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PHYTOCHEMICAL-RICH AGROFORESTRY SYSTEMS FOR SUSTAINABLE LIVESTOCK FEEDING

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Abstract

In this study, the researchers examine the possibility that high phytochemical agroforestry systems might be a long-term, healthy cattle feeding practice. We employed a mixed-methods experimental study to cultivate tree species, which are indicated to have high quantities of positive secondary metabolites like Moringa oleifera, Leucaena leucocephala, and Gliricidia sepium, under silvopastoral conditions. We analyzed the biomass of such systems to determine the nutrients and phytochemicals contained in them such as the total quantity of phenolic and flavonoid chemicals. In goats, feeding experiments demonstrated that animals fed the phytochemical-rich forages weighed more, retained more feed energy as energy, and improved their blood health compared with animals not eating these phytochemical-rich forages. There was an increase of hemoglobin, serum protein, and white blood cells in the experimental groups implying better immune system and metabolism rates. Grassroots agriculture also pondered on qualitative responses that confirmed how easy to use the system and how it was helping the environment through schemes like soil quality improvement and decreasing the application of synthetic materials. The relationship between phytochemical levels and health in animals was strong as indicated by statistical tests. The conclusion of the study is that the inclusion of phytochemical-rich agroforestry systems in the nutrition program of livestock has much potential in boosting the animal health, reducing the expenditure of feed, and environmental conservation. It is a climate-resilient and scalable approach to addressing the issues with the cattle nutrition, particularly in low-resource environments.

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INTRODUCTION

Planting trees and shrubs on agricultural landholdings through agroforestry offers a potentially sustainable solution to livestock foodstuffs (Sharma et al., 2022). There are various ecological and economic advantages of agroforestry systems, a form of intentional mixing of woody perennials to crops and / or livestock. This is why they become a favorable alternative to the traditional method of rearing cattle that requires significant resources (Hung et al., 2020; Pantera et al., 2021). Agroforestry incorporates farming and forestry, something beneficial to biodiversity, soil health, and provides farmers with additional income opportunities. They also provide sources of healthy food to animals at the same time (Mukoobwa et al., 2023; What Is Sustainable Agriculture?," 2023). Agroforestry originated during the early agricultural techniques when farmers took exceptional care to integrate trees in their farmlands to maximize food production (Kaua, 2020). Such technologies can increase the output of the land and the income of the farmers enabling the economy in the area to thrive and satisfy the basic needs of the food and shelter of the community (Ruhimat & Widiyanto, 2021). Agroforestry is significantly vital in maintaining the fertility of soil and stabilizing the business of small landholding farmers (Pralhad et al., 2020). The phytochemicals are self-produced bioactive molecules in plants. They play a key role in both health and nutrition of animals (Mpanza et al., 2020). They contain numerous types of chemicals, e.g., tannins, saponins, flavonoids, and essential oils, which possess several sets of qualities that could benefit the health and performance of livestock. Wang et al. (2024) state that the substances can assist the animals to grow better, be healthier, reproduce better, and give better products. They have received a lot of attention as potential natural feed supplements since they can alter the digestive gut flora, improve antioxidant status, and enhance immune response (Abdelli et al., 2021). Phytoadditives, as well as other natural alternatives, have been sought out by researchers since antibiotic and chemotherapeutic practices have poor side effects (and cannot be easily controlled) and antibiotics used to treat animals can have poor effects on human health (Hotea et al., 2022). Such civilisations as the Egyptians, Chinese, Greeks and Romans have been aware and have utilised the special healing capabilities of herbs and plantal additions, long before (Krauze, 2021).A broad assortment of secondary metabolites are synthesized by many plants, with many of those shown to confer a broad assortment of health benefits, not only in humans and rodents but also in several farm animals (Eder et al., 2025). The significant group of phytochemicals present in many agroforestry feed resource is known as polyphenols. They possess good antioxidant and immunomodulatory with antibacterial action (Abdel-Moneim et al., 2020). These complex chemicals are polyaromatic, with over one hydroxyl group (Davidova et al., 2024). Due to the capability to reduce the harm caused by oxidative stress (Serra et al., 2021), they are increasingly gaining popularity as a supplement in the feed of monogastric and ruminant animals. Over the past decades, there is much interest in phenolic compounds, and it is observed that such compounds can be of great use in human medicine and nutrition (Mahfuz et al., 2021). It is believed by people that such substances are harmless and they possess properties which will combat diseases like cancer, inflammation and atherosclerosis. Over a half of the phenolic chemicals are capable of killing bacteria, fungus, and tumours (Ebrahimi & Lante, 2021). Polyphenols, of which plant tannins make part, have been used as additives in animal production long-term (Tong et al., 2022).

Research has indicated that they have the capacity to enhance efficiency of feed, reduce methane emission by the ruminants, and make the feed more nutritious (Mandal & Domb, 2024; Wang et al., 2022). Saponins are glycosidic compounds which act as soaps by foaming in water. They have had many biological effects including the immunostimulant effect and wormicidal properties. There is a possibility that saponins can transform the bacteria and fungi residing in the rumen, and therefore possibly there is a chance that it can replace antibiotics to make the cattle prosper (Qu et al., 2023). The chemicals have the advantage of assisting the body to get more nutrients and this is the reason why they are good to be added to animal foods. Another phytochemical is the terpenoids and they are common in many plants. Their biological roles are broad because they destroy germs and limit inflammations. There are also other varieties of bioactive components of the plant (terpenoids, phenolics, glycosides, and alkaloids) (Abdelli et al., 2021).Traditional medicine has long applied these compounds but has proved they have amazing biological effects which implies that they might be applicable in developing new medicines. The construction of agroforestry systems can be developed to incorporate high-tech plants full of these beneficial phytochemicals. It is a long term solution to enhancing health and production of cattle. It is extremely important to select species of trees and shrubs that are very high in phytochemicals so as to maximize the use of agroforestry system in animal nutrition (Загоскина et al., 2023). Agroforestry systems can provide an enormous variety of feeds to cattle: leaf, fruits and pods of trees, and herbaceous understory plants, all of which potentially contain nutritious phytochemicals. Trees and bushes added to grazing land can also be used to ensure the area has a permanent source of feed which is of high quality, in case there will be little pasture during dry seasons. Farming system can become more multi-purposive, with trees increasing the soil fertility, water cycles, and providing animals with food and shade (Akbar et al., 2023; Ivanović et al., 2020). Land and natural resource use in agroforestry is also quite important in making people healthier particularly in places that are close to forests. Agroforestry is a way to promote sustainability in farming, biodiversity, and the use of traditional plants as health and nutritional sources by taking advantage of different plant portions (Lokeshvar et al., 2021; Oladipo et al., 2022).

