, the grasses were randomly selected while avoiding visibly over-matured or damaged parts. The selected grasses were cut, and their leaves were carefully plucked to minimise disturbance. All harvested leaves were carefully bulked into separate containers by species to prevent cross-contamination. The selected plant species used in this study are illustrated in Fig. 2.

2.2.2. Leaf sample processing and laboratory analyses

To prepare the plant samples for nutritional analysis, freshly harvested leaves were initially chopped into smaller pieces using a chaff cutter[1] to facilitate uniform drying. Triplicate samples for each plant species were prepared separately from the three sampling locations, ensuring statistical replicability. In the Nutritional Laboratory at the Department of Animal Science, KNUST, the samples underwent a two-step drying process. First, they were air-dried at room temperature for 24 hours to reduce surface moisture. Subsequently, the air-dried samples were oven-dried at 60 °C for 48 hours to achieve a constant weight. This method ensured that the samples were adequately dried while minimising the loss of bioactive compounds sensitive to higher temperatures. Once dried, the samples were coarsely milled using a laboratory mill (Wiley Mill[2]) equipped with a 2 mm mesh screen. The ground samples were then carefully transferred into labelled Ziploc bags to prevent contamination and preserve their integrity during storage. These prepared samples were used for subsequent nutritional and bioactive compound analyses. Fig. 3 illustrates a schematic flow chart of the entire sample preparation process, including harvesting, chopping, drying, milling and packaging for laboratory analyses. The chemical composition of the leaf samples was determined using standard analytical protocols. The proximate composition, including dry matter (DM), crude protein (CP = N × 6.25), ether extract (EE), crude fibre (CF) and ash, was analysed according to the methods described by the Association of Official Analytical Chemists (AOAC, 1990). Fibre fractions including neutral detergent fibre (NDF), acid detergent fibre (ADF), acid detergent lignin (ADL), cellulose (CEL) and hemicellulose (HEM), were quantified using an ANKOM 2000 Automated Fibre Analyzer,[3] following the procedures of Van Soest et al. (1991). Mineral content was analysed using a combination of established methods to determine the concentrations of phosphorus (P), calcium (Ca), potassium (K), magnesium (Mg), iron (Fe), copper (Cu) and manganese (Mn). The methods included protocols described by Motsa et al. (2005), and Lee and Campbell (1969). Phytochemical analyses encompassed both qualitative and quantitative assessments. For qualitative screening, seven bioactive compounds were identified: tannins, saponins, glycosides, flavonoids, alkaloids, triterpenoids and phytosteroids. Quantitative assessments involved the determination of six specific compounds, including tannins, saponins, oxalates, phenolics, flavonoids, and total antioxidants. These analyses were conducted using the milled leaf samples, applying methodologies outlined by Chapman (1980), Banerjee (1957), Lolas and Markakis (1975) and Alavi and West (1983).

2.3. Experimental phase 2

2.3.1. In vitro gas production

An *in vitro* gas production (IVGP) study was conducted to evaluate the fermentative characteristics of bamboo leaves (*O. abyssinica* and *B. vulgaris*) and their potential to mitigate greenhouse gas emissions. The experiment was conducted over three incubation periods (12, 24, and 48 hours) and repeated in two independent runs. For each treatment, 200 mg of the bamboo leaves were mixed with a basal diet of *C. purpureus* and *B. ferruginea* (1:1 ratio) and incubated in calibrated glass syringes containing 40 mL of a rumen liquor-buffer mixture (1:4 ratio). Each treatment was replicated three times per incubation period, amounting to nine samples per treatment in each run. A control treatment, comprising the basal diet without bamboo supplementation, was included for comparison. This setup ensured adequate replication and

[1] High Speed Motor Operated Chaff Cutter: SAMYAK AGRO INDUSTRIES, PUNJAB: Made in India.

[2] The Thomas ® Model 4 Wiley Mill. Made in the USA. Marketed and distributed by Onrion LLC. 93 South Railroad Avenue, STE C Bergenfield, 07621–2352, New Jersey, USA.

[3] The ANKOM 2000 Automated Fiber Analyzer. Made in USA. Marketed and distributed by ANKOM Technology, Macedon NY 14502, 2052 O'Neil Road.

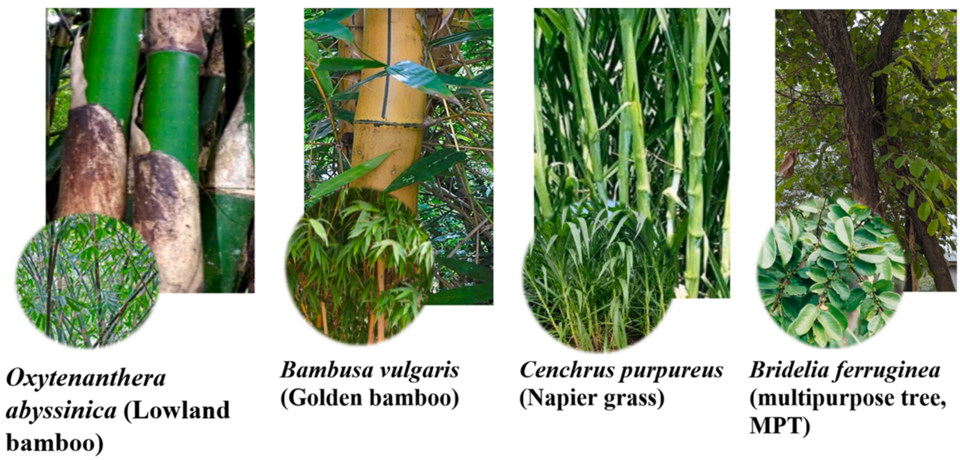

Fig. 2. Plant species selected for the study.

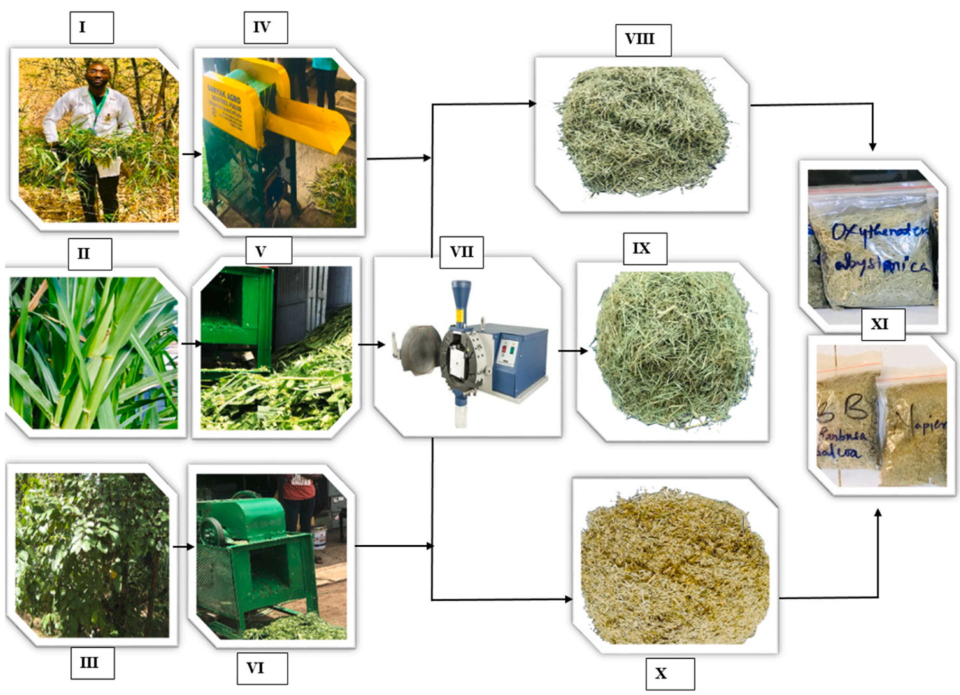

Fig. 3. Schematic representation of leaf harvesting and sample processing for nutritional analyses. Key: I: Bamboo leaves at harvesting stage, II: Cenchrus purpureus at harvesting stage, III: *Bridelia ferruginea* leaves at harvesting stage, IV: Bamboo leaves at chopping stage, V: *Cenchrus purpureus* at chopping stage, VI: *B. ferruginea* leaves at chopping stage, VII: Wiley milling and oven drying of leaf samples, VIII: Milled bamboo samples, IX: Milled *C. purpureus* samples, X: Milled *B. ferruginea* samples, XI: Packaged feed samples prepared for nutritional and biochemical analyses.

statistical evaluation. The rumen liquor was sourced from ten male West African Dwarf goats (mean weight: 29 kg, age: 1.5 years) slaughtered at the Kumasi Abattoir Company Limited, Ghana. Rumen digesta was collected immediately after slaughter, placed in pre-warmed vacuum flasks, and brought to the laboratory, where it was strained through four layers of cheesecloth under continuous carbon dioxide flushing to maintain anaerobic conditions. Incubations were conducted in a water bath at 39 °C for 12, 24 and 48 hours, with gas production measured at each time point. Volatile fatty acids (VFAs: acetate, propionate and butyrate) were quantified to evaluate energy-yielding potential, while methane emissions were measured to assess greenhouse gas mitigation potential. Additionally, the pH of the rumen liquor was recorded before and after incubation. All analyses followed the standard protocols of Menke et al. (1979), Krishnamoorthy et al. (1995), Anderson and Yang (1992) and De Haas and Adam (1995).

