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Toward smallholder bamboo-integrated agro-silvopastoral systems in sub-Saharan Africa: assessing the impact of bamboo leaves on consumption pattern, growth performance and manure characteristics of West African dwarf goats

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Introduction: The selection of appropriate plant species, particularly those tailored to supplement ruminants raised under agrosilvopastoral systems, remains a persistent challenge.

Objective: In a 30-day study, the feed intake, growth performance, and manure characteristics of West African dwarf (WAD) goats fed bamboo leaf supplement were evaluated.

Materials and methods: A total of 30 animals with an average weight of 9.9 ± 0.21 kg were divided into a control group, and four bamboo-supplemented groups, following a 2 x 2 factorial arrangement within a completely randomized design. Each group had six animal replicates and received the following dietary treatments: T1 (control) – 400g of basal diet composed of 60% Megathyrsus maximus and 40% Bridelia ferruginea leaves per day; T2—basal diet composed of the T1 diet supplemented with 400 g of Oxytenanthera abyssinica (A. Rich.) Munro leaves per day; T3—basal diet composed of the T1 diet supplemented with 400 g of Bambusa balcooa (Beema) leaves per day; T4—basal diet composed of the T1 diet supplemented with 600 g of O. abyssinica (A. Rich.) leaves per day; and T5—basal diet composed of the T1 diet supplemented with 600 g of B. balcooa leaves per day. The data were analyzed using generalized linear model procedures in Minitab Statistical Software at a 5% significance level.

Results: The results showed varied ($p < 0.05$) dry matter compositions spanning from 894.3 to 910 g/kg with the highest contents of crude protein (194 g/kg), nitrogen (31 g/kg), crude fibre (302 g/kg), ash (156 g/kg), acid detergent fibre (429 g/kg), and acid detergent lignin (3.6 g/kg) recorded for B. ferruginea. The leaves of Bambusa balcooa contained the highest neutral detergent fibre (481 g/kg) while M. maximus had the highest organic matter content (911 g/kg). Significant interaction effect ($p < 0.05$) was observed between the supplement type and the supplementation level, impacting various parameters including feed intake ranging from 398 g (T1) to 469 g (T3) per day, weight gain from 27 g (T1) to 72 g (T2) per day, feed conversion efficiency from 6% (T1) to 15% (T2), manure output from 241 g (T2) to 260 g (T5) per day, carbon- nitrogen (C: N) ratio from 9 (T2) to 20 (T5), faecal acidity levels from 4 (T1) to 5 (T4). Comparatively, higher daily dry matter intake was recorded for the animal groups fed the B. balcooa supplement than their counterparts fed the O. abyssinica supplement. However, the O. abyssinica supplemented groups were more efficient in converting feed to body weight, with feed conversion efficiency approximately 9% higher than the B. balcooa-supplemented groups. Furthermore, in general, the animal groups that received a daily supplement of 400 g gave higher feed efficiency, with performance approximately 3.2% higher compared to the groups receiving 600 g. Likewise, these groups displayed higher faecal N output while concurrently achieving a reduced C: N ratio, indicative of enhanced nutrient utilization and potential environmental benefits.

Conclusion: To conclude, integrating 400 grams of bamboo leaves into animal diet can enhance basal diet consumption, accelerate animal growth, and yield manure akin to chemical fertilizers, making it a valuable strategy for bamboo-integrated agro-silvopastoral systems practitioners.

KEYWORDS

bamboo leaves, smallholder farming, agro-silvopastoralism, organic manure, sustainable agriculture

Introduction

Sub-Saharan Africa (SSA) currently harbors a population exceeding 950 million individuals, constituting about 13% of the global populace, with projections indicating a substantial surge to approximately 22% that will see the population reaching 2.1 billion people by 2050 (OECD, 2016a; OECD, 2016b). In anticipation of this impending demographic growth, it is imperative that agricultural production is increased to meet escalating food demands. This has led the global agricultural and development spheres to pivot their focus toward smallholder farms on a global scale (Wiggins et al., 2010; World Bank, 2022). Research that advocates for the vital role played by smallholder and family farms in global food security has been steadily amassing (Birner and Resnick, 2010; FAO, 2014; Lowder et al., 2016). Thus, effective policies geared toward alleviating poverty, ensuring food security, and safeguarding biodiversity and natural resources hinge on the inclusive participation of these small-scale farmers. The United Nations has, consequently, emphasized the importance of investing in small farms as a strategic approach aligned with its sustainable development goals (SDGs) concerning poverty, nutrition, hunger, and environmental sustainability (UNCTAD, 2015). Such investments also resonate with the amplified global attention toward sustainable development goals, particularly in the context of SSA, where agricultural advancement is pivotal to tackling the primary goal of eradicating poverty and hunger (Wiggins et al., 2010).

However, despite the crucial contribution of smallholder farmers to SSA's food production, their farms exhibit modest productivity, thereby perpetuating the cycle of food inflation and poverty. This becomes particularly important considering that agriculture remains the predominant source of income for a substantial proportion of the region's workforce. Consequently, the specter of food insecurity looms large, affecting nearly 30% of SSA's population and constituting an entrenched concern (Pfister et al., 2011). This is especially pronounced in economies reliant on food imports, where the impoverished segment constitutes a significant portion of net food-purchasing households (Wodon and Zaman, 2008; Simler, 2010). Adding to these challenges is the economic situation in almost three-quarters of the countries in SSA led to their being classified as food deficit countries before the recent surge in global food prices (FAO, 2021).

Compounding the situation, SSA is grappling with mounting food inflation due to the escalation of global food prices. Numerous countries within the region are witnessing annual food inflation rates exceeding 20%, with a pronounced inflationary trend observed for Ghana in particular (Figure 1), marking a confluence of factors contributing to the complex interplay of food security and economic dynamics (World Bank, 2022k).

The consistent rise in food prices across SSA has had significant effects. Many households in SSA spend a large portion of their income on food, leading to decreased domestic demand and hindering the recovery of non-resource sectors (Wodon et al., 2008; OECD/FAO, 2020; FAO et al., 2021; OECD/FAO, 2021; World Bank, 2022k). The high food prices are partly due to the increasing demand for land for non-agricultural purposes, coupled with the challenge of making marginal lands productive for farming and grazing. As a result, farmers face various issues, including declining soil fertility, worsening land degradation, and limited access to fertilizers. These problems affect agricultural productivity and efforts to combat hunger. In regions where land is used for farming, nutrients are often removed by crops, weeds, grazing, and fodder harvesting (Powell et al., 2004). Research has shown that low soil fertility is a primary factor limiting crop yields in SSA (Fischer and Qaim, 2012; Gicheru, 2012). One issue is negative net nutrient balance, which occurs when more nutrients are removed than are added to soil (FAO, 2014). Traditional practices such as shifting cultivation and land rotation cannot counteract this effectively due to population growth, limited land availability, and other competing land uses (Partey and Thevathasan, 2013). Addressing these challenges faced by smallholder farming in the SSA necessitates the exploration of alternative methods to enhance soil quality and restore nitrogen content. These strategies can contribute to improved crop growth and higher yields, which are especially crucial in the context of rising food prices and land constraints and play a pivotal role in the region's sustainable development and efforts toward food security.

In this pursuit, agroforestry innovations emerge as pragmatic avenues to sustainably enhance soils, increase crop yields, and uphold ecological equilibrium. The incorporation of trees, particularly of leguminous species, has been proven to enhance soil quality through various mechanisms such as nitrogen fixation, erosion prevention, soil stabilization, moisture retention via litter cover, and nutrient enrichment through decomposition and nitrogen mineralization (Partey and Thevathasan, 2013). Despite their gradual acceptance on a larger scale, agroforestry practices such as improved fallows and alley cropping have demonstrated their efficacy in bolstering crop yields and elevating soil quality in various agro-ecological settings (Partey et al., 2017; Bayala et al., 2018; Wolz and DeLucia, 2018). However, the selection of appropriate tree species, particularly those tailored to agro-silvopastoral systems, remains a persistent challenge (Partey et al., 2011). Hindrances such as the scarcity of species adaptable to diverse agroecological zones, difficulties in sourcing seeds, and protracted tree maturation periods frequently deter farmers from integrating these multifunctional trees into their cultivation systems. As a result, they find themselves constrained, frequently resorting exclusively to natural pastures and agricultural residues as the sole sources of animal sustenance. Amid these circumstances, the exploration of novel plant species well suited for agro-silvopastoral practices assumes paramount importance.

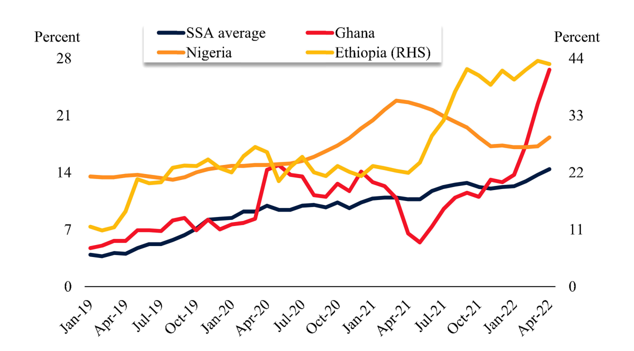

FIGURE 1
A surge in food prices across emerging markets and developing economies within sub-Saharan Africa (SSA), (i.e., countries heavily reliant on food imports). *Source: Comtrade (database); Haver Analytics;* World Bank, 2022k.

Bamboos (Poaceae), intrinsic components of natural ecosystems, hold the potential to strike a balance in the animal food supply equation by providing evergreen leaf fodder and concurrently contributing to soil enrichment through their nutrient-dense leaf litter. The rapid growth of bamboo, characterized by its perennial green leaf canopy amenable to regular trimming, offers a consistent source of livestock feed. The fondness of wildlife, including pandas, for consuming bamboo shoots and leaves (Hayashi et al., 2005; Asaolu et al., 2009; Halvorson et al., 2011), highlights their palatability and nutritional value. Mammalian herbivores, particularly ruminants, known for their dietary versatility, exhibit the discerning ability to select nutrient-rich foods and avoid toxic elements and nutritional imbalances (Villalba et al., 2002; Distel et al., 2020). In harmony with this selective dietary preference, bamboo emerges as a promising candidate for optimal fodder provision. The nutrient-dense leaves it yields resonate with the discerning appetites of these animals, offering the potential to enhance their wellbeing and productivity (Sasu et al., 2023b). Extensive research on using bamboo leaves as livestock food has consistently shown that they are rich in nutrients. These studies suggest that bamboo leaves can effectively meet the nutritional needs of animals that consume them (Artabandhu et al., 2010; Sahoo et al., 2010; Andriarimalala et al., 2019; Kitaw et al., 2022; Sasu et al., 2022; Sasu et al., 2023a, Sasu et al., 2023b).

As a result, adopting a bamboo agro-silvopastoral system allows for the coexistence of food crops and animals such as cattle, sheep, and goats, along with bamboo growth up to the canopy level. With effective management, bamboo can provide a consistent source of leaves for animal feed across seasons. Extensive documentation highlights bamboo's versatile appeal and its ability to yield leaves consistently, even during dry periods (Antwi-Boasiako et al., 2011; INBAR, 2019; Sasu et al., 2022; Sasu et al., 2023a). This perennial grass, characterized by its "unfamiliar" yet fascinating nature (Zehui, 2007 cited in Sasu et al., 2023b), has a valuable resource in its abundant leaf biomass, which not only provides shade for grazing livestock but also offers a solution for increasing the roughage in smallholder livestock communities. This concept finds applicability in sub-Saharan Africa (SSA), particularly in countries such as Ghana, where urban and peri-urban populations largely depend on livestock rearing for their livelihoods (Baah et al., 2012). Therefore, the integration of bamboo into agroforestry systems, coexisting alongside various crops and vegetation, represents a savvy land-utilization strategy (INBAR, 2019). This not only enhances livestock health but also enriches the soil through manure recycling (Figure 2).