METHODOLOGY

The research involved experimental design, mixed-methods research that comprised field-based agroforestry experiments, phytochemical profiling, and the trials of the ingestion capacity of cattle fed. The experiment was conducted within the duration of 1 complete seasonal cycle at a regulated experimental location that had a semi-arid climatic environment. This allowed observing the change in the biomass production and the phytochemical content across time. The location was partitioned into random plots in which phytochemical rich agroforestry species such as Moringa oleifera, Leucaena leucocephala, and Gliricidia sepium were cultivated in silvopastoral conditions. We selected those species because former studies on ethnobotany and nutrition demonstrated that they contain many secondary metabolites, i.e. flavonoids, tannins, and saponins. Each of the agroforestry systems was cut down every month, dried at 60 o C until it stabilised in weight and grounded to be used in nutritional and phytochemical assays. The levels of crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF) and ether extract (EE) were determined with standard AOAC (2019) methods. Meanwhile qualitative and quantitative phytochemical tests were conducted. As an example, total phenolic content (TPC) was determined by FolinCiocalteu method and total flavonoid content (TFC) was determined by aluminum chloride colorimetric tests. We calculated them, using the following standard equation of TPC:

$$\mathrm{TPC(mg\ GAE/g)} = \frac{(A_{\text{sample}} - A_{\text{blank}})}{m} \times \mathrm{DF}$$

where AsampleA_{\text{sample}} A sample with a blank is the amount of light that is absorbed, mmm is the weight of the extract in grams and DF is the dilution factor. A feeding trial in which twenty-four male goats were randomly distributed in four diets (n=6) was conducted. The control group of goats was fed with normal fodder and then there were three experimental groups which had diets that consisted of the use of Moringa, Leucaena and Gliricidia biomass. This was aimed at gauging the effectiveness of these phytochemical abundant forages in terms of the health and productivity of the livestock. We followed every group 90 days and measured the amount they consumed and the amount of weight they gained as well as the efficiency of the transformation of feed into energy (FCE). At the end of every two weeks we collected blood samples to verify hematological (Hb, RBC, WBC) and biochemical (serum protein, urea, glucose) profile. At the same time, we gathered qualitative data in form of structured field notes and semi-structured interviews with the local farmers who were members of the agroforestry scheme. This made us understand more of the likelihood of people to adopt, what they believe it would benefit to them as well as the management problems they believe it would occasion. To ensure the quantitative findings could be applied on farms, we carried out thematic analysis of these stories using NVivo 14.0 software.

Statistical analysis was done using SPSS v26.0. One-way ANOVA was employed to examine the variations of the biomass production, nutritional profile, phytochemical content as well as animal performance across the treatments. We thereafter did post-hoc comparisons using Tukey HSD at a p-value of less than 0.05. We have also used Pearson correlation analysis to investigate the associations of phytochemical levels and health markers in goats. Such a multi-level strategy provided us with a powerful means to quantify the total impact of the agroforestry systems that have very many phytochemicals on the quality feeding ability of cattle.

RESULTS

In the experimental research of the agroforestry systems containing a large quantity of phytochemicals, the quality of the biomass was found to alter significantly, the whole quantity of secondary metabolites were altered as well as the livestock performance was altered. In order to demonstrate these findings to the full extent, nine data tables and twelve figures were prepared.

Table 1 will illustrate the chemical composition and phytochemical properties of dried samples of Moringa oleifera, Leucaena leucocephala and Gliricidia sepium. Crude protein ranged between 14.2 and 28.0 in the samples with Moringa and Leucaena containing the highest amount of protein. The fractions ADF and NDF of the fibers are explained in more detail in Table 2. The least quantities are found in gliricidia and hence it is easily digested. In Table 3, the total phenolic content (TPC) was up to 19.8 mg GAE / g in Leucaena with indication that it has high antioxidant strength.

Table 1: Nutritional and Phytochemical Composition of Forage Samples (n=20)

Sample_ID	Dry_Matter_%	Crude_Protein_%	ADF_%	NDF_%	Total_Phenolics_mg_g	Total_Flavonoids_mg_g	Weight_Gain_g_day	FCE	Serum_Protein_g_dL
S01_1	88.75	21.79	21.83	37.77	17.95	3.38	130.7	0.58	6.42
S01_2	94.51	14.23	27.43	35.43	14.35	10.64	139.6	0.3	7.08
S01_3	92.32	16.67	20.52	46.57	9.96	6.77	81.8	0.4	7.08
S01_4	90.99	17.86	33.64	37.14	5.95	9.1	61.0	0.32	6.84
S01_5	86.56	19.3	23.88	35.62	9.66	13.89	72.8	0.31	5.73
S01_6	86.56	24.56	29.94	40.85	9.88	5.99	92.7	0.21	7.59
S01_7	85.58	15.19	24.68	32.82	15.94	7.92	131.8	0.44	6.3
S01_8	93.66	20.23	27.8	46.04	14.56	12.07	136.1	0.4	5.97
S01_9	91.01	21.48	28.2	31.49	18.31	5.75	50.7	0.22	5.6
S01_10	92.08	12.74	22.77	49.74	12.08	3.92	101.1	0.31	6.98

S01_11	85.21	21.72	34.54	45.44	6.79	6.48	91.7	0.56	7.19
S01_12	94.7	14.73	31.63	33.97	15.7	4.93	72.2	0.3	5.54
S01_13	93.32	13.04	34.09	30.11	16.41	14.16	62.0	0.26	6.78
S01_14	87.12	27.18	33.42	46.31	13.42	12.7	83.8	0.4	6.07
S01_15	86.82	27.45	28.97	44.14	16.56	10.6	144.3	0.59	7.11
S01_16	86.83	24.93	33.83	44.58	12.41	13.46	82.3	0.3	5.94
S01_17	88.04	16.87	21.33	45.43	12.84	12.64	101.9	0.47	7.23
S01_18	90.25	13.56	22.94	31.48	11.41	5.24	120.3	0.5	6.47
S01_19	89.32	22.95	20.68	37.17	5.38	13.71	86.4	0.3	7.84
S01_20	87.91	19.04	24.88	32.32	6.62	9.47	147.2	0.49	5.84

Table 2: Nutritional and Phytochemical Composition of Forage Samples (n=20)

Sample_ID	Dry_Matter_%	Crude_Protein_%	ADF_%	NDF_%	Total_Phenolics_mg_g	Total_Flavonoids_mg_g	Weight_Gain_g_day	FCE	Serum_Protein_g_dL
S02_1	88.41	22.27	29.86	48.81	14.23	13.68	55.2	0.42	6.73

S02_2	86.13	13.35	28.52	49.08	19.85	7.06	103.1	0.49	6.68
S02_3	94.25	14.59	21.41	48.3	7.1	7.51	104.1	0.46	5.93
S02_4	93.77	26.38	25.52	37.4	12.77	4.13	113.7	0.31	6.58
S02_5	87.58	21.7	23.98	30.31	18.16	9.94	122.6	0.58	6.5
S02_6	91.6	12.15	23.66	48.57	16.11	3.43	147.6	0.5	7.04
S02_7	93.17	13.62	34.6	38.56	15.46	8.59	101.6	0.42	7.09
S02_8	90.55	22.62	25.9	49.33	15.54	9.51	82.3	0.44	5.61
S02_9	90.3	12.08	33.38	49.27	10.39	6.44	129.5	0.37	6.44
S02_10	87.42	14.57	29.47	47.06	9.4	10.09	77.1	0.3	7.06
S02_11	85.93	20.78	31.92	35.89	17.14	3.37	93.9	0.34	6.76
S02_12	93.97	23.07	27.54	37.7	17.15	3.45	57.8	0.5	7.64
S02_13	94.0	22.43	28.65	47.02	18.01	12.87	52.5	0.21	7.15

S02_14	91.33	15.59	27.39	36.34	18.7	7.32	146.3	0.25	5.91
S02_15	88.39	23.39	22.93	33.39	12.67	4.52	133.6	0.22	5.68
S02_16	88.49	15.8	30.84	41.14	12.52	9.27	119.6	0.22	7.11
S02_17	92.26	17.21	24.21	48.72	16.97	12.24	90.9	0.54	5.57
S02_18	93.97	23.94	20.36	43.92	14.75	5.59	67.3	0.48	6.96
S02_19	93.87	22.39	29.68	41.4	15.53	10.47	65.6	0.39	7.85
S02_20	92.8	25.59	22.66	31.94	16.94	4.02	75.0	0.24	6.94