2.4. Experimental phase 3

2.4.1. In vivo nutrient digestibility trial and blood profiling

The two bamboo species (*O. abyssinica* and *B. vulgaris*) were integrated into diets comprising a grass-tree leaf mix (*Cenchrus purpureus* and *Bridelia ferruginea*) to assess their effects on *in vivo* apparent nutrient digestibility, nitrogen balance and the blood profiles of goats. The metabolic trial was conducted using 15 male goats, aged 7 months, with 5 goats per treatment group serving as replicates. The control group was fed a basal diet composed of *C. purpureus* and *B. ferruginea* mixed in a 1:1 ratio without any supplementation. The experimental groups included the basal mix supplemented with either 400 g of *O. abyssinica* leaves or 400 g of *B. vulgaris* leaves. Each goat was housed individually in metabolic crates equipped for collecting urine and faecal samples, which were immediately refrigerated to preserve them for chemical analysis.

Before the trial, the goats were ear-tagged, dewormed vaccinated against peste des petits ruminants (PPR), and given multivitamin injections every 21 days during the 60-day study. Goats were provided continuous access to feed, water and a mineral salt lick containing 38.05 % sodium chloride. At the end of the trial, refrigerated faecal samples were pooled by the treatment group, and 10 % subsamples, along with feed samples, were prepared for analysis at the Crop and Soil Science Laboratory, Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ghana. Nutritional parameters analysed included dry matter, crude protein, crude fibre, ether extract, ash, neutral detergent fibre and acid detergent fibre to assess apparent nutrient digestibility and nitrogen balance.

At the end of the digestibility trial, 5 mL of blood was drawn from the jugular vein of each goat at 07:00 AM before the morning feeding. The samples were divided into EDTA-coated tubes for haematological analysis and plain tubes for serum metabolite analysis (Ansah, 2015). The tubes were gently mixed for one minute to ensure proper preservation. Blood samples in plain tubes were centrifuged at 3000 rpm for 15 minutes to separate the serum, which was then transferred to clean tubes and stored at 4 °C (Blood et al., 1979). Haematological parameters were analysed using a Dymind DH36 3-part Auto Haematology Analyzer,[4] while serum metabolite analysis was performed using a BT 3000 Random Access Chemistry Analyzer[5] with methods adapted from Gornall et al. (1949) and Doumas et al. (1971). Haematological indices such as red blood cell count (RBC), haemoglobin (HB), and haematocrit (HCT) were evaluated to assess oxygen transport and overall blood health. Mean corpuscular volume (MCV), mean corpuscular haemoglobin (MCH) and mean corpuscular haemoglobin concentration (MCHC) were calculated to diagnose anaemia types, while white blood cell (WBC) counts served as indicators of immune response (Blood et al., 1979). Serum analysis included the determination of total protein, albumin and globulin concentrations using biuret and bromocresol green dye-binding methods. Kidney function was assessed by quantifying urea through enzymatic methods and creatinine using the Jaffe reaction. Liver function markers, including alkaline phosphatase (ALP), alanine aminotransferase (ALT) and gamma-glutamyl transferase (GGT), were measured spectrophotometrically. Glucose concentrations were determined enzymatically, and cholesterol levels were quantified using the cholesterol oxidase-peroxidase method. All analyses adhered to reference values established by Blood et al. (1979), Olafadehan (2011), and modifications from Ansah (2015).

2.5. Experimental phase 4

2.5.1. Adoption potential of bamboo leaves among livestock-rearing communities

In phase 4, a structured questionnaire, designed with input from five key informants in the study area, gathered insights on agricultural practices, land tenure systems, gender-related issues, and the ethnic, religious and socio-economic dynamics of the communities. Snowball sampling was used, starting with extension agents familiar with the local context, who identified other informants keen to share their expertise. The survey was administered in Kasei and Kobriti, purposefully selected for their location in the transitional zone, accessibility and prevalence of small ruminant-rearing households.

The study targeted 150 farmers initially identified through key informants in the study area. However, only 31 farmers were selected for data collection based on specific inclusion criteria. Farmers with flock sizes below 20 were excluded from the study, as this number was considered below the threshold for small-scale farming. The final sample comprised 31 respondents who met the criteria, allowing the study to focus on farming operations with sufficient livestock numbers to provide meaningful data. Semi-structured questionnaires were administered to these respondents to gather information on demographics, farming practices, characteristics and perceptions of feeding bamboo leaves to livestock, including its recognition, community applications and opinions on the challenges of feeding to animals. Further, the survey allowed the respondents to rate the significance of these factors in their fodder choices, revealing knowledge gaps and highlighting the need for more information to support bamboo leaf adoption as livestock feed.

2.6. Ethical considerations

This study adhered to the Animal Research Ethics Committee (AREC) Standard Operating Procedures, ensuring compliance with national and international animal welfare guidelines. All animals involved were treated with the utmost care to minimise stress and suffering. In addition, the rights and privacy of research participants were prioritised through informed consent and confidentiality measures. Data storage protocols were securely implemented to protect participant information. Each participant was fully informed about the study's objectives, methods, potential risks and benefits before consenting, with the right to withdraw at any time. These ethical practices, guided by the Humanities and Social Sciences Research Ethics Committee (HuSSREC) at KNUST, upheld both research integrity and participant well-being.

2.7. Statistical analytical procedures

The statistical analysis was conducted systematically and thoroughly, starting with rigorous data cleaning and preparation to ensure the integrity and consistency of the datasets. For the nutritional data, a one-way ANOVA was employed to examine differences in key parameters such as chemical and biochemical constituents, nutrient digestibility, nitrogen balance, blood metabolites, *in vitro* gas production and methane emission. The data followed a completely randomized design (CRD), with different forages as the treatments and sample locations as replicates. The analysis was carried out using the Generalised Linear Model (GLM) procedure in Minitab Statistical Software, with significant treatment effects determined by Tukey's pairwise comparison at a 5 % significance level ($p < 0.05$). In parallel, the adoption potential of bamboo leaves as livestock fodder was examined using descriptive statistical techniques. The demographic and socio-economic characteristics of the livestock farmers, such as age, gender, years of farming experience, herd sizes and farming practices, were assessed through frequency distributions and percentages. These measures provided an in-depth understanding of the farmer profiles and their perspectives on the use of bamboo leaves. Furthermore, categorical variables related to perceptions of bamboo use including cultural, economic and environmental factors were analysed using frequencies and percentages, allowing for a detailed view of farmers' knowledge gaps, cultural beliefs and the potential barriers to adoption. This descriptive approach, supported by data visualisation generated through GraphPad Statistical Software, offered a comprehensive overview of the data, revealing the underlying trends, challenges and opportunities for bamboo leaf adoption in livestock feeding systems.

3. Results and discussion

3.1. Analytical proximate compositions of bamboo leaf samples

The proximate composition analysis of bamboo leaf (BL) samples in this study (Table 1) reveals a similar nutritional profile across the two species, *Oxytenanthera abyssinica* (OA) and *Bambusa vulgaris* (BV), with minimal significant differences in most parameters. The moisture content ranged between 8.0 % and 8.3 %, while the dry matter (DM) content was high, spanning 91.7–92.0 %. These findings align with previous

[4] Dymind DH36 3-part Auto Haematology Analyzer: JHB Medical, Shenzhen City, China.

[5] BT 3000 Random Access Chemistry Analyzer: JHB Medical, Shenzhen City, China.

Table 1
Analytical proximate constituents of bamboo leaf samples.

Bamboo Species	Composition (% of DM)					
	Moisture	Dry matter	Crude protein	Crude fibre	Crude fat	Ash
O. abyssinica	8.28	91.72	12.54	28.90	6.90	12.44[a]
B. vulgaris	8.00	92.00	14.52	26.33	5.32	10.96[b]
SEM	0.413	0.414	0.803	1.02	0.381	0.506
P-value	0.118	0.119	0.152	0.154	0.202	0.005

Within the column, parameters with similar superscripts (a, b, c) are not significantly different ($p > 0.05$). SEM = standard error of means.

studies by Antwi-Boasiako et al. (2011), which noted similar DM content in various bamboo species, reinforcing the consistency of bamboo leaves as a high-DM fodder source. Dry matter is a key determinant of forage quality, as it is directly linked to the availability of nutrients; therefore, the high DM content of BL suggests their potential as a valuable feed resource, especially during periods when conventional forages may lose nutritional value, such as in dry seasons (Babayemi Adebayo, 2020).