According to a report from INBAR, (2020a; 2020b), Ghana contains approximately 42,889.63 hectares of native bamboo habitats. These are predominantly concentrated in the southern regions, with the Ashanti region claiming the largest bamboo coverage, at around 10,325.51 hectares. Following closely are the Central (9,518.23 ha), Western (9,397.49 ha), Eastern (8,991.80 ha), and Western North regions (4,656.60 ha), all of which contribute to Ghana's bamboo landscape. The prominence of bamboo resources in the southern parts of Ghana highlights the ample foliage available for local livestock sustenance that is present there.

In areas such as Northern Ghana, which are characterized by extended dry periods (Figure 3), introducing bamboo plantations could be highly advantageous. These plantations might serve as essential resources for feeding ruminant livestock during dry spells. Bamboo's resilience to drought sets it apart from conventional grasses. Integrating bamboo into agro-silvopastoral systems not only enhances crop productivity but also, through the recycling of organic matter, contributes to soil enrichment. This comprehensive strategy, utilizing bamboo as both livestock feed and a catalyst for soil fertility improvement, captures the essence of sustainable agricultural practices in various regions in Ghana.

Furthermore, in urban and peri-urban regions, where approximately 25% of the 13.3 million small ruminants (most of which are goats) are reared by local communities (Oppong-Anane, 2011; Adzitey, 2013), the significance of bamboo leaves to the revolutionization of small ruminants' diets becomes pronounced. This significance is emphasized by the growing number of goats in the country, which increased from 7.8 million in 2019 to 8.2 million in 2020, meaning that goats constitute the largest population of small ruminants in the country (Statista, 2022). Goats, with their natural tendency to eat leaves from trees and shrubs (Figure 4), are particularly suited for processing nutrient-rich plant matter, resulting in valuable manure. As such, they are strong candidates for integration into bamboo-based agro-silvopastoral systems, aligning well with the dynamics of such setups (Figure 5). Integrating goats into bamboo-based agro-silvopastoral systems, given that their activity aligns well with the dynamics of these ecosystems, is a potential means of establishing a symbiotic relationship between livestock and bamboo resources. This integration capitalizes on goats' innate browsing behavior, leveraging their affinity for consuming bamboo leaves and other foliage. As goats process and convert these nutrient-rich leaves into valuable manure (Figure 6), the ecosystem benefits from enhanced soil fertility. Furthermore, the utilization of goats as a livestock component in bamboo-centric systems not only addresses the challenge of providing nutritious feed during dry spells but also contributes to sustainable waste recycling and soil enrichment. Research findings indicate that goat manure plays a vital role in enhancing soil quality through the increasing of organic matter,

FIGURE 3
The arid conditions of Northern Ghana create persistent feeding challenges for livestock, making bamboo agroforestry a promising means of addressing the nutritional needs of ruminant livestock during these dry periods. Picture courtesy: Field Photo taken by Sasu, 2021.

FIGURE 2
Indigenous bamboo stands with copious bamboo leaf biomass providing shade and roughage in smallholder livestock communities Picture courtesy: Field Photo taken by Sasu, 2021.

FIGURE 4
Goats—naturally browsers (i.e., head-up grazers)—eat the leaves of trees or shrubs, making them the preferred potential animal candidates in bamboo-based agro-silvopastoral systems. Picture courtesy: Field Photo taken by Sasu, 2021.

FIGURE 5
Integrating goats into bamboo-based agro-silvopastoral systems, aligns well with the dynamics of the ecosystem and contributes to sustainable waste recycling and soil enrichment. Picture courtesy: Field Photo taken by Sasu, 2021.

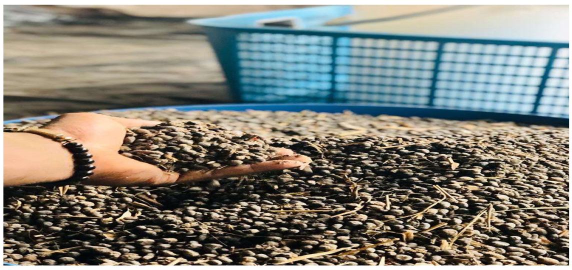

FIGURE 6
Manure (dried) collected from goats fed bamboo leaf-supplemented diets: Source: field data, 2021; bamboo fodder research, Department of Animal Science, KNUST, Kumasi, Ghana. Picture courtesy: Field Photo taken by Sasu, 2021.

replenishment of nutrients, fostering of the proliferation of antagonistic organisms against plant-parasitic nematodes, increasing of soil moisture levels, and elevation of cation exchange capacity (Mitchell, 1992; Giyinyu et al., 2005; Ansah et al., 2019). Moreover, goat manure contributes to a reduction in the soil carbon-to-nitrogen ratio (C:N), which catalyzes soil biological activity and ultimately leads to improved crop yields (Aggarwal and Power, 1997; Kimani and Lekasi, 2004; Saha et al., 2008).

In the contemporary landscape marked by post-COVID pandemic disruptions, mobility constraints, and escalating food prices exacerbated by global geopolitical events such as Russia's invasion of Ukraine, sub-Saharan Africa (SSA) faces profound economic challenges that have disrupted food affordability and real incomes across the region, including in Ghana. These circumstances emphasize the importance of increasing agricultural production, particularly by expanding smallholder farming systems and employing straightforward yet effective farming techniques supported by accessible technology.

Against this backdrop, the focal objective of this study was to evaluate the potential of bamboo leaves as a sustainable feed source for livestock within smallholder bamboo-based agro-silvopastoral systems in SSA. Our hypothesis was that integrating bamboo leaves into goats' diets would increase the nutritional profile of their feed, stimulate feed consumption and growth, and culminate in the production of nutrient-rich manure akin to conventional chemical fertilizers. This investigation aimed to contribute to the enhancement of livestock production and also to align with the broader goal of ameliorating food security and agricultural sustainability in SSA in the face of prevailing challenges.

Materials and methods

Study area

The study was conducted at the Livestock Section of the Department of Animal Science, Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ghana, from mid-April to mid-May 2021. The experimental site is located at latitude 06°43′N and longitude 1°36′W and falls within the moist semi-deciduous forest belts of Ghana, which have a bimodal rainfall pattern of 1,300 mm per year. The average temperature is 26°C, with temperatures ranging from 20°C to 35°C and a relative humidity of 67%–80% (unpublished 2022 meteorological data, Department of Animal Science, KNUST, Kumasi, Ghana).

Source of leaves and sampling procedure

In this study, an examination was conducted on fresh leaves from different plant types. These types comprised *Oxytenanthera abyssinica* (A. Rich.) Munro and *Bambusa balcooa* (Beema), *Megathyrsus maximus* (a type of grass), and *Bridelia ferruginea* (multipurpose trees, MPT). Leaves from *Megathyrsus maximus* and *Bridelia ferruginea* were sourced before reaching the flowering stage from naturally regrown plants located within a 1-km radius of the research site. Bamboo leaves were sourced from an INBAR[1] bamboo agroforestry site in the Ashanti region of Ghana. For leaf collection, specific criteria were followed. Two branches (that were not in an overly mature state) from approximately 4-year-old bamboo stands of each plant species were selected. Subsequently, the leaves were carefully removed from the branches and placed in separate containers. Primary dietary compositions were formulated using *M. maximus* and *B. ferruginea* leaves as the basal diet, and additional leaves from *O. abyssinica* and *B. balcooa* (bamboos) were used as supplementary components.

To enhance the reliability of the data, leaves for the laboratory analyses were also collected from three distinct locations for each group of plants: grass, MPT, and bamboo. Within each group, three sets (triplicates) of leaf samples were gathered from different locations. This approach ensured the accuracy of the data

[1] International Network of Bamboo and Rattan (INBAR) bamboo agroforestry cultivated in the Sekyere Central District of the Ashanti region, Ghana.

through the utilization of multiple statistical repetitions. For each fresh plant leaf biomass, approximately 3.0 kg of representative samples were packed in airtight bags separately and transported to the Animal Nutrition Laboratory at the Department of Animal Science, KNUST, Kumasi, Ghana, for chemical analysis.

Sample preparation and laboratory chemical analyses

At the lab, the leaf samples were chopped into smaller pieces and allowed to air dry in a room for 24 hours; afterwards, the samples were dried for 48 hours at 60°C in an oven to achieve a constant weight. The oven-dried samples were coarsely milled individually using a laboratory mill (Wiley Mill[2]), passed through a 2-mm screen, and then placed in ziplock bags. The nutritional composition of the milled plant biomass samples was subsequently determined using the proximate analytical procedure, following the standard methods outlined by the Association of Official Analytical Chemists (AOAC, 1990). This process encompassed the assessment of dry matter (DM), crude protein, ether extract (EE), crude fiber (CF), and ash content.

For the dry matter (DM) determination, fresh leaf samples were subjected to a hot air oven at 105°C for a duration of 8 hours. The DM content of forages were determined using the formula

$$\text{Dry matter (DM)} = \frac{weight\ \ of\ \ dry\ \ sample}{weight\ \ of\ \ fresh\ \ sample} \times\ \ 100\,\%$$

In this formula, the weight of dry sample refers to the weight of the forage sample after it has been dried in an oven at a specified temperature for a set duration. The weight of fresh sample refers to the initial weight of the forage sample before it is dried. The result is expressed as a percentage, indicating the proportion of the sample that remains after the removal of moisture. Meanwhile, total ash content was established through incineration at 550°C for 8 hours using a muffle furnace.

The calculation of crude protein involved determining nitrogen values (CP = N concentration × 6.25) using the Kjeldahl method (Rothman et al., 2006). This procedure capitalizes on the fact that amino acids, which contain nitrogen, form the basis of proteins. As amino acids in plants and muscle proteins generally contain 16% nitrogen, the multiplication of nitrogen concentrations by 6.25 (which is 100% divided by 16%) yields the protein content in the analyzed plant biomass.

The assessment of neutral detergent fiber (NDF) and acid detergent fiber (ADF) contents was carried out using an ANKOM[3] 2000 Automated Fiber Analyzer. This approach adhered to the established protocols as outlined by Van Soest et al. (1991). The acid detergent lignin (ADL) content was deduced by subjecting the acid detergent fiber residue to 72% sulfuric acid. All analyses were conducted in triplicate for each individual sample of the collected plant biomass, ensuring robust and reliable results.

Experimental design and dietary treatments

A total of 30 West African dwarf goats, with a mean initial body weight of 9.9 ± 0.21 kg, were allotted to five dietary treatment groups in a completely randomized design (CRD). Each treatment group consisted of six animals, employing a 2 × 2 factorial arrangement of treatments alongside a control treatment (basal diet). The treatments encompassed the following: T1 (control)—basal diet mix, comprising 60% *M. maximus* and 40% *B. ferruginea* leaves, offered to each animal under the assumption that an animal could consume 5% dry matter per day of forage relative to its body weight (NRC, 2007); T2—T1 diet supplemented with 400 g of *O. abyssinica* leaves per animal per day; T3—T1 diet supplemented with 400 g of *B. balcooa* leaves per animal per day; T4—T1 diet supplemented with 600 g of *O. abyssinica* leaves per animal per day; and T5—T1 diet supplemented with 600 g of *B. balcooa* leaves per animal per day.