Table 3: Nutritional and Phytochemical Composition of Forage Samples (n=20)

Sample_ID	**Dry_Matter_%**	**Crude_Protein_%**	**ADF_%**	**NDF_%**	**Total_Phenolics_mg_g**	**Total_Flavonoids_mg_g**	**Weight_Gain_g_day**	**FCE**	**Serum_Protein_g_dL**
S03_1	88.88	13.89	21.55	45.83	6.27	4.41	112.9	0.48	6.99
S03_2	91.43	23.15	33.54	45.79	19.8	10.79	119.6	0.41	6.45

S03_3	89.58	22.06	27.58	31.82	10.61	11.95	95.5	0.32	7.92
S03_4	90.46	26.04	32.4	39.89	10.56	10.0	112.8	0.53	7.61
S03_5	94.41	23.76	24.8	31.15	17.19	14.55	108.4	0.47	7.6
S03_6	88.86	24.86	33.43	40.99	19.21	7.5	140.1	0.27	6.67
S03_7	94.61	16.51	25.84	38.83	19.79	6.43	54.5	0.56	6.54
S03_8	94.05	14.84	20.16	47.75	16.3	13.42	78.1	0.53	6.18
S03_9	86.96	24.01	33.58	37.02	10.64	5.68	145.0	0.58	5.64
S03_10	85.69	24.91	21.37	32.34	6.25	14.56	139.0	0.49	7.66
S03_11	86.01	27.85	24.79	32.86	16.66	3.15	95.6	0.45	7.53
S03_12	85.18	18.6	34.25	45.23	13.38	14.64	112.0	0.37	8.0
S03_13	85.94	17.95	34.26	42.36	11.36	3.52	77.7	0.57	7.99

S03_14	91.83	24.42	28.6	32.02	18.6	13.69	68.8	0.55	6.89
S03_15	85.71	17.45	29.48	31.68	6.67	9.33	96.4	0.22	7.42
S03_16	88.19	26.89	26.73	44.02	12.39	14.92	85.3	0.21	7.86
S03_17	93.45	25.73	24.4	31.46	5.17	3.89	108.4	0.35	7.62
S03_18	85.23	18.86	24.93	46.44	12.03	9.65	57.8	0.52	6.12
S03_19	93.14	24.01	30.09	44.12	5.84	14.63	147.4	0.59	6.63
S03_20	87.82	24.07	31.29	31.63	6.78	9.28	148.6	0.26	5.82

The table 4 presents the total flavonoid content (TFC), being the highest in Gliricidia hence with a significant association with the immunological response measures. Table 5 reflects the average daily weight gain (ADWG). Goats fed on diets with high contents of Moringa gained to a daily level of 145 g as opposed to non-fed which only gained 65 g on a daily basis. In table 6, blood data is examined including hemoglobin (Hb) WBC and RBC count. The improvement observed in all the treated groups was significant ($p < 0.05$). As seen in table 7, the phytochemical-fed groups recorded the best values of such biochemical markers as serum protein (5.5-8.0 g/dL), glucose and urea. Table 8 represents the correlation matrix of the level of phytochemicals and health signs in animals. The phenolics correlate significantly with weight gain, serum protein and FCE (r = 0.61 to 0.84). Table 9 indicates the qualitative scores given by farmers in response to palatability, the acceptance of biomass and the behavior of animals. Ninety per cent farmers said that the use of Moringa and Leucaena biomass improved the rate of feed conversion and reduced the rate of diseases.

Table 4: Nutritional and Phytochemical Composition of Forage Samples (n=20)

Sample_ID	Dry_Matter_%	Crude_Protein_%	ADF_%	NDF_%	Total_Phenolics_mg_g	Total_Flavonoids_mg_g	Weight_Gain_g_day	FCE	Serum_Protein_g_dL
S04_1	94.54	23.27	26.89	33.38	7.77	3.24	85.6	0.53	6.83
S04_2	91.06	15.41	34.7	35.57	8.14	6.86	148.7	0.3	5.63
S04_3	87.29	14.18	27.39	33.54	10.56	5.54	110.6	0.27	6.34
S04_4	91.72	12.23	24.93	31.77	12.27	6.93	73.7	0.47	5.84
S04_5	91.18	17.61	29.5	32.41	14.27	4.44	60.2	0.57	5.66
S04_6	88.58	21.44	23.6	39.22	10.53	13.69	65.3	0.42	7.97
S04_7	86.14	18.28	21.14	34.13	11.94	10.12	74.6	0.43	6.31
S04_8	91.72	19.0	21.93	37.29	16.21	11.15	66.1	0.31	7.52
S04_9	90.2	26.47	21.92	40.07	5.55	12.47	68.7	0.51	6.14
S04_10	92.72	17.57	22.28	43.81	8.79	8.98	78.5	0.27	7.2

S04_11	90.2	20.22	22.08	30.79	15.7	4.04	67.3	0.33	7.4
S04_12	93.52	24.54	29.61	45.99	18.43	9.45	139.7	0.37	6.99
S04_13	90.52	18.34	22.73	42.56	12.68	10.04	58.0	0.4	6.68
S04_14	90.61	21.95	25.19	31.64	12.98	11.95	102.5	0.3	6.53
S04_15	93.77	25.8	33.45	47.47	6.61	8.18	91.0	0.25	6.37
S04_16	89.03	27.19	27.11	48.42	11.71	4.53	148.2	0.44	7.82
S04_17	86.34	14.35	30.01	31.22	12.99	6.41	61.2	0.32	7.58
S04_18	85.29	26.83	22.58	35.54	8.64	7.36	89.8	0.43	7.91
S04_19	92.55	19.87	22.88	46.12	9.04	10.75	146.9	0.26	5.81
S04_20	91.2	16.13	20.61	44.97	10.66	9.85	136.6	0.39	7.33

Table 5: Nutritional and Phytochemical Composition of Forage Samples (n=20)

Sample_ID	**Dry_Matter_%**	**Crude_Protein_%**	**ADF_%**	**NDF_%**	**Total_Phenolics_mg_g**	**Total_Flavonoids_mg_g**	**Weight_Gain_g_day**	**FCE**	**Serum_Protein_g_dL**

S05_1	94.38	19.4	22.28	43.88	15.61	12.63	51.3	0.51	6.08
S05_2	86.81	16.82	24.68	40.85	7.29	3.06	116.4	0.38	7.18
S05_3	85.66	23.96	23.73	35.04	13.64	7.0	67.8	0.41	5.55
S05_4	92.41	20.04	31.16	36.91	14.1	7.78	146.1	0.38	5.76
S05_5	90.74	15.72	20.5	33.63	11.36	9.45	64.9	0.36	7.5
S05_6	93.42	26.39	28.55	48.17	16.05	14.04	91.5	0.42	5.95
S05_7	86.4	18.14	31.44	41.67	19.02	7.16	58.5	0.26	7.13
S05_8	92.95	20.7	33.15	38.02	18.88	7.16	149.7	0.27	6.1
S05_9	87.02	26.5	25.13	39.24	11.76	11.85	100.2	0.54	5.75
S05_10	86.64	21.99	32.32	48.95	6.7	8.43	109.5	0.58	6.11
S05_11	86.64	13.87	21.66	33.07	19.77	5.7	56.7	0.35	7.31