The crude protein (CP) contents of the BL ranged from 12.5 % to 14.5 %, which is notably higher than those typically found in commonly grazed pasture grasses, particularly in the dry season when grasses can contain as little as 4 % CP (Sasu et., 2023). This aligns with Bhandari et al. (2015), who reported CP values between 8 % and 17 % in bamboo leaves, supporting the argument that BL offers a superior protein source for ruminants. Furthermore, the CP content in our study exceeded the 7 % minimum required for optimal ruminant intake and growth as reported by Nori et al. (2009) and Njidda (2010), highlighting their nutritional value. Crude protein is crucial for ruminant growth, and the higher protein content in BL could help mitigate protein deficiencies during seasons when other forages are less nutritious. In comparison, crop residues like rice straw, which typically contain around 5 % CP and 35 % crude fibre (Babayemi et al., 2020), are much lower in protein and thus less capable of supporting optimal growth and productivity in ruminants, showing that BL can provide a more suitable alternative, particularly during protein-deficient dry seasons.

The crude fibre (CF) content of bamboo leaves in this study ranged from 26.3 % to 28.9 %, which is lower than the 30 % typically observed in pasture grasses (Anele et al., 2008). This lower fibre content can be beneficial for rumen fermentation, as it is more easily degraded by rumen microorganisms, facilitating better nutrient absorption and improving feed efficiency (Li et al., 2021). The reduced fibre content also makes BL more digestible than many conventional forages, contributing to higher intake and potentially better overall animal performance. Additionally, the relatively low lignin content in bamboo leaves, as compared to some other forages, can further enhance enzymatic degradation in the rumen, aiding in the breakdown of plant cell walls and improving digestibility (Bhardwaj et al., 2018).

The ash content, a critical indicator of the mineral profile of the plant, varied between 10.9 % and 12.4 %, with *B. vulgaris* having a lower ash content than *O. abyssinica*. While both species exceed the 10 % threshold for ideal ash content as suggested by Bhandari et al. (2015), this difference in ash content could have implications for the mineral composition of the leaves, which may influence their suitability for specific ruminant nutritional needs. Higher ash content generally indicates a higher crude mineral content, but the impact of this difference on animal health and productivity would need further investigation.

3.2. Analytical fibre fractions of bamboo leaf samples

The fibre fractions of bamboo leaves, as presented in Table 2, show that the majority of fibre components, including neutral detergent fibre (NDF), acid detergent fibre (ADF), hemicellulose (HEM) and cellulose (CELL), did not exhibit significant differences ($p > 0.05$) between the two bamboo species. However, a notable difference was observed in the acid detergent lignin (ADL) content ($p < 0.05$), with *B. vulgaris* having a significantly higher ADL content (4.3 %) compared to *O. abyssinica* (1.8 %).

Table 2
Analytical fibre fractions of bamboo leaf samples.

Bamboo Species	Composition (% of DM)				
	NDF	ADF	ADL	HEM	CELL
O. abyssinica	54.76	32.66	1.78[b]	22.10	30.88
B. vulgaris	58.76	37.32	4.25[a]	21.44	33.07
SEM	1.140	1.380	0.464	2.150	1.630
P-value	0.375	0.053	0.015	0.046	0.047

Within the column, parameters with similar superscripts (a, b, c) are not significantly different ($p > 0.05$). SEM = standard error of means. NDF =neutral detergent fibre; ADF =acid detergent fibre; ADL=acid detergent lignin; HEM =hemicellulose; CEL= cellulose.

The NDF content, which ranged from 54.8 % to 58.8 %, represents the total cell wall material in the leaves, including cellulose, hemicellulose, and lignin. This range of NDF content suggests that both species have a significant amount of fibre in their structure, which plays a key role in the feed intake and digestibility of bamboo leaves by ruminants. The ADF content, ranging from 32.7 % to 37.3 %, indicates the portion of the cell wall that is less digestible, composed primarily of cellulose and lignin. These values are within typical ranges for forage, highlighting the relatively high cell wall content of bamboo leaves. The similarity in NDF and ADF values across species suggests that bamboo leaves, irrespective of the species, offer a similar degree of rumen fermentation potential, which is crucial for digestibility and nutrient absorption in ruminants.

The HEM content, ranging from 20.4 % to 22.1 %, reflects the hemicellulose content, which is considered a less fibrous fraction that can be more readily fermented by rumen microorganisms. This, along with the cellulose (CELL) content ranging from 30.9 % to 33.4 %, indicates that bamboo leaves have a balanced mix of fermentable and less fermentable components, making them suitable for inclusion in ruminant diets. The presence of cellulose contributes to the structural integrity of the plant, but its digestibility in ruminants may be slower compared to more readily available carbohydrates.

The higher ADL content in *B. vulgaris* compared to *O. abyssinica* suggests a greater presence of lignin, which is more resistant to microbial degradation. Lignin can lower the overall digestibility of the plant material, making *B. vulgaris* potentially less efficient as a feed source compared to *O. abyssinica*. Lignin's role in the plant's rigidity and resistance to breakdown could therefore influence the intake and digestibility rates in ruminants (Kononott, 2005). The fibre fractions of bamboo leaves observed in this study are comparable to those found in other commonly used fodder plants, such as *Amaranthus viridis* L., *Chenopodiastrum murale* (L.) S.Fuentes, Uotila & Borsch (syn. *Chenopodium murale* L.), *Nasturtium officinale* W.T.Aiton and *Scandix pecten-veneris* L., as reported by Imran et al. (2010). These similarities in fibre composition suggest that bamboo leaves, like other well-established fodder plants, have the potential to serve as a valuable feed resource for ruminants, offering a comparable nutritional profile in terms of their fibre content. This reinforces the suitability of bamboo leaves for livestock feeding, especially in regions where other types of forage may be less available or of lower quality.

3.3. Analytical mineral compositions of bamboo leaf samples

Table 3 shows the analytical mineral composition of bamboo leaves from *Oxytenanthera abyssinica* and *Bambusa vulgaris*. Significant differences ($p < 0.05$) in the mineral content were observed between the species. Phosphorus (P) content was higher in *B. vulgaris* (0.18 %) than in *O. abyssinica* (0.12 %), suggesting that *B. vulgaris* could be a better source of phosphorus for ruminant diets, supporting bone health and

Table 3
Analytical mineral compositions of bamboo sample.

Bamboo Species	P (%)	Ca (%)	K (%)	Mg (%)	Fe (mg/kg)	Cu (mg/kg)	Mn (mg/kg)
O. abyssinica	0.12[b]	0.48[a]	2.09[b]	0.15[a]	38.23[b]	14.93[b]	11.69[b]
B. vulgaris	0.18[a]	0.25[b]	2.31[a]	0.07[b]	65.63a	20.49[a]	12.85[a]
SEM	0.011	0.036	0.038	0.012	5.720	1.040	0.290
P-value	0.002	< 0.001	< 0.001	0.008	< 0.001	< 0.001	0.003

Means along a column with different superscripts (a, b, c) differed significantly ($p < 0.05$). SEM= standard error of the mean.

metabolic processes. The calcium (Ca) content was significantly higher in *O. abyssinica* (0.48 %) than in *B. vulgaris* (0.25 %). This higher calcium content in *O. abyssinica* could be beneficial for supporting bone formation and physiological functions, in line with previous studies by Singh (1999) who reported higher calcium levels in bamboo leaves. Potassium (K) content was highest in *B. vulgaris* (2.31 %), followed by *O. abyssinica* (2.09 %), supporting muscle function and electrolyte balance in livestock. Magnesium (Mg) content was higher in *O. abyssinica* (0.15 %) than in *B. vulgaris* (0.07 %), indicating that *O. abyssinica* may be a more suitable source of magnesium for enzyme activity and metabolic functions, as supported by Asaolu et al. (2009). The iron (Fe) content was highest in *B. vulgaris* (65.6 mg/kg), followed by *O. abyssinica* (38.2 mg/kg). This higher iron content in *B. vulgaris* is important for blood formation and oxygen transport, aligning with Singh (1999), who noted that bamboo leaves are a good source of iron. The copper (Cu) content was highest in *B. vulgaris* (20.5 mg/kg), while *O. abyssinica* had the lowest copper content (14.9 mg/kg). Copper is crucial for enzymatic functions and overall health. Similarly, manganese (Mn) content was higher in *B. vulgaris* (12.9 mg/kg) than in *O. abyssinica* (11.7 mg/kg), meeting trace mineral requirements for enzymatic functions and antioxidant defence, comparable to values reported in *Senna siamea* (Lam.) H.S.Irwin & Barneby (syn. *Cassia siamea* Lam.) leaves (Smith, 2009).