Animal management, feed preparation, feeding, and manure collection

The goats were individually housed within a barn featuring a slatted floor measuring 4 × 7 ft. Before the commencement of the experiment, the animals underwent several preparatory procedures, including the application of plastic ear tags for identification, weighing, deworming, and vaccination against peste des petits ruminants (PPR). Furthermore, a multivitamin injection was administered, which was followed by a repeat administration on the 21st day of the experimental period. Throughout the 30-day study duration, uninterrupted access to feed, water, and a commercial mineral salt lick containing sodium chloride (with a sodium content of 38.05%) was maintained.

Before feed preparation and feeding, the bamboo leaf supplements were air dried in a drying room for 72 hours. Subsequently, they were chopped into 2.5-cm segments (Figure 7A) following weighing (Figure 7B), with allocation in accordance with the different treatment levels: 0 g (basal/control), 400 g, and 600 g. These prepared supplements were offered to the goats prior to their basal diet (Figure 7C) and administered twice daily at 09:00 and 16:00 using wooden feeding troughs (Figure 7D). This approach was chosen to ensure that the goats had adequate time to consume the bamboo supplements. The daily feed intake was quantified by calculating the difference between the provided feed quantity and the remaining amount. The intake rate, expressed as a percentage, was determined for both the basal diet and the supplements, representing the proportion of consumed feed to the provided feed. In addition, the supplement substitution rate, denoting the portion of total supplement intake relative to the overall feed intake, was assessed as a percentage. To evaluate the goats' efficiency in

[2] The Thomas ® Model 4 Wiley Mill. Made in the USA. Marketed and distributed by Onrion LLC, 93 South N Railroad Avenue, Bergenfield, NJ 07621-2352, USA.

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

converting feed into growth, the feed conversion efficiency was computed by dividing the cumulative weight gain of each goat by their total feed intake, and this value was expressed as a percentage.

To gather the manure samples, the slatted panels in each pen were removed each morning to collect fresh manure, which was promptly refrigerated. The manure sampling occurred throughout the 30-day span of the experiment. After the trial concluded, the refrigerated manure samples were combined (Figure 7E), and 10% of the pooled samples were selected, packaged (Figure 7F), and dispatched to the Crop and Soil Science Laboratory at KNUST, Kumasi, Ghana for chemical analysis. The total quantity of manure generated by the animals in the slatted pen was calculated using the following formula

$$Total\ \ manure = ASFM\ +\ DRMS$$

where ASFM refers to the accumulated slatted floor manure collected at the end of the trial period, and DRMS refers to the daily refrigerated manure samples.

The manure samples were analyzed to determine their organic carbon content, macrominerals (N, P, K, Ca, and Mg) content, microminerals (Fe, Zn, Cu, and Mn) content, pH level, and carbon-to-nitrogen ratio.

Statistical analysis

All data collected were statistically analyzed using the generalized linear model (GLM) procedures of Minitab 19 (Minitab, LLC 2019). Available at: www.minitab.com with the species of bamboo and the level of inclusion as fixed effects and with their interaction following the model $y_{ij} = \mu + \tau_j + \epsilon_{ij}$, in which μ=general mean, τ= treatment effect, and ϵ= random error. The statistical tests were conducted at a significance level of 5%. The Tukey method was used to compare the significant differences between the treatment means.

Results and discussion

Analysis of the chemical composition of the individual leaf ingredients

The analysis of the chemical composition of forage is of critical importance to the evaluation of its nutritional suitability for animals. In this study, the chemical compositions of various leaf ingredients were examined to gain insights into the variations and the implications for forage quality. Table 1 shows the nutrient compositions of the experimental leaf ingredients fed to the animals. In this study, the chemical compositions of various leaf ingredients were examined to gain insights into the variations and the implications for forage quality. The results revealed significant differences (p < 0.05) in key parameters, providing valuable information for optimizing animal nutrition and performance. The notable variation (p = 0.003) in dry matter (DM) content across the different feed ingredients holds significance for feed formulation. The observed values ranged from 894.3 g/kg DM in *B. ferruginea*, to 894.7 g/kg DM in *M. maximus*, to 909.9 g/kg DM in both *B. balcooa* and *O. abyssinica*. These values were found to be consistent with the DM content of various forage species, including

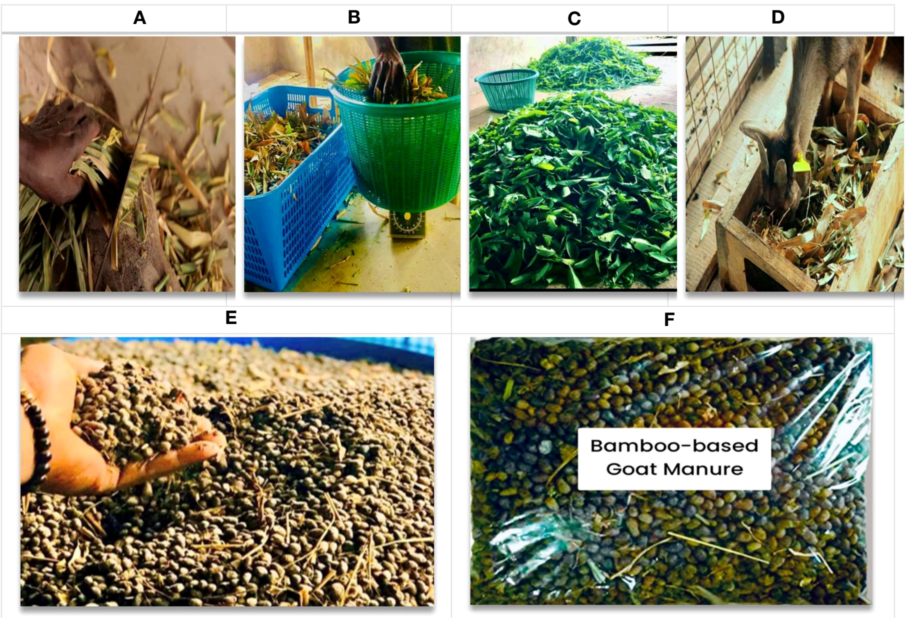

FIGURE 7
Experimental feed processing, feeding, and manure sampling procedures. **(A)** Chopping of bamboo leaf supplement. **(B)** Weighing of bamboo leaf supplement in accordance with the different treatment levels. **(C)** Mixing of basal diet. **(D)** Feeding bamboo leaf supplement before the basal diet, administered twice daily at 09:00 and 16:00, using wooden feeding troughs. **(E)** Pooled refrigerated manure samples. **(F)** Packing of 10% of pooled samples for analysis. *Source: Field data, 2021; Bamboo fodder research, Department of Animal Science, KNUST, Kumasi, Ghana*. Picture courtesy: Field Photo taken by Sasu, 2021.

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TABLE 1 Analytical chemical compositions of the dry matter in the leaf ingredients fed to goats.

	Composition (g/kg DM)								
Leaf Ingredients	DM	Ash	CP	N	OM	CF	NDF	ADF	ADL
B. balcooa	909.9[a]	131.6[b]	103.1[c]	16.5[c]	868.4[b]	279.2[b]	481.0[a]	320.2[c]	0.9[c]
O. abyssinica	904.3[ab]	138.8[b]	142.9[b]	22.9[b]	851.2[b]	270.5[b]	457.8[b]	326.5[c]	0.5[c]
B. ferruginea	894.3[c]	155.5[a]	194.0[a]	31.0[a]	844.4[c]	301.9[a]	478.5[a]	429.3[a]	3.6[a]
M. maximus	894.7[bc]	88.8[c]	53.7[d]	8.6[d]	911.2[a]	261.7[b]	480.5[a]	341.6[b]	2.4[b]
SEM	0.212	0.757	1.560	0.250	0.757	1.59	0.221	0.624	0.037
p-value	0.003	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

[a,b,c,d] Mean values within a column with the same superscript letter are not significantly ($p > 0.05$) different.
DM, dry matter; CP, crude protein; N, nitrogen; OM, organic matter; CF, crude fiber; NDF, neutral detergent fiber; ADF, acid detergent fiber; ADL, acid detergent lignin; SEM, standard error of means.

Moringa oleifera, Terminalia catappa, Mangifera indica, and *Blighia sapida*. Similar findings to these were reported in a study conducted within the same geographic region (Sasu et al., 2023a; Sasu et al., 2023b).

The data reveal variations in moisture content among the different leaf types, which impact on nutrient concentration and digestion. Leaves with lower moisture levels, such as those of *B. balcooa* and *O. abyssinica* (assessed both in this study and in previous studies), are nutrient rich due to their reduced water content. Conversely, leaves with a slightly higher moisture content, such as those of *B. ferruginea* (examined in this study), and others such as those of *M. oleifera, T. catappa, M. indica, B. sapida*, and *M. maximus* (previously studied), may influence overall feed nutrient levels. Consideration of the moisture content of ingredients is vital when designing ruminant diets. Variations in DM content and moisture levels significantly impact how different forages are chosen and mixed. The goal is to create a balanced feed while considering these moisture-related differences so that the overall nutritional content and digestibility of the feed are improved. Importantly, all the leaves studied had similar DM contents to common tropical leguminous trees (Norton, 1994), tropical browses (Le Houerou, 1980), and the leaves and stems of *Stylosanthes hemata* (Attoh-Kotoku, 2003). This similarity suggests that they are excellent choices for feeding ruminant animals.

Furthermore, their abundant nitrogen content gives them an advantage, since nitrogen is pivotal in ruminant nutrition as it forms the basic building block for synthesizing protein. Proteins are essential for various bodily functions in ruminants, including tissue growth, milk production, and enzyme creation. Maintaining a proper balance of nitrogen in the diet ensures optimal microbial fermentation in the rumen and the effective use of dietary nutrients, contributing to the overall wellbeing and productivity of the animals. The substantial variations ($p < 0.001$) observed in nitrogen (N) content among the forages assayed in this study carry noteworthy implications for their integration into the diets of small ruminants, especially of goats. The nitrogen content ranged from 8.6 g/kg DM in *M. maximus* to 31.0 g/kg DM in *B. ferruginea*, with intermediate values of 16.5 g/kg DM in *B. balcooa* and 22.9 g/kg DM in *O. abyssinica*. This variation indicates the presence of various nitrogenous compounds, derived from both protein and non-protein nitrogen sources, collectively contributing to the overall nutritional composition of the forages. The marked variability in the crude protein (CP) content of the forages is noteworthy, with values ($p < 0.001$) ranging from 53.7 g/kg DM in *M. maximus* to 194.0 g/kg DM in *B. ferruginea*. This wide range highlights the distinct protein profiles within these ingredients. The examination of crude protein (CP) content within different leaf ingredients provides valuable insights into their nutritional profiles and potential applications in ruminant diets. In the context of this study, *B. ferruginea* leaves had a slightly lower CP content than *M. oleifera* leaves, yet a higher content than *T. catapa* and *M. indica* leaves. Interestingly, the CP content of *B. ferruginea* leaves was found to be similar to that of *B. sapida* leaves from the same geographical area, and also to those of *Gliricidia sepium* and *Leucaena leucocephala* leaves, as reported by Abdulrazak et al. (1997). The observed CP content in *B. ferruginea* indicates its richness in terms of essential amino acids, which, by supporting the amino acid requirements of the ingesting animals, are of paramount significance to the facilitation of optimal animal growth and fundamental physiological functions. Conversely, the comparatively lower CP content in *M. maximus* suggests that there is a reduced availability of amino acids in this forage.