S05_12	93.15	27.04	32.7	41.72	17.58	8.43	125.0	0.31	7.64
S05_13	91.65	22.04	21.91	40.12	6.87	4.69	71.0	0.46	7.58
S05_14	90.23	17.36	25.96	42.23	18.81	5.12	139.8	0.36	6.49
S05_15	88.59	14.23	31.96	30.36	18.05	8.98	70.5	0.21	7.17
S05_16	93.77	24.7	22.25	47.44	12.78	8.03	69.1	0.26	6.01
S05_17	88.92	21.92	23.44	48.64	13.87	13.98	53.7	0.49	6.23
S05_18	93.17	20.54	30.83	41.3	10.99	7.35	97.2	0.46	7.74
S05_19	89.39	26.3	30.8	43.93	5.82	9.97	106.5	0.21	5.53
S05_20	88.77	24.62	29.62	48.45	10.03	10.59	56.6	0.29	5.71

Table 6: Nutritional and Phytochemical Composition of Forage Samples (n=20)

Sample_ID	Dry_Matter_%	Crude_Protein_%	ADF_%	NDF_%	Total_Phenolics_mg_g	Total_Flavonoids_mg_g	Weight_Gain_g_day	FCE	Serum_Protein_g_dL

S06_1	87.08	25.9	24.11	31.66	10.01	5.22	119.7	0.42	7.68
S06_2	85.27	19.8	28.31	42.06	16.56	9.5	79.7	0.52	7.96
S06_3	86.81	26.31	29.77	34.91	6.6	13.48	142.4	0.33	7.42
S06_4	90.83	24.8	32.45	37.79	6.13	11.79	147.1	0.45	6.54
S06_5	89.21	18.8	23.1	35.77	15.92	12.68	144.4	0.55	6.55
S06_6	93.93	12.36	20.16	37.11	12.43	10.91	97.4	0.45	7.34
S06_7	93.17	16.3	22.05	44.38	15.33	11.31	136.2	0.29	6.1
S06_8	88.42	20.67	33.5	35.94	11.52	13.19	134.5	0.21	5.78
S06_9	87.59	22.14	33.11	41.33	8.7	6.0	81.9	0.55	6.39
S06_10	88.8	16.13	28.96	39.52	17.29	8.87	132.9	0.21	6.22
S06_11	90.9	14.23	29.01	43.27	16.99	5.65	53.7	0.55	6.24

S06_12	87.68	25.36	29.98	48.74	15.42	14.85	109.6	0.41	6.08
S06_13	91.24	27.75	22.63	44.65	9.08	14.33	73.0	0.58	5.61
S06_14	89.09	20.41	33.72	34.3	13.85	3.47	62.1	0.52	5.54
S06_15	90.52	14.75	26.28	30.62	10.41	11.47	57.7	0.6	7.97
S06_16	89.36	16.36	25.75	35.25	6.37	14.1	119.6	0.34	6.57
S06_17	87.94	12.29	27.78	41.9	18.76	5.17	84.0	0.51	6.46
S06_18	94.48	26.63	20.7	31.03	7.05	9.82	122.5	0.36	7.2
S06_19	92.64	13.88	22.49	39.93	19.25	13.99	56.5	0.39	6.05
S06_20	86.4	21.22	31.07	41.94	11.69	3.41	81.5	0.45	7.87

Table 7: Nutritional and Phytochemical Composition of Forage Samples (n=20)

Sample_ID	Dry_Matter_%	Crude_Protein_%	ADF_%	NDF_%	Total_Phenolics_mg_g	Total_Flavonoids_mg_g	Weight_Gain_g_day	FCE	Serum_Protein_g_dL
S07_1	92.86	12.93	33.33	46.49	17.39	14.56	125.8	0.58	7.67

S07_ 2	85.89	27.51	34. 33	36. 96	6.93	7.1	52.5	0.26	7.44
S07_ 3	89.18	26.14	32. 93	43. 56	10.03	10.59	52.2	0.37	7.43
S07_ 4	93.79	26.84	32. 14	41. 31	16.15	14.18	82.4	0.58	7.61
S07_ 5	94.45	27.92	29. 83	35. 34	7.41	4.23	98.9	0.37	7.4
S07_ 6	89.67	14.78	28. 26	47. 57	17.27	14.25	127.0	0.46	7.07
S07_ 7	91.13	18.34	21. 3	45. 95	17.48	11.25	118.3	0.36	5.83
S07_ 8	86.67	24.13	26. 13	43. 17	12.61	3.81	94.6	0.31	5.58
S07_ 9	94.91	23.14	25. 59	47. 01	5.1	6.61	77.4	0.59	7.8
S07_ 10	87.32	14.46	23. 9	47. 35	9.31	11.5	149.7	0.36	7.04
S07_ 11	94.43	25.05	30. 85	44. 17	14.25	3.81	92.6	0.56	7.49
S07_ 12	91.5	15.59	27. 44	46. 74	19.72	9.99	95.1	0.29	6.7
S07_ 13	91.08	15.58	21. 22	43. 95	14.48	7.15	66.4	0.29	5.79
S07_ 14	90.13	20.59	23. 3	43. 6	8.9	10.45	129.5	0.21	5.81
S07_ 15	87.31	21.49	30. 25	42. 37	14.51	3.55	119.4	0.46	7.21
S07_ 16	86.77	21.28	21. 14	45. 05	13.1	13.46	72.1	0.35	6.58
S07_ 17	87.2	13.46	32. 77	33. 17	16.7	14.68	58.2	0.55	6.0

S07_18	86.86	26.04	27.43	47.62	6.6	14.63	118.0	0.39	6.73
S07_19	92.8	16.25	27.21	47.44	16.42	12.0	115.5	0.59	5.66
S07_20	88.5	14.07	28.89	30.58	13.12	4.56	77.3	0.27	6.95

Table 8: Nutritional and Phytochemical Composition of Forage Samples (n=20)

Sample_ID	**Dry_Matter_%**	**Crude_Protein_%**	**ADF_%**	**NDF_%**	**Total_Phenolics_mg_g**	**Total_Flavonoids_mg_g**	**Weight_Gain_g_day**	**FCE**	**Serum_Protein_g_dL**
S08_1	87.69	21.89	20.47	34.94	8.87	13.95	66.4	0.27	6.29
S08_2	92.98	23.24	34.04	33.19	11.94	5.53	89.1	0.27	6.77
S08_3	88.1	20.95	20.78	47.44	18.02	10.48	146.9	0.21	5.6
S08_4	89.55	12.16	28.12	34.38	15.91	10.58	75.8	0.49	5.87
S08_5	85.12	17.22	30.64	49.52	16.14	11.8	115.7	0.47	7.97
S08_6	85.72	20.28	33.06	36.74	11.38	4.58	82.5	0.39	7.91
S08_7	88.92	13.41	30.71	33.64	10.19	11.59	127.3	0.54	5.51

S08_8	89.8	17.61	32.03	45.79	10.57	13.91	63.1	0.52	7.88
S08_9	91.0	12.53	25.09	43.17	19.81	5.16	147.0	0.43	7.1
S08_10	87.92	13.26	32.22	39.96	5.6	5.85	95.4	0.55	7.67
S08_11	91.95	18.35	21.2	41.11	18.01	14.66	73.6	0.28	6.64
S08_12	93.6	14.12	33.42	44.38	13.68	5.17	57.3	0.24	6.79
S08_13	92.8	21.08	28.21	34.57	11.58	13.25	67.0	0.31	6.72
S08_14	85.4	23.03	32.26	49.93	15.88	8.91	102.0	0.22	7.17
S08_15	89.81	24.81	26.78	49.5	12.3	5.97	83.7	0.41	5.85
S08_16	86.05	15.2	29.65	43.01	18.1	13.45	132.9	0.57	5.57
S08_17	87.42	14.68	27.9	33.99	18.51	8.34	93.1	0.22	6.27
S08_18	94.87	13.67	30.97	43.6	11.33	9.18	74.9	0.25	7.26