3.4. Analytical bioactive compositions of bamboo leaf samples

Table 4 summarises the qualitative biochemical constituents of *O. abyssinica* and *B. vulgaris O. abyssinica* had a high presence of saponins, flavonoids, alkaloids and triterpenoids, with glycosides and phytosteroids also present, but lacking tannins. In contrast, *B. vulgaris* exhibited a high presence of tannins, saponins, glycosides and alkaloids, with phytosteroids present but no flavonoids or triterpenoids. These differences in biochemical profiles highlight the distinct physiological effects and potential applications of each species in livestock nutrition. The presence of bioactive compounds such as saponins, alkaloids and phytosteroids in both species suggests that they may offer various health benefits to livestock. Specifically, saponins are well known for their ability to improve digestion and reduce cholesterol levels (Rashmi and Negi, 2020), while alkaloids can have antimicrobial properties, and phytosteroids may support immune function and stress resilience.

Table 5 further presents the quantitative analytical constituents of bamboo leaves from *O. abyssinica* and *B. vulgaris*. The tannin content was significantly higher in *B. vulgaris* (0.003 %) compared to *O. abyssinica* (0.001 %), indicating a marked difference in this compound between the two species. Similarly, the saponin content was higher in *B. vulgaris* (0.28 %) than in *O. abyssinica* (0.24 %). However, *O. abyssinica* contained the highest oxalate content (0.015 %), while *B. vulgaris* had the lowest (0.012 %), suggesting that *O. abyssinica* may have a higher potential to impact mineral absorption in livestock. Additionally, the phenolic content was higher in *B. vulgaris* (22.0 mg/l) compared to *O. abyssinica* (19.6 mg/l), with *O. abyssinica* having a significantly lower flavonoid content (0.885 mg/l) and *B. vulgaris* showing no flavonoids. Interestingly, total antioxidant capacity was highest in *B. vulgaris* (96.8 %), compared to *O. abyssinica* (92.1 %), suggesting that *B. vulgaris* may provide stronger antioxidant properties.

Our findings are consistent with existing reports that bamboo leaves contain various bioactive compounds, such as flavonoids and phenolic acids, known for their antioxidant, antimicrobial, immunoregulatory, anti-allergenic, anti-atherogenic and cardioprotective properties (Rashmi and Negi, 2020). Fitri et al. (2020) and Tripathi et al. (2015) have previously highlighted the significant antioxidant properties of bamboo leaves, which are critical for alleviating oxidative stress in high-production ruminants and enhancing their immune function, reducing inflammation, and improving overall animal health and performance (Hu et al., 2000). Overall, these bioactive compounds in both bamboo species could offer valuable nutritional and therapeutic benefits for livestock, as suggested by Kweon et al. (2001).

However, the differences in the biochemical compositions of the two bamboo species could influence their suitability for various livestock applications. While *O. abyssinica* lacks tannins and has a higher presence of flavonoids and triterpenoids, *B. vulgaris* contains higher levels of tannins and glycosides. These variations suggest that each species may offer distinct therapeutic effects. For instance, the higher tannin content in *B. vulgaris* could contribute to its potential as a more effective antimicrobial agent, while the higher flavonoid content in *O. abyssinica* might provide stronger antioxidant benefits. Therefore, while both bamboo species show promising bioactive profiles, the specific biochemical differences may influence their suitability for different livestock purposes, including improving digestion, reducing inflammation, and enhancing immune function.

3.5. In vitro fermentation profile and greenhouse gas emission reduction in bamboo leaf supplementation

The fermentation profile of bamboo leaves as substrates within a grass-tree-leaf mixture revealed significant benefits in enhancing rumen fermentation efficiency and mitigating greenhouse gas emissions. As presented in Table 6, supplementation with *O. abyssinica* (OA+Mix) and *B. vulgaris* (BV+Bmix) resulted in notable increases ($p < 0.05$) in the pH of the incubation medium, total gas production and volatile fatty acids (VFAs). These findings highlight bamboo's buffering capacity, which is essential for maintaining an optimal rumen environment. For example, the pH values for OA+Bmx and BV+Bmix reached 7.01 and 7.09 at 12 hours compared to 5.33 in the control group, reflecting an enhanced buffering effect. Similarly, total gas production for OA+Bmix peaked at 155.1 mL/200 mg DM at 48 hours, surpassing the control's 145.2 mL. The increased VFA levels in bamboo-supplemented groups, 89.6 mmol/

Table 4
Qualitative analytical constituents of bamboo samples.

Bamboo Species	Tannins	Saponins	Glycoside	Flavonoids	Alkanoids	Triterpenoids	Phytosteroids
O. abyssinica	-	+ +	+	+ +	+ +	+ +	+
B. vulgaris	+ +	+ +	+ +	-	+ +	-	+

Legend: '+ ' = present; '+ +' = highly present; '-' = absent.

Table 5
Quantitative analytical constituents of bamboo samples.

*Bamboo Species	Tannins (%)	Saponins (%)	Oxalates (%)	Phenolics (mg/l)	Flavonoids (mg/l)	Antioxidants (%)
O. abyssinica	0.001[b]	0.240[b]	0.015[a]	19.64	0.885[a]	92.13
B. vulgaris	0.003[a]	0.280[a]	0.012[b]	22.03	0.000[b]	96.84
SEM	0.0003	0.0056	0.0004	1.650	1.230	1.300
P-value	< 0.001	< 0.001	< 0.001	0.132	0.001	0.083

Means along a column with different superscripts (a, b, c) differed significantly ($p < 0.05$). SEM= standard error of means

Table 6
In vitro fermentation profile of bamboo leaf-supplemented diets and pH of the incubation medium.

Incubation Time (h)	CONT	OA+Bmix	B.V+Bmix	SEM	P-value
pH of incubation medium					
12	5.33[b]	7.01[a]	7.09[a]	0.013	< 0.0001
24	5.23[b]	6.56[a]	6.51[a]	0.034	0.0004
48	5.20[b]	6.50[a]	6.49[a]	0.012	0.0317
Total gas (mL/200mgDM)					
12	81.01[c]	89.0[a]	84.4[b]	0.003	< 0.001
24	118.1[b]	125.0[a]	124.0[a]	1.217	0.003
48	145.2[c]	155.1[a]	150.0[b]	1.880	0.015
Total Volatile fatty acid production (mmol/100 g)					
12	53.90[b]	61.22[a]	60.22[a]	0.322	0.009
24	72.54[c]	81.55[a]	77.09[b]	0.543	0.001
48	76.11[c]	89.61[a]	82.72[b]	1.104	0.045
Lactic acid (mmol/100 g)					
12	5.00[b]	7.23[a]	7.21[a]	0.010	0.001
24	6.54[c]	9.25[a]	7.09[b]	0.045	0.002
48	7.11[c]	11.31[a]	9.72[b]	1.104	0.015
	Acetate (mmol/100 g)				
12	32.00[c]	40.00[a]	38.21[b]	0.011	0.001
24	37.54[c]	49.20[a]	40.01[b]	0.097	0.007
48	41.11[c]	51.21[a]	45.72[b]	0.104	0.004
Propionate (mmol/100 g)					
12	12.10[c]	18.28[a]	16.21[b]	0.071	0.002
24	17.21[b]	19.12[a]	18.01[b]	0.081	0.038
48	19.20[c]	25.11[a]	21.72[b]	0.202	0.001
Valerate (mmol/100 g)					
12	12.10[c]	18.28[a]	16.21[b]	0.071	0.002
24	17.21[b]	19.12[a]	18.01[b]	0.081	0.038
48	19.20[c]	25.11[a]	21.72[b]	0.202	0.001
Short-chain fatty acid (mmol/100 g)					
12	0.22[b]	0.33[a]	0.21[b]	0.011	0.021
24	0.27[c]	0.39[a]	0.34[b]	0.012	0.011
48	0.30[c]	0.42[a]	0.37[b]	0.110	0.031

Mean values on the same row with different superscripts (a, b, c) are significantly ($p < 0.05$) different. SEM = standard error of means.
Abbreviations: CONT = Control consisting of a mixture of *Cenchrus purpureus* and *Bridelia ferruginea* leaf meal; O.A+Bmix = *Oxytenanthera abyssinica* plus a mixture of *Cenchrus purpureus* and *Bridelia ferruginea* leaf meal; B.V+Bmix = *Bambusa vulgaris* leaf plus a mixture of *Cenchrus purpureus* and *Bridelia ferruginea* leaf meal.

100 g for OA+Mix at 48 hours, demonstrate improved microbial fermentation and energy availability for ruminants.