In the context of promoting bamboo agroforestry, as emphasized in this study, a thoughtful integration of these forages can be strategically designed to enhance ruminant nutrition. The amino acid richness found in *B. ferruginea* can effectively compensate for the limited amino acid content in *M. maximus*. Concurrently, the inclusion of bamboo leaves can provide additional nutritional supplementation. This amalgamation aims to establish a harmonious equilibrium in the protein and amino acid composition of the feed mixture, effectively mitigating potential nutritional gaps and optimizing overall advantages for the animals. This strategic approach resonates with the holistic goals of agroforestry systems, in which various plant constituents synergize to amplify animal wellbeing and productivity.

Within the scope of this study, the two bamboo species, *O. abyssinica* and *B. balcooa*, exhibited distinctive nutritional traits, as previously noted in related investigations (Sasu et al., 2022; Sasu et al., 2023a; Sasu et al., 2023b). Notably, both bamboo species demonstrated higher levels of crude protein (CP) than their grass counterpart, *M. maximus*. This indicates their substantial nutrient contents, setting them apart from conventional pasture grasses and positioning them as potentially valuable resources for promoting animal growth and productivity. These findings correspond with data on other bamboo species such as *Bambusa tulda* and *Dendrocalamus* spp. (Poudyal, 1993; Bhandari et al., 2015), which reinforce the fact that bamboo has the potential to boost animal wellbeing and productivity. Extensive documentation by various researchers (Artabandhu et al., 2010; Sahoo et al., 2010; Andriarimalala et al., 2019; Kitaw et al., 2022; Sasu et al., 2022; Sasu et al., 2023a; Sasu et al., 2023b) supports this assertion. Notwithstanding, it is important to recognize that bamboo fodder is most effective when incorporated as a supplement within various forage blends and/or alongside concentrates. This strategic approach enhances the organic matter content of the feed concentrate, a contrast to relying solely on bamboo fodder as the primary feed source for ruminants (Sasu et al., 2023b).

Organic matter (OM) is a cornerstone of ruminant nutrition, constituting components of feed subject to microbial fermentation in the rumen. It serves as a pivotal energy source, fostering microbial growth and fermentation, and aiding in the breakdown of complex carbohydrates into volatile fatty acids. The equilibrium of organic matter intake underpins efficient nutrient utilization, energy production, and overall ruminant wellbeing. The appreciable diversity in OM content across the examined forages has profound implications for the nutritional strategies discussed in this study. The observed range ($p < 0.001$) of OM levels in this study spanned from 911.2 g/kg DM in *M. maximus* to 844.4 g/kg DM in *B. ferruginea*, 851.2 g/kg DM in *O. abyssinica*, and 868.4 g/kg DM in *B. balcooa*. This variation highlights differences in the overall organic composition of the leaf ingredients and their potential contributions to the energy availability of the diet. For instance, the inclusion of *M. maximus*, with its relatively high OM content, in the basal diet mixture with *B. ferruginea* could enhance the energy availability of the overall diet. This strategic combination was employed to balance the energy content of the diet, taking advantage of the energy-rich *M. maximus* leaves to complement the nutritional profile of *B. ferruginea*. In addition, the blending of feed ingredients aligns with the aim of optimizing the nutritional intake and performance of the goats. The OM contents of all the forages analyzed in the current study were comparable to forage species that were reported to have higher potential for small ruminant nutrition (Vierre and Van, 1982; Oduro et al., 2009; Sasu et al., 2022; Sasu et al., 2023a; Sasu et al., 2023b). Thus, diets could be formulated to meet the energy–mineral balance supply required by small ruminants for various physiological functions.

Maintaining the right balance of minerals through ash content is pivotal to ruminant nutrition. This equilibrium greatly influences various physiological functions, including bone development, enzyme activity, and general metabolic processes in ruminants. Keeping minerals in check improves the growth, reproductive capacity, and overall health of animals. The spectrum ($p < 0.001$) of ash content recorded for the forages, comprising *B. ferruginea* (155.5 g/kg DM), *B. balcooa* (131.6 g/kg DM), *O. abyssinica* (138.8 g/kg DM), and *M. maximus* (88.8 g/kg DM), underscores the significant disparities in their mineral concentrations. In addition, the variability in ash content has the potential to influence the digestibility and utilization of other nutrients inherent in these feed constituents. The ash content found in *B. ferrugine*, akin to those of other multipurpose tree (MPT) species such as *M. oleifera* and *B. sapida*, and surpassing that of *T. catappa* and *M. indica* analyzed within the same region (Sasu et al., 2023a), implies a potential abundance of mineral elements. Conversely, the relatively low ash content observed in *M. maximus*, as noted previously in the same grass species (Sasu et al., 2023b), suggests a comparably lower mineral concentration, possibly due to varying soil and climatic conditions and differences in plant maturation during the periods when these two studies were conducted. These deviations in mineral levels carry implications for the accessibility of essential nutrients for consuming animals, exerting wider effects on the animals' metabolic processes and overall wellbeing. Hence, a comprehensive grasp of these distinctions is of paramount importance when formulating the diets of small ruminants.

Further analysis of the fiber contents in the forages provided intriguing insights. The crude fiber content ranged ($p < 0.001$) from 261.7 g/kg DM in *M. maximus*, to 270.5 g/kg DM in *O. abyssinica*, to 279.2 g/kg DM in *B. balcooa*, to 301.9 g/kg DM in *B. ferruginea*. By comparison, the neutral detergent fiber (NDF) content ranged ($p < 0.001$) from 457.8 g/kg DM in *O. abyssinica*, to 478.5 g/kg DM in *B. ferruginea*, 480.5 g/kg DM in *M. maximus* to 481.0 g/kg DM in *B. balcooa*, suggesting distinct differences in the fibrous components of the forages. This variation can impact feed intake and digestibility, affecting animal performance. Similarly, the acid detergent fiber (ADF) content varied ($p < 0.001$) from 320.2 g/kg DM in *B. balcooa*, to 326.5 g/kg DM in *O. abyssinica*, to 341.6 g/kg DM in *M. maximus*, to 429.2 g/kg DM in *B. ferruginea*, indicating variations in cellulose and lignin levels. These differences in fibrous components can affect rumen function, nutrient utilization, and overall digestibility. The acid detergent lignin (ADL) content displayed variation ($p < 0.001$), ranging from 0.5 g/kg DM in *O. abyssinica*, to 0.9 g/kg DM in *B. balcooa*, to 2.4 g/kg DM in *M. maximus*, to 3.6 g/kg DM in *B. ferruginea*, which in turn demonstrates variations in the proportion of lignin. Lignin is a complex compound that provides structural integrity to the plant cell wall. Its content can influence forage digestibility and nutrient availability for animals. These variations in fiber components have multifaceted implications for ruminant animal nutrition and performance, intertwining them with the concept of agroforestry involving bamboo. This pivotal insight emphasizes the need for farmers to meticulously account for these differences when constructing diets for their animals within agroforestry setups. By combining feeds with contrasting fiber profiles, such as bamboo, farmers have the opportunity to craft an integrated diet that increases animals' feed intake, eases their digestion, and improves their health—an approach that resonates harmoniously with the holistic ethos of agroforestry. Bamboo leaves bring their own distinctive fiber characteristics, making their thoughtful inclusion key to the formulation of diets within agroforestry contexts. The overarching objective is to strike a harmonious balance, one that ensures animals receive the requisite nutrients, that their digestion is streamlined, and that elevates their overall performance. This synergy between feed components and agroforestry principles optimizes the sustainable, multifaceted benefits of such integrated systems.

In examining the nutritional content of the two bamboo species, valuable insights emerge for their relevance within agroforestry frameworks. Notably, *O. abyssinica* leaves manifest superior nutritional attributes compared with *B. balcooa* leaves. This discovery resonates with earlier findings (Sasu et al., 2022; Sasu et al., 2023a; Sasu et al., 2023b), indicating the nutritional consistency of *O. abyssinica* across different seasons, aligning seamlessly with the dynamic agroforestry landscape. This constancy is especially important when contrasted with the fluctuating quality of naturally growing pasture grasses, solidifying the role of bamboo within the agroforestry narrative.

Feed intake and growth performance of the experimental goats

Table 2 shows the feed intake and growth performance of the experimental animals.

The assessment of supplement type, represented by distinct bamboo species, did not have a significant effect (p = 0.79) on the average daily gain (ADG) of the goats. Nonetheless, an intriguing trend emerged in the feeding behaviors and outcomes. Notably, the goats consuming the *B. balcooa* supplement exhibited a higher intake (247 g per day) than those consuming the *O. abyssinica* supplement (191 g per day). However, this heightened consumption was paralleled by a lower feed conversion efficiency of 2.3% for the goats that consumed the *B. balcooa* supplement, contrasting with the greater feed conversion efficiency of 11.5% recorded for those consuming the *O. abyssinica* supplement.

Upon further scrutiny of the dietary patterns, a distinct and significant trend emerges. Notably, the group of animals fed with the *B. balcooa* supplement displayed a marked reduction in both basal intake (195 g per day) and daily feed intake (442 g per day) compared with their counterparts consuming the *O. abyssinica* supplement, which exhibited notably higher basal intake and daily feed intake values of 260 g per day and 450 g per day, respectively. These subtle yet substantive variations in consumption dynamics and efficiency contribute comprehensively to our understanding of how these supplements intricately interact with goat performance within the controlled experimental context. This distinction in intake could be attributed to the higher substitution potential of *B. balcooa* leaves (57%) relative to *O. abyssinica* leaves (43%). In contrast, the levels of supplementation exerted a discernible impact on several metrics, namely, average daily gain, daily supplement intake, and basal diet intake (p < 0.001). Interestingly, the data reveal that, on average, animal groups given 600 g of the supplement per day exhibited a heightened consumption, showing an increase of 178 g per day (equivalent to a 30% rise) compared with those receiving 400 g per day, which showed a rise in consumption of 114 g per day (reflecting a 29% increase). Bringing these findings together enhances our understanding of the intricate dynamics behind supplement consumption and its interplay with goat performance. This finding emphasizes the multifaceted factors that shape dietary preferences and their tangible effects on the wellbeing of the studied animals.

Correspondingly, a substitution effect of the supplement on the basal diet was observed, with animal groups provided 600 g of the supplement per day substituting 42% of the basal diet, resulting in an intake of 241 g per day (equivalent to 60% of the basal diet). In contrast, those receiving 400 g of the supplement per day showed a substitution of 25% and consumed 326 g of feed per day (equivalent to 82% of the basal diet). This phenomenon could contribute to the lower daily feed intake (DFI) and reduced feed conversion efficiency

TABLE 2 Feed intake and growth performance of goats fed either a basal diet only or a basal diet supplemented with bamboo leaves.