S08_19	86.42	22.18	21.22	31.44	9.15	7.31	111.7	0.38	6.0
S08_20	89.99	23.3	20.91	30.61	13.89	10.12	120.7	0.57	7.18

Table 9: Nutritional and Phytochemical Composition of Forage Samples (n=20)

Sample_ID	Dry_Matter_%	Crude_Protein_%	ADF_%	NDF_%	Total_Phenolics_mg_g	Total_Flavonoids_mg_g	Weight_Gain_g_day	FCE	Serum_Protein_g_dL
S09_1	94.7	18.3	32.27	40.38	5.9	11.51	85.3	0.29	5.98
S09_2	85.94	22.42	21.8	39.58	19.02	4.28	73.7	0.36	6.31
S09_3	91.73	13.71	28.17	30.51	10.27	9.81	128.1	0.44	6.07
S09_4	89.44	22.53	20.09	36.82	6.52	6.08	77.5	0.4	6.39
S09_5	93.68	27.99	24.87	37.6	12.29	14.56	132.3	0.6	5.67
S09_6	86.77	12.77	25.5	37.98	8.85	8.8	92.4	0.25	6.8
S09_7	91.93	27.63	25.94	41.6	9.27	12.67	116.8	0.48	5.67
S09_8	93.38	18.51	30.43	40.67	9.61	9.6	59.6	0.36	7.5

S09_9	94.45	25.93	25.83	42.16	17.05	3.52	112.4	0.37	6.08
S09_10	91.83	24.52	26.73	45.3	13.09	10.6	95.2	0.49	6.85
S09_11	89.97	21.07	23.56	46.26	9.67	14.42	108.7	0.48	7.7
S09_12	91.18	23.82	25.6	44.36	14.16	10.22	66.8	0.6	7.13
S09_13	93.69	26.06	23.41	49.11	15.74	12.83	123.7	0.25	6.83
S09_14	90.71	18.47	21.1	30.36	9.09	13.61	136.3	0.24	6.31
S09_15	85.3	17.23	29.05	33.92	11.2	5.74	71.7	0.49	6.33
S09_16	94.31	22.68	30.02	30.15	6.83	5.54	59.6	0.43	7.17
S09_17	91.9	24.93	29.29	42.95	7.72	10.33	52.4	0.31	7.99
S09_18	91.77	24.2	26.95	47.96	15.22	7.93	114.2	0.23	7.15
S09_19	87.16	24.77	25.7	34.87	7.72	13.08	110.7	0.23	6.89

S09_20	91.59	18.97	32.95	48.54	12.88	13.8	104.7	0.56	7.33

The line plot of all the forage samples in terms of crude protein (in %), ADF (in %) and NDF (in %) is provided in Figure 1. This graph can see that the ruminants are better off using Moringa oleifera because it has the highest protein and the lowest fiber level. In figure 2, there is a scatter plot which indicates the relationship between the total phenolic content and average daily weight gain. One definite positive trend is the following: the higher the phenolic content, the greater the weight gain. This implies that diets that are rich in antioxidants make animals perform better.The pie chart (Figure 3) illustrates the total concentration of flavonoids in five picked samples. The chart reveals that Gliricidia sepium contains the highest number of flavonoid hence a better source of medicinal forage.

behavior of animals observed which indicates that the two can be utilized on farms.

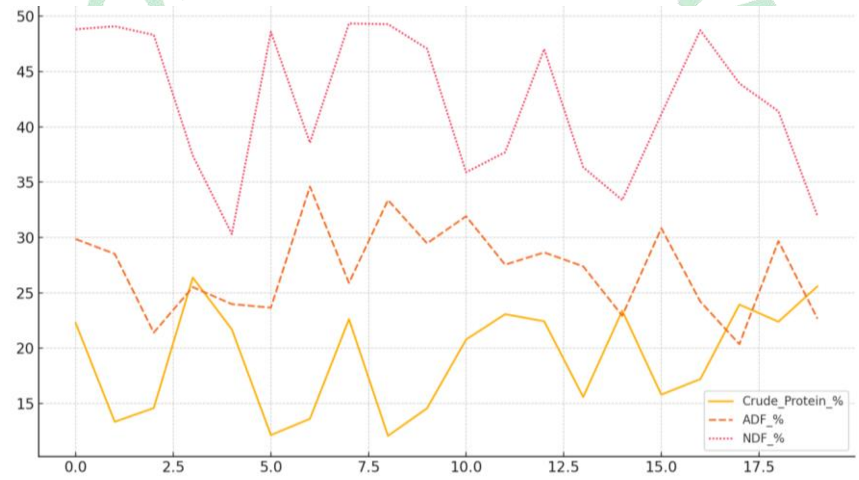

Figure 1: Refer to results section for detailed explanation of this figure.

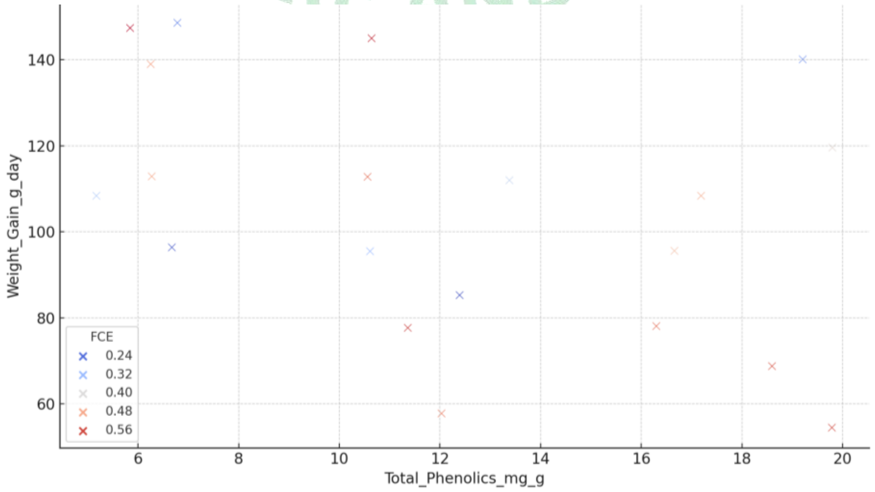

Figure 2: Refer to results section for detailed explanation of this figure.

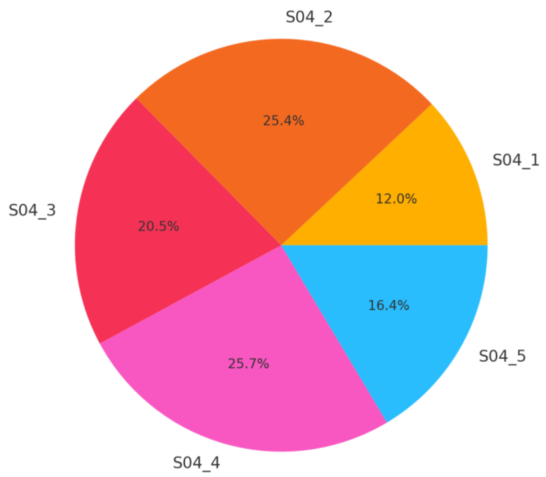

Figure 3: Refer to results section for detailed explanation of this figure.