A key observation is the significant ($p < 0.05$) reduction in greenhouse gas emissions (Table 7). Methane and carbon dioxide production declined markedly in bamboo-supplemented groups, with OA+Bmix producing the least methane (14.1 mL/200 mg DM at 48 hours) compared to the control's 24.3 mL. This reduction aligns with earlier studies, such as Jo et al. (2022), that also reported decreased methane emissions and improved fermentation efficiency with bamboo supplementation. The lower emissions are likely attributable to bamboo's bioactive compounds, which may inhibit methanogenic archaea and promote efficient fermentation pathways. The reduction in carbon dioxide production, which fell from 84.2 mL in the control to 69.0 mL in OA+Mix at 48 hours, further shows bamboo's potential for mitigating greenhouse gas environmental impacts.

Increased pH, VFAs and short-chain fatty acids (SCFAs) across incubation times suggest enhanced microbial activity and fermentation

Table 7
Greenhouse gas emission potential of bamboo leaf-supplemented diets.

Incubation Time (h)	CONT	OA+Bmix	B.V+Bmix	SEM	P-value
Methane (mL/200mgDM)					
12	9.00[a]	4.97[c]	6.04[b]	0.106	0.002
24	14.12[a]	9.35[c]	10.14[b]	1.211	0.041
48	24.30[a]	14.05[c]	17.10[b]	1.230	0.001
Carbon dioxide (mL/200mgDM)					
12	31.01[a]	15.51[c]	27.12[b]	0.206	0.001
24	51.16[a]	37.42[c]	48.13[b]	1.111	0.002
48	84.22[a]	69.01[c]	71.10[b]	1.320	< 0.001

Mean values on the same row with different superscripts (a, b, c) are significantly ($p < 0.05$) different. SEM = standard error of means.
Abbreviations: CONT = Control consisting of a mixture of *Cenchrus purpureus* and *Bridelia ferruginea* leaf meal; O.A+Bmix = *Oxytenanthera abyssinica* plus a mixture of *Cenchrus purpureus* and *Bridelia ferruginea* leaf meal; B.V+Bmix = *Bambusa vulgaris* leaf plus a mixture of *Cenchrus purpureus* and *Bridelia ferruginea* leaf meal.

efficiency with bamboo supplementation. Notably, higher acetate and valerate levels were observed in OA+Mix and BV+Mix, providing essential energy substrates for ruminants. Propionate, crucial for gluconeogenesis, also increased, reflecting improved energy metabolism. The significant reductions in methane and carbon dioxide, alongside lower percentages of these gases relative to total gas production, emphasise bamboo's potential role in sustainable ruminant nutrition. These effects not only improve livestock productivity and health but also contribute to reducing the carbon footprint of animal agriculture.

These findings align with previous research on the role of plant-derived bioactive compounds in modulating fermentation dynamics (Jo et al., 2022), For instance, Jo et al. (2022) observed improvements in fermentation profiles and methane emission reduction and concluded that bioactive compounds in bamboo leaves, such as phenolic acids and tannins, influence rumen microbial activity and gas production pathways. This study confirms bamboo's dual benefits of enhancing rumen efficiency and addressing environmental concerns, making it a promising feed additive for sustainable livestock systems.

3.6. Nutrient digestibility and nitrogen balance in bamboo leaf supplementation

Table 8 illustrates significant differences in the apparent nutrient digestibility and nitrogen balance in goats fed diets supplemented with different bamboo leaves. The diet supplemented with *O. abyssinica* (OA+Bmix) demonstrated the highest digestibility values across all parameters. The digestibility of dry matter (58.7 %), crude protein (72.2 %), crude fibre (67.8 %), and ether extract (74.4 %) were notably higher in the OA+Bmix diet compared to the *B. vulgaris* (BV+Bmix) and the control diet (CONT), which had the lowest digestibility values (dry matter: 33.6 %, crude fibre: 31.6 %). This suggests that *O. abyssinica* may have more favourable nutrient characteristics that enhance nutrient absorption and digestion in goats, possibly due to a higher concentration of readily digestible compounds or more efficient enzymatic breakdown. Our findings suggest that bamboo leaf supplementation can improve nutrient digestibility due to the presence of tannins in line with the work

Table 8
Apparent nutrient digestibility and nitrogen balance potential of bamboo leaf-supplemented diets.

Nutrient	Digestibility Coefficient (% of DM)			SEM	P-value
	CONT	OA+Bmix	B. V+mix		
Dry matter	33.59[b]	58.66[a]	53.67[a]	1.018	< 0.001
Ash	52.00[c]	85.64[a]	75.87[b]	1.105	< 0.001
Crude fibre	31.57[b]	67.82[a]	67.11[a]	1.550	< 0.001
Ether extract	27.13[c]	74.43[a]	62.82[b]	0.829	< 0.001
Crude protein	60.32[c]	72.15[a]	67.55[b]	0.300	< 0.001
NDF	28.55[c]	53.24[a]	35.01[b]	1.606	< 0.001
ADF	32.30[c]	48.05[a]	45.37[b]	1.519	0.002
Nitrogen (N) intake	6.98[b]	9.22[a]	6.96[b]	0.338	< 0.001
Faecal N	2.49[a]	0.72[c]	0.87[b]	0.318	< 0.001
Urinary N	0.37[a]	0.37[a]	0.30[b]	0.018	< 0.001
Apparent digestible N	4.49[c]	8.50[a]	6.09[b]	0.433	< 0.001
Retained N	4.12[c]	8.13[a]	5.79[b]	0.430	< 0.001
Urinary N, % of apparent digestible N	8.12[a]	4.35[b]	4.10[c]	0.508	< 0.001
N retention (balance), % of N intake	59.10[c]	88.14[a]	83.17[b]	3.780	< 0.001

Means in the same row for each parameter with different superscripts (a, b, c) are significantly different ($p < 0.05$).
SEM = standard error of means.
Abbreviations: CONT = Control consisting of a mixture of *Cenchrus purpureus* and Bridelia *ferruginea* leaf meal; O.A+Bmix = *Oxytenanthera abyssinica* plus a mixture of *Cenchrus purpureus* and *Bridelia ferruginea* leaf meal; B.V+Bmix = *Bambusa vulgaris* leaf plus a mixture of *Cenchrus purpureus* and *Bridelia ferruginea* leaf meal.
Apparent digestible N = N intake –Faecal N; Retained N = N intake – (Faecal N + Urine N); Urinary N, % of apparent digestible N = (Urinary N/Apparent Digestible N x 100); N retention (balance), % of N intake = N retained /N intake x 100.

of Akinmoladun (2022), who suggested that tannins in bamboo leaves may play a role in enhancing nutrient utilization.

Additionally, nitrogen balance data further support the beneficial effects of bamboo leaf supplementation. The OA+Bmix exhibited the highest nitrogen intake (9.22 g/day), apparent digestible nitrogen (8.5 g/day), and retained nitrogen (8.13 g/day), with a nitrogen retention of 88.1 %. This shows that goats fed OA+Bmix retained a greater proportion of nitrogen, which is indicative of improved protein efficiency. The *B. vulgaris*-supplemented diet also demonstrated improvements in nitrogen retention (83.2 %) and nitrogen intake (6.96 g/day), though these were lower than OA+Bmix. The control group, in contrast, had the lowest nitrogen retention (59.1 %), highlighting its less efficient nitrogen utilisation. These results align with studies by Osman et al. (2023) and Iyeghe-Erakpotobor et al. (2006), who observed higher nitrogen retention values with bamboo leaf-supplementation and lower nitrogen retention values without bamboo leaf-supplementation respectively in different dietary treatments. The superior nitrogen retention in bamboo-supplemented diets is likely due to the enhanced protein quality and digestibility observed in these diets, which supports the claim that bamboo leaves improve nitrogen utilisation in goats. While there is broad agreement in the literature regarding the effects of bamboo supplementation on nutrient digestibility and nitrogen balance, some previous studies, such as those by Iyayi and Odueso (2003), reported lower protein digestibility coefficients than those observed in our study. This could be attributed to differences in the bamboo species used, preparation methods or animal species. The increased nitrogen retention could have significant implications for reducing environmental nitrogen excretion, which is a key concern in sustainable animal production systems. Additionally, the presence of tannins in bamboo leaves could contribute to the observed improvements in nitrogen balance in our experimental goats, as tannins are known to bind proteins and reduce protein degradation in the rumen, thus enhancing protein efficiency as mentioned by Akinmoladun (2022). We believe that since tannins are polyphenolic compounds found in many plants, including bamboo leaves in the diets of ruminants like goats, tannins can bind to proteins in the rumen, forming complexes that are less likely to be broken down by rumen microbes. This can reduce protein degradation in the rumen, which is often a problem with rapidly fermentable proteins. When this happens, more of the protein could pass through the GIT to the abomasum ("true stomach"), where it can be digested by enzymes, leading to better overall absorption in the small intestine.