	Species (S)		Level (L)		S×L					SEM	*p*-value		
Variable	OA	BB	400	600	T1-CON	T2-OA400	T3-BB400	T4-OA600	T5-BB600		S	L	S×L
Animals (n = 30)	*15*	*15*	*15*	*15*	*6*	*6*	*6*	*6*	*6*				
ILW (kg)	9.8	9.9	9.9	9.9	9.5	9.8	9.9	9.9	9.9	0.04	0.874	0.716	0.874
FLW (kg)	11.5^{a}	11.4^{a}	11.6^{a}	10.9^{b}	10.8^{b}	12.2^{a}	11.8^{a}	11.1^{b}	11.1^{b}	0.10	0.675	<0.001	<0.001
ADG (g/d)	52.8^{a}	50.0^{a}	53.7^{a}	33.3^{b}	27.8^{b}	72.2^{a}	61.1^{a}	33.3^{b}	38.9^{b}	3.20	0.786	<0.001	<0.001
BI (g/d)	260^{a}	195^{b}	326^{a}	241^{b}	397^{a}	309^{b}	273^{c}	211^{d}	117^{e}	16.90	<0.001	<0.001	<0.001
BIR (%)	64.9^{a}	48.8^{b}	81.6^{a}	60.4^{b}	99.3^{a}	77.3^{b}	68.3^{c}	52.6^{d}	29.3^{e}	4.22	<0.001	<0.001	<0.001
SI (g/d)	191^{b}	247^{a}	114.^{b}	178^{a}	0.00^{e}	147^{d}	195^{c}	235^{b}	298^{a}	19.30	<0.001	<0.001	<0.001
SIR (%)	38.0^{b}	49.2^{a}	28.5^{a}	29.7^{a}	0.00^{c}	36.8^{b}	48.7^{a}	39.2^{b}	49.7^{a}	3.60	<0.001	0.331	<0.001
SSR (%)	42.7^{b}	56.5^{a}	24.6^{b}	41.5^{a}	0.00^{e}	33.2^{d}	41.5^{c}	53.1^{b}	71.5^{a}	4. 50	<0.001	<0.001	<0.001
DFI (g/d)	450^{a}	442^{b}	441^{a}	418^{b}	398^{c}	456^{a}	469^{a}	443^{ab}	415^{bc}	5.75	0.003	<0.001	0.009
%FCE	11.5^{a}	2.3^{b}	8.5^{a}	5.3^{b}	6.9^{b}	15.6^{a}	3.0^{c}	7.4^{b}	9.4^{c}	0.81	<0.001	<0.001	<0.001

$^{a, b, c, d, e}$ Mean values within a row with the same or no superscript letter are not significantly (p > 0.05) different.
T1 = treatment 1 (basal diet of Megathyrsus maximus and Bridelia ferruginea leaves as control); T2 = treatment 2 (T1 supplemented with 400 g of O. abyssinica leaves); T3 = treatment 3 (T1 supplemented with 400 g of B. balcooa leaves); T4 = treatment 4 (T1 supplemented with 600 g of O. abyssinica leaves); and T5 = treatment 5 (T1 supplemented with 600 g of B. balcooa leaves). ILW, initial live weight; FLW, final live weight; ADG, average daily gain; BI, basal intake; BIR, basal intake rate; SI, supplement intake; SIR, supplement intake rate; SSR, supplement substitution rate; DFI, daily feed intake; FCE, feed conversion efficiency; S= species; L, level of supplementation; S×L, species by level interaction; OA, Oxytenanthera abyssinica bamboo; BB, Bambusa balcooa bamboo; CON, control.

(FCE) observed among animal groups receiving 600 g per day of the supplement, for which DFI and FCE values of 418 g per day and 5.3% were registered, respectively. In comparison, the animal groups given 400 g of the supplement per day exhibited a DFI and FCE of 441 g per day and 8.5%, respectively.

The dry matter intake of bamboo leaves ranged from 1.6 kg per day to 7.1 kg per day, with an average intake of 4.8 kg per day. Notably, this intake surpassed the value reported by Andriarimalala et al. (2019), signifying an improved dry matter consumption of bamboo leaves in this study.

A significant interactive effect of the bamboo species and supplementation level on dry matter intake (DFI), average daily gain (ADG), and feed conversion efficiency (FCE) was observed (p = 0.009). Among the animal groups, those fed the T2 diet exhibited the highest values across these parameters, recording a DFI of 456 g per day, an ADG of 72 g per day, and an FCE of 16%. Subsequently, the groups that received T3, T5, T4, and T1 followed with DFI values of 469 g per day, 415 g per day, 443 g per day, and 398 g per day, respectively, and had ADG values of 61 g per day, 39 g per day, 33 g per day, and 29 g per day, respectively. The corresponding FCE values were 3%, 9%, 7%, and 6% for these groups.

The outcomes observed for T2, namely that the animal group fed this diet displayed the highest values for dry matter intake (DFI), average daily gain (ADG), and feed conversion efficiency (FCE), could be attributed to the specific combination of bamboo species and supplementation level. This interaction might have led to a synergistic effect that optimally supported the nutritional requirements and physiological processes of the goats. The factors influencing this result could include the nutrient profile of the chosen bamboo species in T2, the compatibility of these nutrients with the goats' digestive system, and the potential interaction between bamboo leaves and the basal diet.

The presence of these vital nutrients within bamboo leaves, as noted by Andriarimalala et al., 2019, could have synergistically complemented the energy content and intake provided by the grass-tree leaf basal diet. This harmonious nutrient interplay might have consequently contributed to enhanced feed intake, growth, and overall efficiency among the goats.

Consequently, the feed conversion efficiency (FCE) results were as follows: the T2-fed group had the highest efficiency, followed by the T4-, T1-, T3-, and T5-fed groups. A higher FCE signifies an animal's adeptness in converting consumed food into body mass, rendering the animal group that were fed T2 the most efficient in this aspect. This phenomenon could potentially be attributed to the high crude protein (CP) content inherent in the supplement employed for diet formulation, an observation consistent with previous findings showing that a combination of 50% bamboo leaves and 20% neem seed cake supplement led to improved feed-to-gain ratios, subsequently enhancing average daily gain and body weight in growing rams (Okoruwa et al., 2021). In contrast, the addition of bamboo leaves to maize silage did not influence the milk production capacity of dairy cattle (Andriarimalala et al., 2019), indicating species-specific responses to bamboo supplementation in different livestock.

Quantity and quality of manure from the experimental goats

Table 3 summarizes the quantity and quality of manure from the experimental goats.

The choice of supplement type, represented by different bamboo species, displayed a mixed impact on various manure attributes. Notably, it had no significant effect on manure weight (p = 0.481), the feed intake-to-manure ratio, (p = 0.621), or the calcium (Ca) (p = 0.631) and copper (Cu), (p = 0.255) contents of the manure. However, the supplement type significantly influenced ($p < 0.05$) other manure characteristics, such as the carbon-to-nitrogen (C:N) ratio; the pH levels; and the contents of fecal nitrogen (N), organic carbon (C), ash, phosphorus (P), potassium (K), magnesium (Mg), iron (Fe), zinc (Zn), and manganese (Mn).

Comparative analysis revealed that the *B. balcooa*-supplemented animals produced manure with higher contents of organic C (287 g/kg DM), C:N ratio (18), zinc (Zn) content (89 mg/kg DM), magnesium (Mg) content (4.8 g/kg DM), manganese (Mn) content (196 mg/kg DM), and ash content (160 g/kg DM) than the *O. abyssinica*-supplemented groups. Conversely, the *O. abyssinica*-supplemented groups yielded manure with the highest nitrogen (N) content (20 g/kg DM), pH level (5.2), phosphorus (P) content (7 g/kg DM), potassium (K) content (7 g/kg DM), and fluorine (F) content (185 mg/kg DM). These outcomes indicate the varied impact of different bamboo species supplements on the resulting manure attributes.

The impact of supplementation levels on various aspects of manure attributes was further examined, revealing significant outcomes ($p < 0.05$). Specifically, it affected the manure weight; feed intake to manure ratio; contents of fecal organic C and N; the C:N ratio; pH levels; and the contents of K, Ca, Mg, Zn, and Cu. However, the supplementation levels did not significantly impact ($p > 0.05$) the contents of ash, Fe, Mn, and P.

Comparatively, goats receiving 400 g of the supplement recorded a higher feed intake-to-manure ratio (1.8) and fecal N content (19 g/kg DM) than those fed 600 g of the supplement per day, which recorded values of 1.6 and 17 g/kg DM for the intake-to-manure ratio and fecal N content, respectively. Conversely, animals fed 600 g of the supplement per day produced a greater manure weight (258 g per day) than those fed 400 g of the supplement per day (247 g per day). In addition, higher levels of fecal organic C (307 g/kg DM); a higher C:N ratio (19); higher pH level (5.1); and higher K (6 g/kg DM), Ca (10 g/kg DM), Mg (4.4 mg/kg DM), Zn (92 mg/kg DM), and Cu (68 mg/kg DM) contents were observed in goats receiving 600 g of the supplement per day than in those that received 400 g of the supplement per day, for which we observed a fecal organic C level of 279 g/kg DM; a C:N ratio of 15; a pH of 5; and K, Ca, Mg, Zn, and Cu contents of 5.4 g/kg DM, 8.4 g/kg DM, 3.9 mg/kg DM, 84 mg/kg DM, and 58 mg/kg DM, respectively.

Furthermore, there was a significant ($p < 0.05$) combined interaction effect the supplement types (bamboo species) and supplementation levels on various manure attributes. This interaction effect impacted manure weight; the feed intake-to-manure ratio; fecal organic C and N contents; the C:N ratio; and

TABLE 3 Quantity and quality of the manure from the goats fed either a basal diet only or a basal diet supplemented with bamboo leaves.

	Species (S)		Level (L)		S×L					SEM	*p*-value		
Variable	OA	BB	400	600	T1-CON	T2-OA400	T3-BB400	T4-OA600	T5-BB600		S	L	S×L
Animals (n=30)	*15*	*15*	*15*	*15*	*6*	*6*	*6*	*6*	*6*				
MWT (g/d)	250^{a}	254^{a}	247^{b}	258^{a}	252^{ab}	241^{b}	247^{b}	261^{a}	260^{a}	1.540	0.481	<0.001	0.001
I:M ratio	1.8^{a}	1.8^{a}	1.8^{a}	1.6^{b}	1.6^{b}	1.9^{a}	1.9^{a}	1.7^{b}	1.6^{b}	0.027	0.621	<0.001	0.001
C (g/kg DM)	249.5^{b}	287.2^{a}	278.7^{b}	306.8^{a}	341.4^{a}	210.1^{c}	284.5^{b}	289.0^{b}	289.9^{b}	1.080	<0.001	<0.001	<0.001
N (g/kg DM)	19.5^{a}	16.5^{b}	19.4^{a}	16.8^{b}	18.2^{b}	21.1^{a}	18.8^{b}	17.8^{b}	14.2^{c}	0.050	<0.001	<0.001	<0.001
C: N ratio	13.1^{b}	17.8^{a}	14.6^{b}	18.5^{a}	18.7^{b}	9.9^{d}	15.2^{c}	16.2^{c}	20.3^{a}	0.836	<0.001	<0.001	<0.001
Acidity (pH)	5.2^{a}	5.1^{b}	5.0^{b}	5.1^{a}	4.8^{a}	5.2^{a}	5.1^{a}	5.3^{a}	5.1^{a}	0.042	<0.001	0.019	0.129
Ash (g/kg DM)	130.2^{b}	160.0^{a}	119.6^{a}	122.8^{a}	73.3^{d}	120.7^{c}	164.7^{a}	139.7^{b}	155.3^{a}	0.889	<0.001	0.141	<0.001
P (g/kg DM)	6.8^{a}	5.0^{b}	5.7^{a}	5.8^{a}	5.5^{a}	6.9^{a}	4.7^{a}	6.6^{a}	5.3^{a}	0.020	<0.001	0.702	0.204
K (g/kg DM)	6.6^{a}	4.5^{b}	5.4^{b}	6.1^{a}	5.9^{b}	6.0^{b}	4.2^{d}	7.3^{a}	5.0^{b}	0.024	<0.001	<0.001	0.008
Ca (g/kg DM)	10.2^{a}	9.7^{a}	8.4^{b}	9.6^{a}	7.5^{d}	9.9^{b}	8.5^{c}	10.5^{ab}	11.0^{a}	0.034	0.631	<0.001	<0.001
Mg (g/kg DM)	4.5^{b}	4.8^{a}	3.9^{b}	4.4^{a}	3.2^{c}	4.6^{b}	3.9^{bc}	4.4^{b}	5.7^{a}	0.022	<0.001	0.009	0.001
Fe (mg/kg DM)	184.9^{a}	176.3^{b}	177.3^{a}	179.5^{a}	176.3^{a}	182.4^{a}	173.0^{a}	187.3^{a}	174.8^{a}	1.760	0.032	0.491	0.813
Zn (mg/kg DM)	80.4^{b}	89.1^{a}	83.6^{b}	91.9^{a}	93.7^{a}	74.4^{c}	82.7^{b}	86.4^{b}	95.6^{a}	1.870	<0.001	<0.001	<0.001
Mn (mg/kg DM)	154.1^{b}	195.8^{a}	132.2^{a}	135.7^{a}	51.9^{c}	145.7^{b}	198.9^{a}	162.4^{b}	192.7^{a}	14.900	<0.001	0.500	0.0200
Cu (mg/kg DM)	61.1^{a}	63.6^{a}	58.0^{b}	68.1^{a}	64.5^{b}	57.0^{bc}	52.6^{c}	65.1^{ab}	74.5^{a}	1.800	0.255	<0.001	0.001