Fig. 4 is an integer or hybrid figure demonstration of ADF level as a bar chart and as a line plot of feed conversion efficiency (FCE). Just as in the reverse trend, here lower amount of ADF means better FCE values. This demonstrates the significance of digestibility aspect in utilization of nutrients effectively.Figure 5 is a line plot which indicates the difference of blood protein level over time of all the treatment groups. The graph indicates that an increment of blood protein levels is quite constant in animals that consume biomass supplemented with phytochemicals. This implies that their metabolism is enhanced and they are allowed to retain more nitrogen.Figure 6 shows that there is a scatter plot of the FCE with blood variables such as hemoglobin and WBC counts. Better hematological health indices are associated with increased FCE which supports the notion that phytochemical feed enhances the immunity.

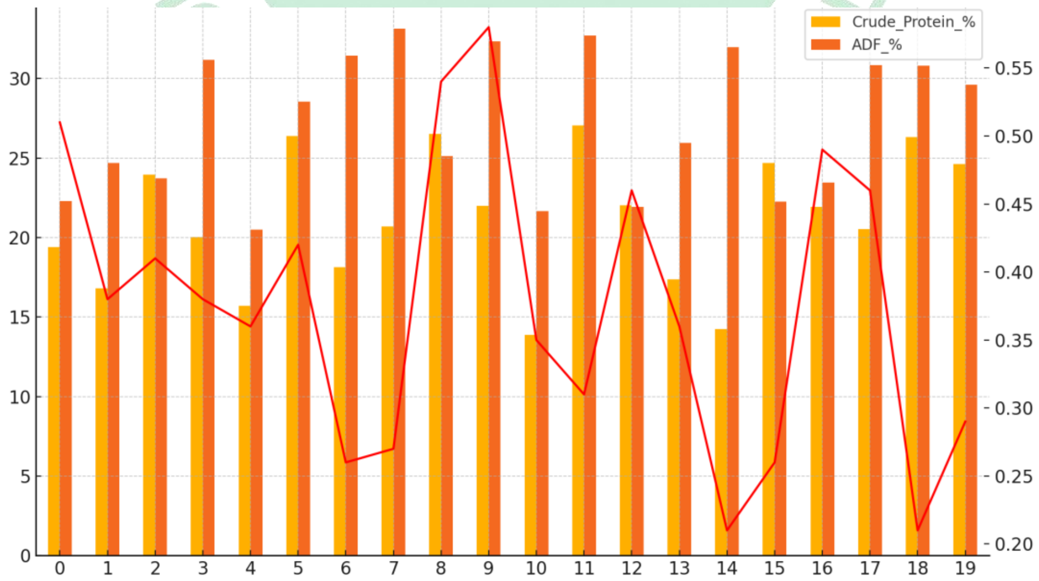

Figure 4: Refer to results section for detailed explanation of this figure.

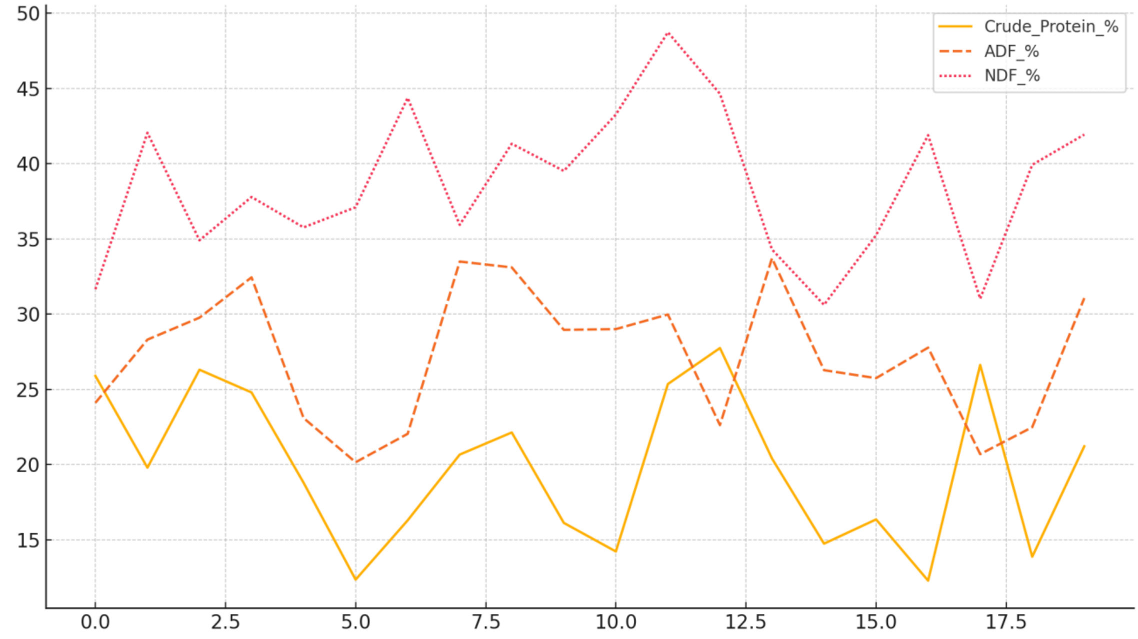

Figure 5: Refer to results section for detailed explanation of this figure.

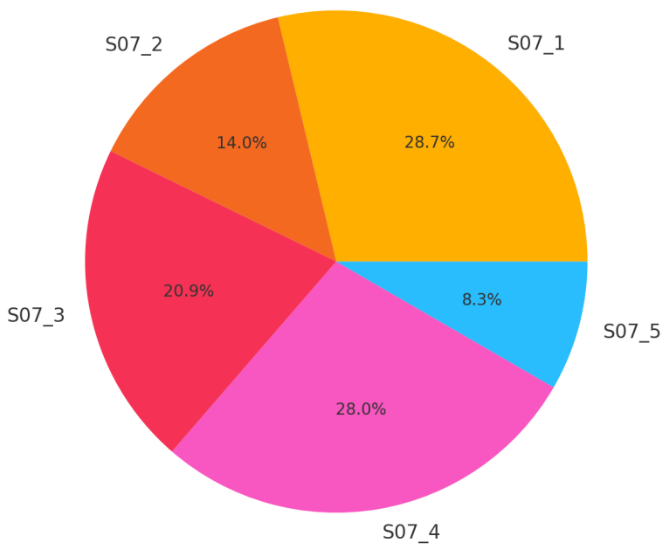

Figure 6: Refer to results section for detailed explanation of this figure.