3.7. Health benefits of bamboo leaf supplementation

Table 9 presents the haematological indices of goats supplemented with bamboo leaf diets and compares them with the normal reference values reported by Merck (2016), along with findings from other studies such as Ansah (2015), Konlan et al. (2012), Tanaka et al. (2012) and Antwi et al. (2023). When comparing our data to the normal physiological reference range of values for goats reported by Merck (2016), RBC counts, haemoglobin (HB) and haematocrit (HCT) values in the bamboo-supplemented goats (OA+Mix and B.V+Bmix) were found to be within or close to the specified range of values. Specifically, the RBC count in the *O. abyssinica*-supplemented group (10.5 × 10ˆ6/uL) and *B. vulgaris*-supplemented group (9.26 × 10ˆ6/uL) were within the normal reference range of 8–18 × 10ˆ6/uL, while the control group showed a significantly lower RBC count (5.82 × 10ˆ6/uL), below the normal range, indicating an inadequate diet. Similarly, the HB levels in the supplemented groups (90.4 g/L for OA+Bmix and 85.6 g/L for B. V+Bmix) fell within the normal reference range of 80–120 g/L, while the control group recorded lower HB levels (75.0 g/L), below the normal range. Haematocrit (HCT) in the bamboo-supplemented goats, though slightly lower than the normal reference range of 10–30 %, was higher than in the control group, suggesting improvements in red blood cell production with bamboo supplementation.

Mean Corpuscular Volume (MCV), MCH and MCHC in the bamboo-supplemented groups also indicated normal red blood cell production, with the values in the *O. abyssinica*-supplemented group (19.0 fL for MCV, 40.8 pg for MCH, and 30.2 g/dL for MCHC) falling respectively within the normal reference range (16–25 fL for MCV, 36–43 pg for MCH, and 30–36 g/dL for MCHC; Merck, 2016). In contrast, the control group showed significantly lower values for MCV (14.7 fL), MCH (27.7 pg), and MCHC (10.1 g/dL), indicating potential nutritional deficiencies, especially in iron and other hematinic nutrients. Red Cell Distribution Width (RDW-CV) in the bamboo-supplemented groups was slightly lower than the normal reference range of 30–45 % (Merck, 2016), with values of 27.0 % for OA+Bmix and 24.6 % for B.V+Bmix, comparable to 24.6 % in the control group. While the RDW-CV in the B. V-supplemented group was within a similar range as the control, its slightly increased in the OA-supplemented group may suggest a more diverse red blood cell population or increased variation in size, which could be associated with a more dynamic red blood cell turnover due to the bioactive compounds in this bamboo species.

White Blood Cell (WBC) counts in the control group (21.0 × 10ˆ3/uL) were significantly higher than the normal reference range of 4–13 × 10ˆ3/uL, suggesting that the control group may have been experiencing an immune response or inflammation, possibly due to the lack of anti-inflammatory compounds in the basal diet. This is in line with findings by Tanaka et al. (2012), who noted antimicrobial properties of bamboo leaves, which in this case might have contributed to the reduction in WBC counts in our supplemented goats (11.6 × 10ˆ3/uL for OA+Mix and 10.7 × 10ˆ3/uL for B.V+Bmix). These lower WBC counts in the supplemented groups suggest a potential reduction in inflammation compared to the control. When comparing our results to the findings of other authors, the RBC, HB, MCV, MCH and MCHC values observed in the bamboo-supplemented goats align with the reports by Ansah (2015) and Konlan et al. (2012), who also found improvements in haematological parameters in animals fed bamboo leaves. In particular,

Table 9
Haematological indices of goats fed bamboo leaf-supplemented diets.

[a]Haematology	CONT	OA+Bmix	B.V+Bmix	SEM	P-value	[b]Reference
RBC (10^6/uL)	5.82[c]	10.49[a]	9.26[b]	1.650	< 0.001	8 – 18
HB (g/L)	75.00[c]	90.40[a]	85.60[b]	0.460	< 0.001	80 – 120
HCT (%)	5.38[c]	9.08[a]	8.06[b]	0.418	0.007	10 – 30
MCV (fL)	14.68[c]	19.04[a]	17.10[b]	0.456	0.017	16 – 25
MCH (pg)	27.72[c]	40.82[a]	35.78[b]	1.770	< 0.001	36 – 43
MCHC (g/dL)	10.12[b]	30.24[a]	29.28[a]	2.000	< 0.001	30 – 36
RDW-CV (%)	24.60[b]	27.00[a]	24.63[b]	0.334	0.045	30 – 45
WBC (10^3/uL	21.00[a]	11.60[b]	10.67[c]	1.190	<0.001	4 – 13

Means in the same row for each parameter with different superscripts (a, b, c) are significantly different ($p < 0.05$). SEM = standard error of means.
Abbreviations: CONT = Control consisting of a mixture of *Cenchrus purpureus* and *Bridelia ferruginea* leaf meal; O.A+Bmix = *Oxytenanthera abyssinica* plus a mixture of *Cenchrus purpureus* and *Bridelia ferruginea* leaf meal; B.V+Bmix = *Bambusa vulgaris* leaf plus a mixture of *Cenchrus purpureus* and *Bridelia ferruginea* leaf meal.
[a]Haematological indices: RBC= Red Blood Cells, HGB = Haemoglobin, HCT = Haematocrit, MCV= Mean Corpuscular Volume, MCH= Mean Corpuscular Haemoglobin, MCHC = Mean Corpuscular Haemoglobin Concentration, RDW-CV= Red Cell Distribution Width - Coefficient of Variation, WBC = White Blood Cells
[b]Reference: Normal physiological range of haematological indices for goats reported by Merck (2016)

these authors reported enhanced erythropoiesis and haemoglobin synthesis, similar to what we observed in the bamboo-supplemented goats in this study. Antwi et al. (2023) also reported improvements in blood health and immune function in Djallonke sheep fed bamboo leaves, supporting the beneficial effects of bamboo supplementation on blood parameters. Thus, the bamboo leaf supplementation positively influenced haematological parameters, supporting its potential health benefits for goats and aligning with previous studies on the positive effects of bamboo in livestock.

Table 10 presents the effects of bamboo leaf supplementation on serum biochemical indices of goats, comparing the treatment groups to normal reference ranges (Olafadehan, 2011). Urea nitrogen (Urea N) levels ranged from 3.96 mmol/L to 4.58 mmol/L, all within the normal range of 3.5 – 10.73 mmol/L, indicating no disruption in protein metabolism, consistent with Antwi et al. (2023). Creatinine levels were significantly highest in the *O. abyssinica* group (97.8 μmol/L) but remained within the reference range of 50 – 180 μmol/L, suggesting that bamboo supplementation, particularly *O. abyssinica*, may support muscle metabolism without impairing kidney function.

Total protein levels remained within the normal range in both the control and supplemented groups, though they were slightly higher in *O. abyssinica*-supplemented goats (88.2 g/L), approaching the upper normal limit of 96 g/L. This increase suggests improved protein synthesis or retention, possibly due to the superior nutritional and bioactive profile of *O. abyssinica*. Albumin levels, ranging from 25.9 g/L to 28.2 g/L, were within the normal range of 18.9 – 44.5 g/L, suggesting normal liver function, possibly enhanced by the antioxidant properties of bamboo. Globulin concentrations were highest in the *O. abyssinica* group (60.1 g/L), exceeding the normal range of 35 – 45 g/L, which may reflect improved immune function due to bamboo's saponins and flavonoids. Alkaline phosphatase (ALP) levels remained within the normal range (66–230 U/L) in both the bamboo-supplemented and control groups, indicating no adverse effects on liver and/or bone metabolism. However, ALP levels were significantly higher in the *O. abyssinica*-supplemented group, suggesting a slight enhancement of liver or bone metabolic activity with supplementation. Alanine aminotransferase (ALT) levels, higher in the *B. vulgaris* group (21.6 U/L), remained within the normal range of 15.3 – 52.3 U/L, indicating potential liver adaptations. Gamma-glutamyl transferase (GGT) levels were slightly elevated in both *O. abyssinica*- and *B. vulgaris*-supplemented goats, reaching up to 54.9 U/L. This suggests increased bile production and liver activity, possibly influenced by bamboo's detoxifying properties. Cholesterol levels were significantly higher in *O. abyssinica*-supplemented goats (2.42 mmol/L), exceeding the normal range of 1.5–1.92 mmol/L, possibly due to its relatively higher saponin and oxalate content upregulating lipid metabolism.

3.8. Adoption potential of bamboo leaves as livestock fodder in the transitional forest zones of Ghana

3.8.1. Demographics of Livestock Farmers in the Study Area

Fig. 4 depicts the demographic profile of farmer respondents, with 76 % being male and 24 % female. Most respondents aged between 36–45 (42 %) and 26–35 (40 %) while younger (18–25) and older farmers (46 and above) each accounted for 9 %. In terms of education, 28 % completed Junior Secondary School (JSS), 24 % Senior Secondary

Table 10
Serum indices of goats fed bamboo leaf-supplemented diets.