[a, b, c, d, e] Mean values within a row with the same superscript letters are not significantly ($p > 0.05$) different.
MWT, manure weight; I:M ratio, feed intake-to-manure ratio; S, bamboo species; L, level of supplementation; S×L, species by level interaction; OA, Oxytenanthera abyssinica bamboo; BB, Bambusa balcooa bamboo.
T1, treatment 1 (basal diet of Megathyrsus maximus and Bridelia ferruginea leaves as control); T2, treatment 2 (T1 supplemented with 400 g of O. abyssinica leaves); T3, treatment 3 (T1 supplemented with 400 g of B. balcooa leaves); T4, treatment 4 (T1 supplemented with 600 g of O. abyssinica leaves); and T5, treatment 5 (T1 supplemented with 600 g of B. balcooa leaves).

ash, K, Ca, Mg, Zn, and Cu contents. However, the pH levels and the contents of P, Fe, and Mn were not significantly ($p > 0.05$) affected by this interaction. Notably, the results indicated that the highest manure weight and, by extension, the lowest feed intake-to-manure ratio was produced by the animal groups that consumed T4 and T5, followed by those that consumed T1 and T3, and the lowest value was recorded for those that consumed T2.

In the context of integrating bamboo as fodder in agroforestry systems, the quality of resulting manure is of paramount importance. Our study's focus on manure quality assessment, particularly nitrogen (N) content and carbon-to-nitrogen (C:N) ratio, holds relevance. Generally, our experimental goats showed a broader range of manure weight (241 g to 261 g per day) than those shown in previous studies on goats (179 g to 218 g per day) and sheep (319 g to 423 g per day) by Ansah et al. (2019), and one on sheep (430 g to 458 g per day) by Irungu et al. (2005). The fecal N output, in descending order, was as follows: it was highest for the T2-fed group, followed by the T3-, T1-, T4-, then T5-fed group.

The increased fecal N output observed in the T2-fed group can be attributed to the relatively high crude protein content of the supplement used for this group, as highlighted in a previous study by Ansah et al. (2019). This underscores the significant role of supplement composition in influencing nutrient excretion patterns, with potential implications for overall livestock performance.

The fecal organic C output followed a descending trend among the treatment groups: the highest was observed for the T1-fed group (control), followed by the T5-, T4-, T3-, then the T2-fed group. Similarly, the C:N ratio, in descending order, was as follows: it was highest for the T5-fed group, followed by the T1-, T4-, T3-, then the T2-fed group. This intriguing pattern suggests that the inclusion of bamboo leaves in the basal diet at comparatively lower levels led to an enhancement in the resulting manure quality. This finding resonates with the observations of Larney et al. (2006), who attributed such improvements to the supplementary effect.

In addition, the organic C and N values recorded in the current study, which ranged from 210 g/kg DM to 341 g/kg DM for organic C and 14 g/kg DM to 21 g/kg DM for N, were consistent with the corresponding values reported by Ansah et al. (2019) and Moral et al. (2005) for similar goat species. Specifically, our results aligned with the values of 230 g/kg DM to 306 g/kg DM for organic C and 16 g/kg DM to 22 g/kg DM for N reported by Ansah et al. (2019), and the values of 264 g/kg DM to 381 g/kg DM for organic C and 14 g/kg DM to 23 g/kg DM for N reported by Moral et al. (2005). A noteworthy observation was made for the range of fecal C:N ratios (10–19) recorded among the supplemented animals. This range notably fell below the value of 20 recorded for the control group. The significance of this lies in the fact that a C:N ratio below 20 is essential for facilitating effective net mineralization when the manure is freshly applied to the soil (Saha et al., 2008; Ansah et al., 2019). This aspect is particularly valuable as it promotes improved soil nutrient availability—an advantageous outcome associated with the application of such nutrient-rich manure (Mando et al., 2005). Our findings show that incorporating bamboo into agroforestry systems holds potential implications for manure quality, a crucial aspect of nutrient cycling and soil health. As highlighted by Bationo et al. (2004), high-quality manure is often characterized by an N content above 16 g/kg DM or a C:N ratio below 10, whereas low-quality manure may exhibit an N content below 6 g/kg DM and a C:N ratio exceeding 17. The fecal C:N ratios across various groups consistently stayed below 17, signifying that predominantly high-quality manure was produced. Notably, that produced by the animals receiving T1 and T5 showed deviations from this trend, underscoring the potential variation in manure quality outcomes based on the type of bamboo leaves used as supplementation. For agroforestry practitioners, these insights are crucial. Bamboo supplementation not only impacts livestock nutrition but also influences manure composition, thereby affecting nutrient cycling and soil health. As agroforestry evolves, understanding the implications of bamboo integration on manure quality enhances the sustainable and productive potential of these systems.

In addition, the observed fecal pH values in our study, ranging from 4.8 to 5.3, demonstrated noticeable variability, surpassing the measurements reported for sheep and goats in the research conducted by Ansah et al. (2019). Nevertheless, this outcome aligns with the common notion that fresh manure tends to exhibit acidity, as indicated by KATC (2004). Intriguingly, our results carry a significant implication—the highest pH values were linked to the manure enriched with bamboo supplementation, which was consistent with the findings of Ansah et al. (2019), hinting a potential avenue for enhancing soil quality.

The ash content, reflecting mineral composition, exhibited significant variation ($p < 0.001$), and was highest for the T3 group, followed by the T5, T4, T2, then T1 group. This variation, which likely stems from dissimilar organic matter levels in the two bamboo supplements, aligns with the idea that varying ash content in manure indicates that there are different levels of inorganic components in feeding materials (Ansah et al., 2019). These findings help elucidate the disparities in fecal mineral composition observed in our study and earlier ones (Kausar, 1983; Alvåsen, 2009; Ansah et al., 2019). Whereas fecal P (p = 0.204) and Fe (p = 0.813) contents were consistent among treatments, notable variation ($p < 0.05$) was observed for Ca, Mg, Mn, Zn, and Cu contents. The order of variation was as follows: Ca content was greatest for the T5-fed group, followed by the T4-, T2-, T3-, then T1-fed group; Mg content was greatest for the T5-fed group, followed by the T2-, T4-, T3-, then T1-fed group; Mn content was greatest for the T3-fed group, followed by the T5-, T4-, T2-, then T1-fed group; Zn content was greatest for the T5-fed group, followed by the T1-, T4-, T3-, then T2-fed group; and Cu content was greatest for the T5-fed group, followed by the T4-, T1-, T2-, then T3-fed group. Overall, our documented fecal mineral compositions paralleled findings from Ansah et al. (2019) and Kausar (1983), as referenced in the study by Alvåsen (2009).

Our findings project that a West African dwarf (WAD) goat, weighing approximately of 9.9 kg and receiving a basal diet with bamboo leaf supplementation, could yield approximately 71.3 kg of dry matter-based manure annually, containing 6.5 kg N, 2.1 kg P, and 2.0 kg K. This projection aligns with the reported values of 3.0 kg N and 1.2 kg K in the fecal samples of Red Sokoto goats (Osuhor et al., 1998), and of 1.7 kg N and 1.9 kg K in those of WAD goats (Ansah et al., 2019). This finding is of particular relevance to Ghana, given its reported goat population of 8.21 million (Statista, 2022), potentially enabling the significant reduction or replacement of synthetic fertilizers. Furthermore, our study suggests that 60 WAD goats fed a bamboo-supplemented diet could produce 388.2 kg of N and 121.5 kg of K, meeting the N and K requirements for optimal maize growth and yield in Ghana, which are recommended at 90 kg N and 60 kg K_2O per hectare (Ansah et al., 2019).

Conclusion

In this study, we investigated the influence of two bamboo species as supplements on the quality of manure produced by West African dwarf (WAD) goats, aiming to contribute to the advancement of smallholder bamboo-integrated agro-silvopastoral systems in sub-Saharan Africa. Among the multifaceted impacts uncovered, the superior nutritional attributes of one of the bamboo species, *Oxytenanthera* abyssinica (A. Rich.) Munro, were evident when compared with those of *Bambusa balcooa (Beema)*. This outcome, in line with previous research, emphasizes the nutritional value of *O. abyssinica* leaves, which is consistent throughout various seasons, establishing it as a reliable fodder within dynamic agro-silvopastoral frameworks.

In addition, our study delved into the intriguing effects of bamboo supplement type on the feeding patterns of goats. Notably, animals consuming the *B. balcooa* supplement exhibited a greater dry matter intake than those fed the *O. abyssinica* supplement. However, this heightened consumption was accompanied by a lower feed conversion efficiency, contrasting with the more efficient outcomes observed for the animals fed the *O. abyssinica* supplement. Moreover, the group of goats receiving a daily supplement of 400 g exhibited a higher feed intake-to-manure ratio and fecal N content than the group fed a 600 g daily supplement. This observation implies that a daily inclusion of 400 g of bamboo leaves especially those of O. abyssinica in animal ration could be an optimal choice for smallholder farmers.

To further enhance the significance of our study, we scrutinized the intricate interplay between supplement type and level on various manure attributes. Whereas some attributes remained unaffected, others displayed substantial variation. This included the contents of fecal nitrogen and organic carbon; carbon-to-nitrogen ratio; pH levels; and ash, phosphorus, potassium, magnesium, iron, zinc, and manganese contents.

Comparative analysis further uncovered specific impacts of the supplements produced from the two bamboo species on the resulting manure attributes. Compared with the *O. abyssinica*-supplemented groups, the *B. balcooa*-supplemented animals yielded manure with elevated contents of organic C; a higher C:N ratio; and increased zinc, magnesium, manganese, and ash contents. Conversely, the *O. abyssinica*-supplemented groups yielded manure with greater contents of nitrogen, phosphorus, potassium, and fluorine, and higher pH levels. The interactions between supplement type and supplementation level also wielded a significant influence on manure attributes, in turn enriching our understanding of their combined effects.