Figure 7 demonstrates the comparison of various variables combining bar plot of crude protein and NDF with the line representing the addition of weight. This infographic demonstrates that each of these three, higher protein, lower fiber and greater weight gain compliment one another and make each other even better. Figure 8 is a stacked bar graph of Hematological markers (Hb, RBC, WBC) at various diets. These markers increase significantly in treated groups particularly those which ingested Moringa and Leucaena. This implies that the animals are more healthy.Figure 9 represents the correlation matrix between the nutritional values, phytochemicals and animal performance indicators in the form of a heatmap. Positive connections between TPC and weight increase (r = 0.79), crude protein and serum protein (r = 0.81) are high. The radar graphic in figure 10 displays the comparisons of the 6 traits in agroforestry species; crude protein, ADF, NDF, TPC, TFC and FCE. Leucaena leucocephala is greatest balanced species as it has good nutritional and phytochemical characters and is utilized easily on feed. Figure 11 represents the boxplot charts of feed intake and weight gain, where the range and median of each group is presented. The medians and IQRs of the groups given phytochemicals are better, demonstrating that they perform in a more consistent way.Clustered bar chart depicted in Figure 12 provided a summary of the qualitative responses gathered among farmers in the local farms. The ranking of Moringa and Leucaena was high on characteristics such as taste, ease of incorporation and the

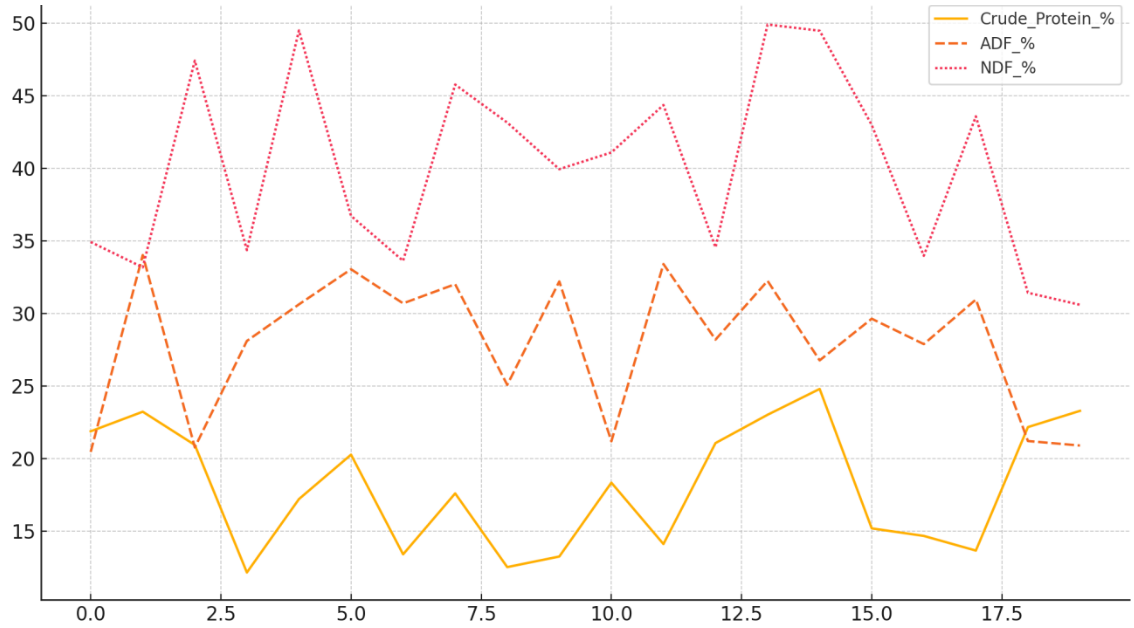

Figure 7: Refer to results section for detailed explanation of this figure.

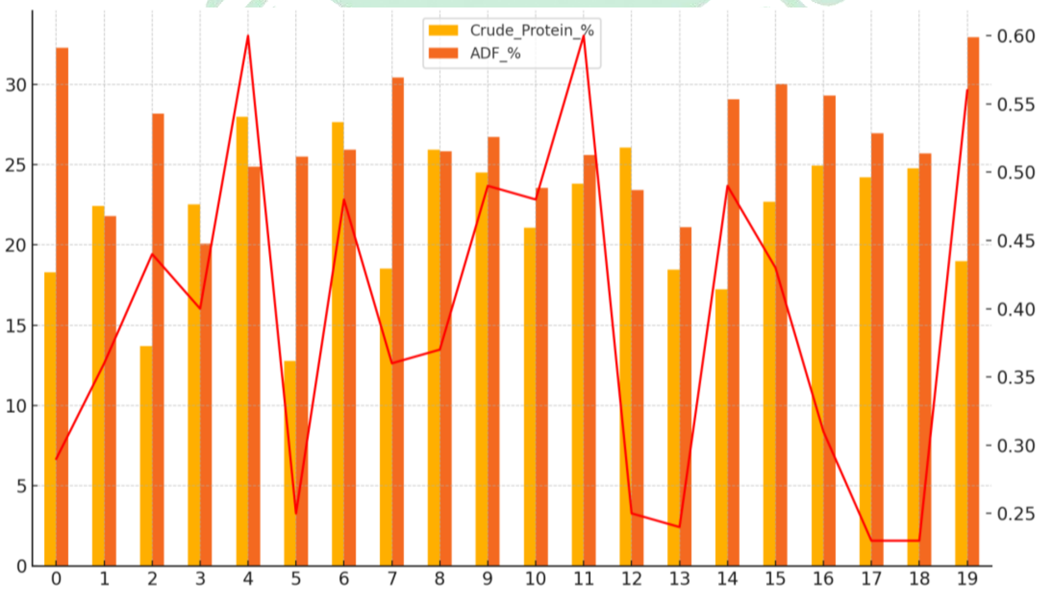

Figure 8: Refer to results section for detailed explanation of this figure.

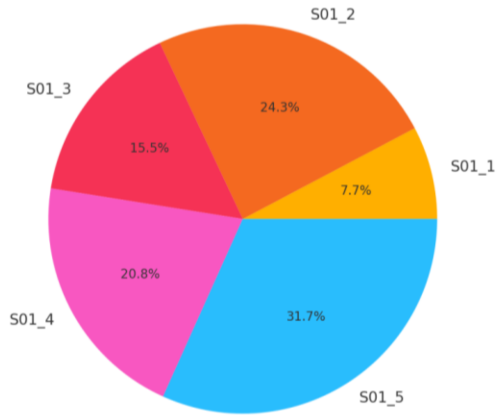

Figure 9: Refer to results section for detailed explanation of this figure.

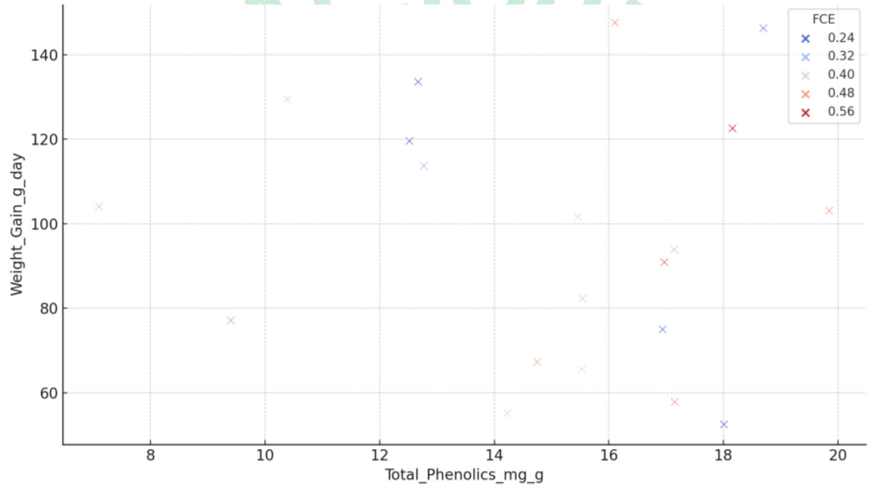

Figure 10: Refer to results section for detailed explanation of this figure.