[a]Serum indices	CONT	OA+Bmix	B.V+Bmix	SEM	P-value	[b]Reference
Urea N (mmol/L)	4.22	4.48	4.22	0.390	< 0.091	3.5 – 10.7[3]
Creatinine (μmol/L)	73.93[b]	97.77[a]	66.60[b]	8.220	< 0.001	50–180
Total Protein (g/L)	76.50[c]	88.24[a]	84.32[b]	7.500	0.002	56–96[1]
Albumin (g/L)	26.70[b]	28.16[a]	26.20[b]	2.490	0.012	18 – 44[1]
Globulin (g/L)	49.80[c]	60.08[a]	58.12[ab]	5.200	< 0.001	35 – 45[2]
ALP (U/L)	138.42[b]	177.32[a]	125.3[b]	16.30	< 0.001	66–230[2]
ALT (U/L)	18.90[b]	18.54[b]	21.56[a]	1.860	0.043	15 – 52[2]
GGT (U/L)	50.24	54.92	52.88	4.750	< 0.001	20–50[2]
Cholesterol (mmol/L)	1.89[b]	2.42[a]	1.64[b]	0.210	< 0.001	1.5 – 1.9[2]

Means in the same row for each parameter with different superscripts (a, b, c) are significantly different ($p < 0.05$).
SEM = standard error of means.
Abbreviations: CONT = Control consisting of a mixture of *Cenchrus purpureus* and *Bridelia ferruginea* leaf meal; O.A+Bmix = *Oxytenanthera abyssinica* plus a mixture of *Cenchrus purpureus* and *Bridelia ferruginea* leaf meal; B.V+Bmix = *Bambusa vulgaris* leaf plus a mixture of *Cenchrus purpureus* and *Bridelia ferruginea* leaf meal.
[a]Serum indices: ALP = alkaline phosphatase; ALT = alanine aminotransferase; GGT = gamma-glutamyl transpeptidase.
[b]References: Normal physiological range of serum indices for goats reported by [1]Žubčić (2001), [2]Olafadehan (2011), [3]Sirois (1995).

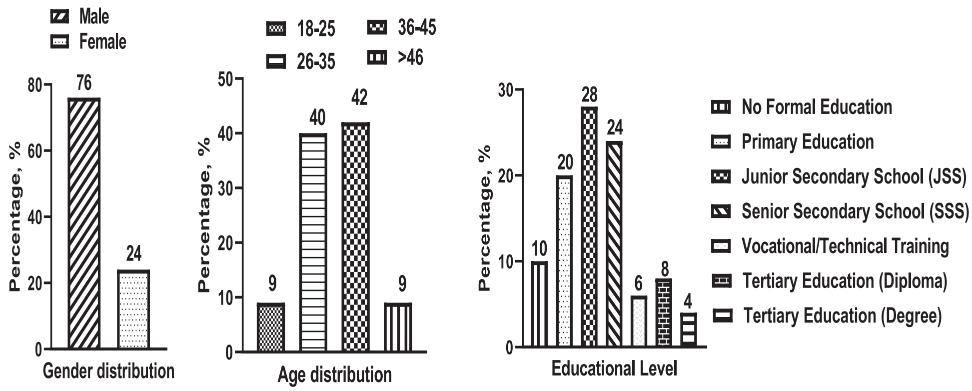

Fig. 4. Demographics of livestock farmers in the study area.

School (SSS), and 20 % primary education; 10 % had no formal education, while 8 % held diplomas, 6 % had vocational training, and 4 % possessed degrees. The predominance of male farmers reflects traditional gender roles of males heavily associated with farming, and this could influence perceptions and use of bamboo leaves as fodder (Uduji et al., 2019; Maponya and Mpandeli, 2012). Bamboo fodder promotion efforts should target men as they are primary decision-makers while considering female farmers' needs. The underrepresentation of younger (18–25) and older (46 and above) farmers (3.03 % each) may indicate challenges or disinterest in farming, particularly among older farmers (Berkowsky et al., 2017). Tailored educational interventions could enhance bamboo leaf adoption, especially since most farmers have received formal education (Kaphle et al., 2015).

3.8.2. Farming systems and crops cultivated in the study area

Table 11 shows that 61.3 % of farmers engage in mixed crop and livestock farming, while 39 % focus solely on livestock. Among crop farmers, 71 % cultivate multiple crop types, with maize (80 %), cassava (67 %) and vegetables (37 %) being the most common. Integrating bamboo as fodder could enhance resource use and address seasonal feed shortages (Alwedyan and Taani, 2021). Research indicates that mixed systems improve resilience and productivity through nutrient recycling (Teklewold et al., 2013). Intercropping bamboo could also boost soil health (Liu et al., 2020), supporting livestock health and long-term sustainability. Thus, introducing bamboo leaves as feed could enhance livestock nutrition and farm resilience in the study area.

3.8.3. Livestock management practices in the study area

Table 12 shows the livestock management systems and available feed resource utilization in the study area. Most farmers (58.62 %) use a semi-intensive system, blending housing with free-ranging. 21 % employ an intensive system with full confinement, while 20.7 % use free-range systems, with half providing no special housing and half offering minimal facilities. Feeding practices show that 71 % rely on natural pasture, while 50 % utilize crop residues. Additionally, 20 % incorporate agro-industrial by-products, and 15 % use commercially prepared feed. The semi-intensive system is recognized for enhancing livestock output and health by allowing natural grazing (Anandh et al., 2012). Integrating bamboo leaves into this system could improve animal nutrition and productivity. For the 21 % using intensive systems, bamboo leaves could serve as a sustainable substitute for commercial feeds, offering a consistent and balanced feed option (Russelle et al., 2007). In free-range systems, bamboo could complement natural forage, particularly in suitable climates (Akoto et al., 2018), thus supporting farmers' efforts to diversify feed sources and enhance resilience against shortages (Franzluebbers et al., 2019; Tsevegemed et al., 2019).

Table 11
Farming systems and crops cultivated in the study area.

Cultivation practices	Percentage (%)
Are you both a crop and livestock farmer?	
Yes (Both)	61
No (Only livestock)	39
Do you cultivate one type of crop or many?	
Yes (Many)	71
No (One type)	29
What crops do you cultivate?	
Maize	80
Cassava	67
Rice	25
Vegetables	37
Yam	29
Cowpeas	26
Others	8

Table 12
Livestock management practices in the study area.

Management systems	Percentage (%)
An intensive system where animals don't move around	21
A semi-intensive where animals are allowed to roam but some housing is provided	59
A free-range where animals roam around freely with no special housing facilities provided	10
A free-range where animals roam around freely with some housing facilities provided	10
Available feed resource utilization	
Commercially prepared feed	15
Natural pasture (Grasses, trees, shrubs, herbs and forbs)	71
Crop residues left after harvesting	50
Agro-industrial by-products	20

3.8.4. Famers' familiarity with bamboo in the study area

Farmers' familiarity with bamboo is crucial for them to adopt its leaves as fodder. As shown in Table 13, 96 % of respondents are familiar with bamboo and can easily identify it in their community, while only 4 % reported difficulty in recognising it. Additionally, 79 % of respondents stated that bamboo is readily visible in their community, whereas 21 % indicated that it is not easily found. This widespread

Table 13
Farmers' familiarity with bamboo in the study area.

Familiarity and availability	Percentage (%)
Do you know bamboo and can you easily identify it?	
Yes	96
No	4
Do you think bamboo is easily available in your community?	
Yes	79
No	21

familiarity with bamboo suggests a strong foundation for adopting bamboo leaves as livestock fodder, as minimal effort would be required to raise awareness or educate farmers about its use. Since most farmers already recognise bamboo, the focus can shift towards demonstrating its potential benefits for livestock health and productivity. The high level of availability of bamboo in the study area indicates that bamboo could be introduced with minimal educational interventions, allowing for quicker adoption and integration into existing farming systems. This familiarity and availability can reduce barriers to entry, making it easier to scale up the use of bamboo leaves as a sustainable and nutritious feed source for livestock. Therefore, leveraging community networks and engaging existing bamboo users in demonstration projects could be an effective way to promote its use as fodder (Berkowsky et al., 2017).

3.8.5. Communal uses of bamboo in the study area

Most respondents (92.9 %) use bamboo for building and construction (Fig. 5). Additionally, 71.4 % use bamboo for furniture and home items, showcasing its sustainability. Bamboo is also used for traditional medicine and charcoal production (25 %). Fig. 6 highlights that 82 % of respondents use bamboo stems (culms) for construction, while only 10 % and 5 % use shoots and roots, mainly for medicinal purposes. Only 3 % use bamboo leaves as livestock feed, with 82 % feeding them sparingly and 18 % feeding them daily. These findings reveal bamboo's underutilized potential as livestock feed in the study area, offering ecological and economic opportunities for sustainable farming.