Limitations

Although our study has significantly advanced our understanding of the effects of different bamboo leaf supplements on various aspects of livestock and bamboo-integrated agro-silvopastoral systems, there are still uncharted territories in this domain. Future research endeavors should probe into the long-term consequences of bamboo-based manure on soil health, crop productivity, and the overall sustainability of these integrated systems. In addition, a thorough assessment of the economic viability of implementing such practices on a larger scale, coupled with an exploration of the potential challenges and benefits for farmers and practitioners of bamboo-integrated agro-silvopastoral systems, would offer a more comprehensive understanding of the practical implications of these findings. Moreover, further studies on digestibility and nitrogen utilization are necessary to substantiate the quality of manure produced from animals fed bamboo leaf supplements, which would contribute to refining the efficacy of this promising agroforestry strategy.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The animal study was approved by Animal Research Ethics Committee (AREC), KNUST/AREC/C.1.0031. The study was conducted in accordance with the local legislation and institutional requirements. Written informed consent was obtained from the individual(s) for the publication of any identifiable images or data included in this article.

Author contributions

Study conception and design: PS. Data collection: PS, VA-K, AA-J, MK, and FKM. Analysis and interpretation of results: PS, BA-M, and OA. Draft manuscript preparation: PS. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Abdulrazak, S. A., Muinga, R. W., Thorpe, W., and Ørskov, E. (1997). Supplementation with Gliricidia sepium and Leucaena leucocephala on voluntary food intake, digestibility, rumen fermentation, and live weight of crossbred steers offered Zea mays stover, Livest. *Prod. Sci.* 49 (1), 53–62. doi: 10.1016/S0301-6226(97)00018-3

Adzitey, F. (2013). Animal and meat production in Ghana-An overview. *J. World's Poultry Res.* 3 (1), 1–4. Available at: http://www.udsspace.uds.edu.gh/handle/123456789/3770 (Accessed on 10/08/2023).

Aggarwal, R. K., and Power, J. F. (1997). Use of crop residue and manure to conserve water and enhance nutrient availability and pearl millet yields in an arid tropical region. *Soil tillage Res.* 41 (1-2), 43–51. doi: 10.1016/S0167-1987(96)01082-3

Alvåsen, K. (2009). *Farmers' perceptions and handling of livestock manure in urban/peri-urban areas of Kampala, Uganda*. SLU, Dept. of Animal Nutrition and Management, Uppsala. Available at: http://stud.epsilon.slu.se/12271 (Accessed on: 10/07/2023).

Andriarimalala, J. H., Kpomasse, C. C., Salgado, P., Ralisoa, N., and Durai, J. (2019). Nutritional potential of bamboo leaves for feeding dairy cattle. *Pesquisa Agropecuária Trop.* 49 (0), 54370. doi: 10.1590/1983-40632019v4954370

Ansah, K. O., Antwi, C., Osafo, E. L. K., Enning, S., and Adu-Dapaah, H. (2019). Manure characteristics of small ruminants fed agro by-products in the Guinea savannah agroecological zone of Ghana. *Ghana J. Agric. Sci.* 54 (1), 67–76. doi: 10.4314/gjas.v54i1.7

Antwi-Boasiako, C., Coffie, G. Y., and Darkwa, N. A. (2011). Proximate composition of the leaves of Bambusa ventricosa, Oxytenanthera abyssinica, and two varieties of Bambusa vulgaris. *Sci. Res. Essays* 6, 6835–6839. doi: 10.5897/SRE11.797

AOAC (1990). *Official methods of analysis. fifteenth* (Arlington, Virginia: Association of Official Analytical Chemists).

Artabandhu, S., Ogra, R. K., Anil, S., and Ahuja, P. S. (2010). Nutritional evaluation of bamboo cultivars in sub-Himalayan region of India by chemical composition and in *vitro* ruminal fermentation. *Grassland Sci.* 56 (2), 116–125. Available at: https://www.cabdirect.org/cabdirect/abstract/20103186895 (Accessed on 10/08/2023).

Asaolu, V. O., Odeyinka, S. M., Akinbamijo, O. O., and Sodeinde, F. G. (2009). Feed intake, nutrient digestibility, and nitrogen utilization of graded levels of moringa and bamboo leaves by West African Dwarf Goats. *Bull. Anim. Health Production Afr.* 57 (4), 0378-9721. doi: 10.4314/bahpa.v57i4.51682

Attoh-Kotoku, V. (2003) *Stylosanthes Hamata Supplementation: Effects on Degradation Characteristics, the Passage Rate of Rice Straw and Performance of Lactating Djallonke Ewes and Their Lambs, A doctoral dissertation was submitted to the Department of Animal Science, Kwame Nkrumah University of Science and Technology* (Accessed 14 August 2023). Available at dspace.knust.edu.gh.

Baah, J., Tuah, A. K., Addah, W., and Tait, R. M. (2012). Small ruminant production characteristics in urban households in Ghana. *Age (years)* 29 (15), 30–39. Available at: http://lrrd.cipav.org.co/lrrd24/5/baah24086.htm (Accessed on 10/08/2023).

Bationo, B. A., Nandwa, S. M., Kimetu, J. M., Kinyangi, J., Bado, B. V., Lompo, F., et al. (2004). *Sustainable intensification of the crop-livestock system through manure management in eastern and western Africa: lessons learned and emerging research approaches* In: Williams, Timothy, O., Tarawali, S. A., Hieraux, P., Fernández Rivera, S., et al (Eds.). Sustainable crop-livestock production for improved livelihoods and natural resource management in West Africa: Proceedings of an international conference held at the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria, 19-22 November 2001. International Livestock Research Institute (ILRI); Wageningen, NL: Technical Centre for Agricultural and Rural Cooperation (CTA), Nairobi, KE. p. 173-198. Available at: https://cgspace.cgiar.org/handle/10568/56088 (Accessed on: 14/07/2023).

Bayala, J., Kalinganire, A., Sileshi, G. W., and Tondoh, J. E. (2018). "Soil organic carbon and nitrogen in agroforestry systems in sub-Saharan Africa: a review," in *Improving the profitability, sustainability, and efficiency of nutrients through site-specific fertilizer recommendations in West Africa agroecosystems*, 51–61. Available at: https://link.springer.com/chapter/10.1007/978-3-319-58789-9_4 (Accessed on 10/08/2023).

Bhandari, M., Kaushal, R., Banik, R. L., and Tewari, S. K. (2015). Genetic evaluation of nutritional and fodder quality of different bamboo species. *Indian For.* 141 (3), 265–274. Available at: https://www.researchgate.net/profile/RKaushal/publication/278026778_Genetic_Evaluation_of_Nutritional_and_Fodder_Quality_of_Different_Bamboo_Species/links/5580f85908ae607ddc323281/Genetic-Evaluation-of-Nutritional-and-Fodder-Quality-of-Different-Bamboo-Species.pdf (Accessed on 10/08/2023).

Birner, R., and Resnick, D. (2010). The political economy of policies for smallholder agriculture. *World Dev.* 38 (10), 1442–1452. doi: 10.1016/j.worlddev.2010.06.001

Distel, R. A., Arroquy, J. I., Lagrange, S., and Villalba, J. J. (2020). Designing diverse agricultural pastures for improving ruminant production systems. Front. Sustain. *Food Syst.* 4. doi: 10.3389/fsufs.2020.596869

FAO. (2014). *The state of food and agriculture: innovation in family farming* (Rome: Food and Agriculture Organization of the United Nations). Available at: www.fao.org/3/a-i4040e.pdf (Accessed 12/09/2022).

FAO, IFAD, UNICEF, WFP and WHO. (2021). *The state of food security and nutrition in the world 2021. Transforming food systems for food security, improved nutrition, and affordable healthy diets for all.* (Rome: Food and Agriculture Organization of the United Nations).

FAO (Food and Agriculture Organization of the United Nations) (2021) *Low-Income Food-Deficit Countries (LIFDCs) - List updated June 2021*. Available at: https://www.fao.org/countryprofiles/lifdc/en (Accessed 14/08/23).

Fischer, E., and Qaim, M. (2012). Linking smallholders to markets: determinants and impacts of farmer collective action in Kenya. *World Dev.* 40, 1255–1268. doi: 10.1016/j.worlddev.2011.11.018

Gicheru, P. (2012). An overview of soil fertility management, maintenance, and productivity in Kenya. *Arch. Agron. Soil Sci.* 58 (1), 22–32. doi: 10.1080/03650340.2012.693599

Giyinyu, B. M., Ahonsi, S. O., and Barau, M. (2005). "Effects of different types of organic manure on growth and yield of tomato var. VFN," in *Proceeding of the 1st national conference on organic agriculture in Nigeria held. The university of agriculture* (Abeokuta. Nigeria), 28. Available at: Google Scholar. (Accessed on 10/08/2023).

Halvorson, J. J., Cassida, K. A., Turner, K. E., and Belesky, D. P. (2011). Nutritive value of bamboo as browse for livestock. Renew. *Agricult. Food Syst.* 26, 161–170. doi: 10.1017/S1742170510000566

Hayashi, Y., Shah, S., Shah, S. K., and Kumagai, H. (2005). Dairy production and nutritional status of lactating buffalo and cattle in small-scale farms in Terai, Nepal. *Livestock Res. Rural Dev.* 17, 65–74. Available at: http://lrrd.cipav.org.co/lrrd17/7/haya17075.htm (Accessed on 10/08/2023).

INBAR (2019) *Bamboo and rattan facts*. Available at: http://www.inbar.int/Board.asp?Boardid=173 (Accessed 14/02/2023).

INBAR (2020a) *Bamboo resource assessment in five regions of Ghana in INBAR working paper*. Available at: https://www.inbar.int/wp-content/uploads/2020/12/Dec-2020_WARO_GhanaBamboo-Resource-Assessment.pdf (Accessed 15/02/2023).

INBAR (2020b) *Promoting sustainable bamboo harvesting and improving incomes in Ghana*. Available at: https://www.inbar.int/harvesting-improves-incomesGhana/ (Accessed 14/02/2023).

Irungu, K. R. G., Ashiono, G. B., Ondabu, N., and Indetie, D. (2005). "Manure output and its nutrient composition when sheep were fed on three cultivars of sweet potato vines," in *African crop science conference proceedings*, 7, 551–554. Available at: https://www.africabib.org/rec.php?RID=Q00041783 (Accessed on: 11/07/2023).

KATC (Kasisi Agricultural Training Centre) (2004). *Manure handling and storage. Study Circle manual* (KATC, Lusaka, Zambia. In assoc. Swedish Cooperative Centre). Available at: Google Scholar, Accessed on 18/08/2023.

Kausar, R. (1983). *Review on recycling of animal wastes as a source of nutrients for freshwater sh culture within an integrated livestock system* (Islam- Abad, Pakistan: Pakistan Agricultural Research Council), 49.

Kimani, S. K., and Lekasi, J. K. (2004). *Managing Manures Throughout their Production Cycle Enhances their Usefulness as Fertilisers: A. Managing nutrient cycles to sustain soil fertility in sub-Saharan Africa*. 187. Available at: Google Scholar (Accessed on 12/08/2023).