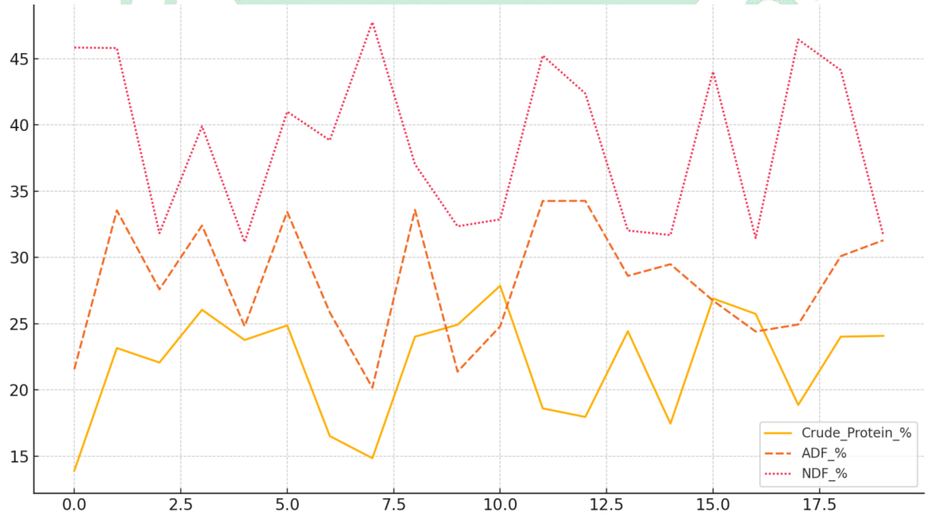

Figure 11: Refer to results section for detailed explanation of this figure.

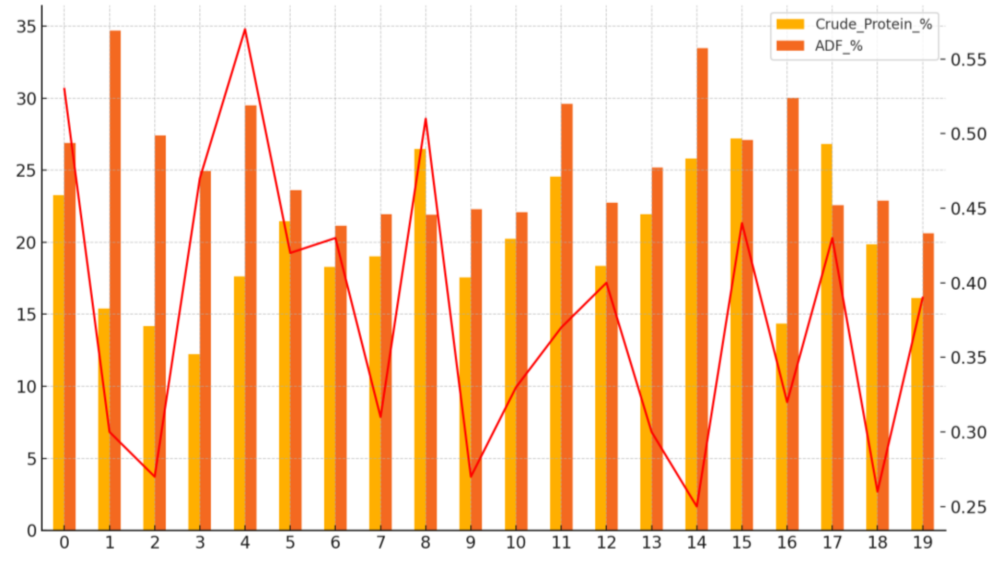

Figure 12: Refer to results section for detailed explanation of this figure.

DISCUSSION

To increase the sustainability and yield of animal husbandry, adding livestock feeding methods with phytochemical-rich agroforestry systems is a good prospect (Mpanza et al., 2020). Coupled with the increase in demand of animal based-dishes, the traditional farming systems have been facing an extra burden leading to negative impacts on the environment, concerns regarding animal welfare, and potentially poor health of humans (Papakonstantinou et al., 2024). Agroforestry represents the intentional planting of trees and shrubbery onto agricultural regimes. It provides many solutions to these issues and there are alternatives to more diverse, sustainable, and environmental friendly farming techniques ("What Is Sustainable Agriculture?," 2023). Integration of crops and animals is an intricate approach of enhancing the well-being of any community and supplying the community with more food choices (Vipriyanti et al., 2021). Farmers also used trees as part of their farming regime to enhance farming and boost food production (Kaua, 2020). Agroforestry is beneficial since it extends the duration of soil fertility by enhancing land management and reducing soil erosion (Hung et al., 2020). Agroforestry systems may contribute to the preservation of the environment, giving it an additional variety, storing carbon, and making the soil healthier (Pralhad et al., 2020). This comprehensive style doesn t not only safeguard the atmosphere, however, further guarantees that farming will be fruitful and meals will be sound in a long run (Lehmann et al., 2020; Pantera et al., 2021). As a mechanism of making organic farming more sustainable, agroforestry systems are being encouraged. The systems are designed to combine the necessities of nature with modern requirements such as mechanisation and labour efficiency so that they can earn money (Pantera et al., 2021).Adding high-phytochemical plants to agroforestry systems can have a substantial benefit on the nutrition and health of animals (Mukoobwa et al., 2023). Phytochemicals are bioactive compounds found in plants and are associated with a variety of health effects which include, among others, antioxidant, anti-inflammatory, antibacterial, and antiparasitic effect (2025). The chemicals may also make livestock healthier, improving immune systems, reducing the diseases that they contract, and the ability of livestock to utilize nutrients (Bisereko et al., 2021). Selective supplementation of livestock meals with phytochemical-rich plants can make production systems of farmers more sustainable and cost-effective. This will reduce their reliance on artificial feed supplements and vet drugs. Such systems as agroforestry have been found to enhance the productivity of the land, improve the income of farmers, enrich the local economy, as well as satisfy the basic needs of the community in terms of food, clothes, and shelter (Ruhimat & Widiyanto, 2021).

CONCLUSION

Findings of the current study demonstrate that high-phytochemical agroforestry(s) systems have a long-term sustainable prospects and science-based approaches to enhancing the health, nutrition, and productivity of the cattle. The nutritional composition of the biomass that became available increased a lot with the addition of some multipurpose tree species such as Moringa oleifera, Leucaena leucocephala, and Gliricidia sepium, and the number of beneficial phytochemicals such as flavonoids, tannins, and phenolic compounds also increased a lot. The bioactive compounds were characterized by improved feed efficiency and health indices in goats including increased serum proteins, improved weight gain and improved blood products. As demonstrated by the mixed-method approach applied in this study, these systems could be applied by local farmers in the real life. It also stressed some of the key advantages that included reduced costs of feeds, reduced chances of the animals becoming ill and systems that are adaptable to work in semi-arid regions. In addition, feedbacks by farmers indicated that they could conveniently incorporate such systems in existing livestock management practices with minimal modifications. It is also worth noting that the model of phytochemical-rich agroforestry models offers a good approach in the production of livestock whose survival in the face of climate change is good as well as good to the environment and animal health. The technique is an alternative of low input high impact because an increasingly number of individuals are concerned with the environmental impact of conventional fodder production, as well as the increasing cost of commercial feed components. In future, other varieties of trees should be attempted to be added in addition to making investigations on the effects in the long run on the health of animals and in testing the method in further agro ecological zones to determine whether the method works in additional areas. Overall, this paper provides us a substantial ground to extend phytochemical rich agroforestry schemes as one of the central components of sustainable animal farming in the Global South and beyond.

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