3.8.6. Adoption drivers of bamboo utilization as livestock fodder in the study area

The adoption of bamboo as livestock fodder was influenced by several factors (Table 14). A key driver is economic feasibility, with 67 % of respondents finding bamboo cost-effective. This indicates the financial benefits of bamboo leaves as an affordable feed alternative. However, 23 % did not find it cost-effective, possibly due to concerns about supply or preparation costs. Accessibility is another critical factor, 51 % of respondents found bamboo easy to access, while 49 % did not, suggesting regional differences in bamboo availability. Additionally, 28 % saw bamboo fodder as a potential source of income through its cultivation and sale. Environmental sustainability also plays a role, with 64 % viewing bamboo as highly sustainable due to its fast growth, resilience, and ability to thrive in marginal areas. However, 27 % saw moderate environmental benefits, and 9 % perceived low sustainability, indicating some scepticism or lack of awareness about bamboo's full ecological advantages.

Key factors that could encourage wider adoption include access to information on bamboo's nutritional benefits (71 %) and potential feeding risks (60 %), highlighting a need for educational efforts. Training in bamboo harvesting and preparation (57 %) and interest in cultivation techniques were also identified as important. Additionally, 33 % of respondents saw access to credit facilities for bamboo cultivation as a motivator for adoption. Peer influence was significant, with 68 % citing bamboo-feeding success stories from fellow farmers as a positive influence.

The general perceptions of bamboo's viability as fodder varied. While 40 % strongly agreed it is viable and an additional 5 % agreed, 35 % strongly disagreed, reflecting reservations or barriers. Despite this, 80 % of respondents would recommend bamboo leaves as a livestock feed option, showing that many farmers recognise its potential as a sustainable, cost-effective alternative. Overall, economic feasibility, accessibility and environmental sustainability were the primary factors driving bamboo fodder adoption. However, logistical barriers and knowledge gaps, especially regarding its nutritional profile and preparation, remain obstacles. Educational initiatives, peer influence and financial support, such as credit facilities or subsidies for bamboo cultivation, could enhance adoption rates. Addressing these needs would help overcome scepticism and increase bamboo's role in livestock farming as a sustainable and viable feed option.

4. Conclusion

This study has demonstrated the nutritional and functional potential of bamboo leaves from *Oxytenanthera abyssinica* and *Bambusa vulgaris* as livestock feed. Both species provided high dry matter, moderate protein levels and balanced fibre content, supporting nutrient absorption and digestibility. While *B. vulgaris* excelled in phosphorus, potassium, iron and copper, *O. abyssinica* offered higher calcium and magnesium, highlighting species-specific advantages for immune function, mineral metabolism and skeletal health. The bioactive compounds in *O. abyssinica* (flavonoids, oxalates) and *B. vulgaris* (tannins, saponins) enhanced antioxidant, antimicrobial and digestive properties, showcasing their functional value in goats' nutrition. Rumen fermentation studies revealed improved energy metabolism and reduced greenhouse gas emissions with bamboo supplementation. Enhanced digestibility, nitrogen retention and protein metabolism further highlight bamboo's suitability as a sustainable feed resource. Haematological and biochemical analyses showed that bamboo supplementation supported erythropoiesis, reduced inflammation, boosted immune function and maintained normal liver enzyme levels in goats, suggesting health-promoting effects. Despite bamboo's traditional use for construction and medicine in Ghana's transitional forest zones, its adoption as livestock feed is limited due to low awareness of its nutritional and environmental benefits. Key drivers for its adoption include its accessibility, economic feasibility and sustainability.

5. Limitations and way forward

While this study demonstrated the potential of bamboo leaves as a sustainable livestock feed, several limitations must be acknowledged. The study's scope was confined to goats, and further research is needed

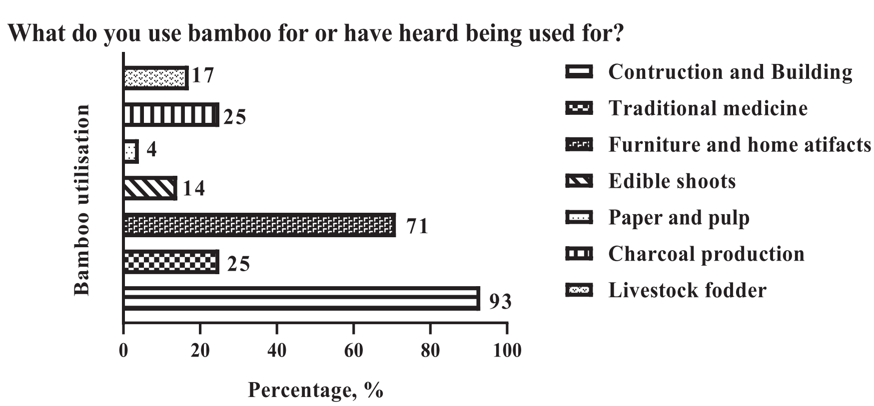

Fig. 5. Communal uses of bamboo in the study area.

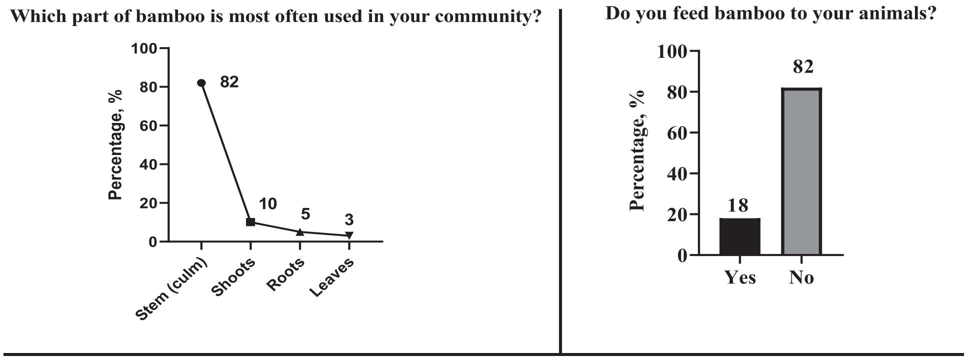

Fig. 6. Parts of bamboo often used in the study area.

Table 14
Drivers of bamboo fodder adoption among livestock farmers in the study area.

Driver	Percentage %
How do you perceive the economic feasibility of bamboo as fodder?	
Cost-effective	67
Less cost-effective	23
Easily accessible	51
How do you perceive the accessibility of bamboo as fodder?	
Less accessible	49
Generation of wealth	28
To what extent do you think using bamboo leaves as fodder contributes to environmental sustainability?	
High contribution	64
Moderate contribution	27
Low contribution	9
What can incentivize you to adopt bamboo as fodder?	
Access to information on bamboo's nutritional benefits to animals	71
Access to information on potential hazards of feeding bamboo to animals	60
Access to training on harvesting and preparation methods of bamboo as feedstock	57
Access to information on bamboo fodder cultivation	57
Access to credit facilities for bamboo cultivation	33
Access to success stories of feeding bamboo leaves from peer livestock farmers	68
How would you rate your overall perception of bamboo leaves as a viable fodder resource for livestock on a rating scale from 1 to 5?	
1 (Strongly disagree)	35
2 (Disagree)	0
3 (Neutral)	20
4 (Agree)	5
5 (Strongly agree)	40
Would you recommend bamboo leaves as a viable livestock feed option to other farmers?	
Yes	80
No	20

to validate the findings across other ruminant species and livestock systems. Additionally, the logistical challenges associated with harvesting bamboo leaves, including labour intensity and seasonal variability, may affect large-scale adoption. Knowledge gaps among livestock farmers regarding bamboo's nutritional and environmental benefits were identified as barriers to utilisation. To address these limitations, future research should explore scalable harvesting techniques, storage methods and processing innovations to improve bamboo's accessibility. Furthermore, conducting longitudinal studies to assess the long-term effects of bamboo supplementation on livestock health and productivity is critical. Educational initiatives, coupled with financial incentives, could enhance farmer awareness and promote bamboo as a climate-smart feed option. This multi-pronged approach could unlock bamboo's potential for widespread adoption, supporting sustainable livestock production systems.

CRediT authorship contribution statement

Sasu Prince: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Kwaku Michael:** Validation, Supervision, Resources, Project administration. **Ellison Felicia Emmanuella:** Writing – review & editing, Visualization, Methodology, Data curation. **Opara Esther:** Writing – review & editing, Validation, Methodology, Data curation. **Koblah Richard Agbehadzi:** Writing – review & editing, Validation, Methodology, Data curation. **Adjei-Mensah Benjamin:** Writing – review & editing, Visualization, Validation, Supervision, Data curation. **Anim-Jnr Antoinette Simpah:** Writing – review & editing, Supervision, Methodology, Data curation. **Attoh-Kotoku Victoria:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Data curation.

Declaration of Competing Interest

The authors declare no conflict of interest regarding the publication of this manuscript. No financial or personal relationships with other people or organizations have influenced this work.

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Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author upon reasonable request.

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