Kitaw, G., Gebregziabhear, E., Urge, B., Mulatu, Y., and Acheampong, E. N. (2022). Nutritional characterization and evaluation of bamboo leaves hay potential as a basal diet for lactating crossbred cows in Ethiopia. *Anim. Nutr. Feed Technol.* 22 (1), pp.107–pp.121. doi: 10.5958/0974-181X.2022.00009.9

Larney, F. J., Buckley, K. E., Hao, X., and McCaughey, W. P. (2006). Fresh, stockpiled, and composted beef cattle feedlot manure: nutrient levels and mass balance estimates in Alberta and Manitoba. *J. Environ. Qual.* 35 (5), pp.1844–1854. doi: 10.2134/jeq2005.0440

Le Houerou, H. N. (1980). *Chemical composition and nutritive value of browse in tropical West Africa*. 261–289. ILCA Addis Ababa. Available at: Google Scholar (Accessed on 12/08/2023).

Lowder, S. K., Skoet, J., and Raney, T. (2016). The number, size, and distribution of farms, smallholder farms, and family farms worldwide. *World Dev.* 87, 16–29. doi: 10.1016/j.worlddev.2015.10.041

Mando, A., Ouattara, B., Somado, A. E., Wopereis, M. C. S., Stroosnijder, L., and Breman, H. (2005). Long-term effects of fallow, tillage, and manure application on soil organic matter and nitrogen fractions and sorghum yield under Sudano-Sahelian conditions. *Soil Use Manage.* 21 (1), 25–31. doi: 10.1079/SUM2005287

Minitab, LLC. (2019). *Minitab statistical software: general linear model. Version 19.0* (NY, US: LLC). Available at: www.minitab.com.

Mitchell, C. (1992). *Using livestock manure as fertilizer. Extension Agronomist. Agronomy* (Agronomy: Auburn University Publishing). Available at: Google Scholar, Accessed 10/08/2023.

Moral, R., Moreno-Caselles, J., Perez-Murcia, M. D., Perez-Espinosa, A., Rufete, B., and Paredes, C. (2005). Characterization of the organic matter pool in manures. *Bioresource Technol.* 96 (2), 153–158. doi: 10.1016/j.biortech.2004.05.003

Norton, B. W. (1994). "The nutritive value of tree legumes," in *Forage tree legumes in tropical agriculture*, 177–191. (Wallingford, UK: CAB International) Available at: https://www.cabdirect.org/cabdirect/abstract/19941400417 (Accessed on 10/08/2023).

NRC (National research council). (2007). "Committee on nutrient requirements of small ruminants, national research council, committee on the nutrient requirements of small ruminants, board on agriculture, division on earth, and life studies," in *Nutrient requirements of small ruminants: sheep, goats, cervids, and new world camelids*. Available at: https://nap.nationalacademies.org/11653 (Accessed on 12/08/2023).

Oduro, I., Larbie, C., Amoako, T. N. E., and Antwi-Boasiako, A. F. (2009). Proximate composition and basic phytochemical assessment of two common varieties of Terminalia catappa (Indian Almond). *J. Sci. Technol.* 29 (2), 1–6. doi: 10.4314/just.v29i2.46217

OECD/FAO (Organisation for Economic Co-operation and Development/Food and Agriculture Organization of the United Nations) (2020). *OECD- FAO agricultural outlook 2020-2029* (Paris: OECD Publishing).

OECD/FAO (Organisation for Economic Co-operation and Development/Food and Agriculture Organization of the United Nations) (2021). *OECD- FAO agricultural outlook 2021-2030* (Paris: OECD Publishing).

OECD, F. (2016a). "Commodity snapshots," in *OECD—FAO agricultural outlook 2016-2025*, 110–129. (OECD-FAO Agricultural Outlook Publishing). Available at: Google Scholar (Accessed on: 14/08/2023)..

OECD, F. (2016b). *OECD-FAO agricultural outlook 2016-2025. Special Focus: Sub-Saharan Africa*. 441.

Okoruwa, M. I., Adewumi, M. K., and Ikhimioya, I. (2021). Performance characteristics and blood profile of rams fed mixture of bamboo (*Bambusa vulgaris*) leaves and neem (*Azadirachta indica*) seed cake. *Nigerian J. Anim. Production* 43 (2), 272–283. doi: 10.51791/njap.v43i2.882

Oppong-Anane, K. (2011). *Ghana livestock sector review report. A report submitted to the Food and Agriculture Organization of the United Nations*. Available at: Google Scholar. (Accessed on: 11/08/2023).

Osuhor, C. U., Alawa, J. P., and Lufadeju, E. A. (1998). "Overnight manure production from Red Sokoto goats in Zaria, Nigeria" in *Proceedings of the Silver Anniversary Conference of Nigerian Society for Animal Production*. 434–435. Available at: google Scholar, Accessed on 11/08/2023.

Partey, S. T., Quashie-Sam, S. J., Thevathasan, N. V., and Gordon, A. M. (2011). Decomposition and nutrient release patterns of the leaf biomass of the wild sunflower (*Tithonia diversifolia*): a comparative study with four leguminous agroforestry species. *Agroforestry Syst.* 81, 123–134. doi: 10.1007/s10457-010-9360-5

Partey, S. T., Sarfo, D. A., Frith, O., Kwaku, M., and Thevathasan, N. V. (2017). Potentials of bamboo-based agroforestry for sustainable development in Sub-Saharan Africa: a review. *Agric. Res.* 6 (1), 22–32. Available at: https://oar.icrisat.org/10005/1/art%253A10.1007%252Fs40003-017-0244-z.pdf (Accessed on 10/08/2023).

Partey, S. T., and Thevathasan, N. V. (2013). Agronomic potentials of rarely used agroforestry species for smallholder agriculture in Sub-Saharan Africa: an exploratory study. *Commun. Soil Sci. Plant Anal.* 44 (11), 1733–1748. doi: 10.1080/00103624.2013.769563

Pfister, S., Bayer, P., Koehler, A., and Hellweg, S. (2011). Projected water consumption in future global agriculture: Scenarios and related impacts. *Sci. Total Environ.* 409 (20), 4206–4216. doi: 10.1016/j.scitotenv.2011.07.019

Poudyal, P. (1993). A analyse divers nutriments des feuilles de Bambusa tulda, Dendrocalamus spp. *J. Am. Bamboo Soc* 10, 27. Available at: https://cir.nii.ac.jp/crid/1573668925774778752?lang=en (Accessed on 10/08/2023).

Powell, J. M., Pearson, R. A., and Hiernaux, P. (2004). Crop-livestock interactions in the West African drylands. *Agron. J.* 96, 469 –483. doi: 10.2134/agronj2004.4690

Rothman, J. M., Dierenfeld, E. S., Molina, D. O., Shaw, A. V., Hintz, H. F., and Pell, A. N. (2006). Nutritional chemistry of foods eaten by gorillas in Bwindi Impenetrable National Park, Uganda. *Am. J. Primatol* 68, 675–691. doi: 10.1002/ajp.20243

Saha, H. M., Muinga, R. W., and Kahindi, R. K. (2008). Evaluation of manure from goats fed Panicum basal diet and supplemented with Madras thorn, Leucaena, or Gliricidia. *Trop. Subtropical Agroecosystems* 8 (3), 251–257. Available at: https://www.redalyc.org/pdf/939/93911235004.pdf (Accessed on 10/08/2023).

Sahoo, A., Ogra, R. K., Sood, A., and Ahuja, P. S. (2010). Nutritional evaluation of bamboo cultivars in sub-Himalayan region of India by chemical composition and in *vitro* ruminal fermentation. *Grassland Sci.* 56 (2), 116–125. doi: 10.1111/j.1744-697X.2010.00183.x

Sasu, P., Attoh-Kotoku, V., Akorli, D. E., Adjei-Mensah, B., Tankouano, R. A., and Kwaku, M. (2023a). Nutritional evaluation of the leaves of Oxytenanthera abyssinica, Bambusa balcooa, Moringa oleifera, Terminalia catappa, Blighia sapida, and Mangifera indica as non-conventional green roughages for ruminants. *J. Agricult. Food Res.* 11, 100466. doi: 10.1016/j.jafr.2022.100466

Sasu, P., Attoh-Kotoku, V., Anim-Jnr, A. S., Osman, A., Adjei, O., Adjei-Mensah, B., et al. (2023b). Comparative nutritional evaluation of the leaves of selected plants from the Poaceae family (bamboos and grasses) for sustainable livestock production in Ghana. *Front. Sustain. Food Syst.* 7. doi: 10.3389/fsufs.2023.1087197

Sasu, P., Attoh-Kotoku, V., Simpah Anim-Jnr, A., Osafo, E. L., Mensah, A. B. M., Tankouano, R. A., et al. (2022). Bamboo leaves: Hope for dry season ruminant livestock production in Ghana. *Int. J. Innov. Res. Technol.* 22, 1463–1468. doi: 10.5281/zenodo.6760039

Simler, R. (2010). *The short-term impact of higher food prices on poverty in Uganda* (Washington, DC: IMF Working Paper 5210, International Monetary Fund).

Statista. (2022). *In a number of live goats in Ghana*. Available at: https://www.statista.com/statistics/1189734/goat-production-in-Ghana/#statisticContainer (Accessed 10/02/2023).

UNCTAD. (2015). *Commodities and development report 2015: smallholder farmers and sustainable commodity development.* (UN: The United Nations Publishing). Available at: https://policycommons.net/artifacts/135346/the-role-of-smallholder-farmers-in-sustainable-commodities-production-trade/192711/ (Accessed on 12/08/2023).

Van Soest, P. V., Robertson, J. B., and Lewis, B. (1991). Methods for dietary fiber, neutral detergent fiber, and non-starch polysaccharides in relation to animal nutrition. *J. Dairy Sci.* 74 (10), 3583–3597. doi: 10.3168/jds.S0022-0302(91)78551-2

Vierre, O. M., and Van, I. M. (1982). Effect of dietary protein in the gastrointestinal tract of sheep. *Nutr. Abstr. Rev.* 53 (18), 52. Available at: Google Scholar (Accessed on 12/08/2023).

Villalba, J. J., Provenza, F. D., and Bryant, J. P. (2002). Consequences of the interaction between nutrients and plant secondary metabolites on herbivore selectivity: benefits or detriments for plants? *Oikos* 97, 282–292. doi: 10.1034/j.1600-0706.2002.970214.x

Wiggins, S., Kirsten, J., and Llambí, L. (2010). The future of small farms. *World Dev.* 38 (10), 1341–1348. doi: 10.1016/j.worlddev.2009.06.013

Wodon, Q., Tsimpo, C., Backiny-Yetna, P., Joseph, G., Adoho, F., and Coulombe, H. (2008). *Potential impact of higher food prices on poverty: summary estimates for a dozen West and Central African countries* (Washington, DC: Policy Research Working Paper 4745, World Bank).

Wodon, Q., and Zaman, H. (2008). *Rising food prices in Sub-Saharan Africa: poverty impact and policy responses* (Washington, DC: Working Paper 4738, World Bank).

Wolz, K. J., and DeLucia, E. H. (2018). Alley cropping: Global patterns of species composition and function. *Agriculture Ecosyst. Environ.* 252, 61–68. doi: 10.1016/j.agee.2017.10.005

World Bank. (2022k). *Global economic prospects, june 2022. Global economic prospects* (Washington, DC: World Bank). Available at: https://openknowledge.worldbank.org/handle/10986/37224 (Accessed 14/11/22). License: CC BY 3.0 IGO.

Zehui, J. (2007). *Bamboo and rattan in the world. 1st* (Beijing, China: China Forestry Publishing House), 360.