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Water Hyacinth (Eichhornia crassipes) as an Alternative Feed Resource for Tropical Sheep and Goat Breeds: Effects on Nutrient Utilization, Growth Performance, and Economic Returns

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Abstract

The use of unconventional feed resources offers a practical strategy for mitigating feed shortages and reducing feeding costs in small-ruminant production systems. This study evaluated the effects of replacing commercial concentrate with water hyacinth (*Eichhornia crassipes*) on nutrient utilization, growth performance, and economic returns in Doyogena sheep and Woyito-Guji goats. Twenty-four yearling intact males (12 sheep and 12 goats) were assigned to a 2 × 4 × 4 randomized crossover design comprising two species, four dietary treatments, and four feeding periods. Treatments consisted of natural grass hay offered *ad libitum* and commercial concentrate replaced by water hyacinth at 0% (T1), 25% (T2), 50% (T3), and 75% (T4) on a dry matter basis. Species and dietary treatment significantly affected nutrient intake, digestibility, and growth performance ($P < 0.05$). Sheep consumed more dry matter, organic matter, digestible crude protein, and metabolizable energy than goats ($P < 0.001$), resulting in greater average daily gain (ADG) and body weight gain ($P < 0.05$). Conversely, goats exhibited higher apparent digestibility coefficients of dry matter, organic matter, crude protein, neutral detergent fiber, and acid detergent fiber ($P < 0.001$). Increasing water hyacinth inclusion significantly reduced nutrient intake, digestibility, ADG, and feed conversion efficiency ($P < 0.05$). ADG declined from 88.1 to 58.7 g/day in sheep and from 75.4 to 36.1 g/day in goats across treatments. Economic analysis showed that increasing water hyacinth inclusion reduced feed costs and improved net income, with the highest returns at 75% replacement (1,323.7 ETB/head for sheep and 1,067.4 ETB/head for goats). Water hyacinth can replace up to 75% of commercial concentrate, although replacement levels of 25–50% are preferable when maximizing animal performance.

1. Introduction

Livestock production is fundamental to Ethiopian agriculture, contributing approximately 45% of agricultural GDP and supporting the livelihoods of millions of smallholder farmers (Amejo, 2024). Small ruminants, particularly sheep and goats, are especially valuable due to their adaptability to harsh environments, rapid reproductive rates, and contribution to household food security and income generation (Jemberu et al., 2022). The Doyogena sheep and Woyito-Guji goats are indigenous breeds well-adapted to the diverse agro-ecological conditions of southern Ethiopia, playing crucial roles in the socio-economic fabric of rural communities (Taye et al., 2016; Lorato, 2014).

Despite their importance, the productivity of these small ruminants is severely constrained by seasonal feed shortages and the poor nutritional quality of available forages (Mekuriaw and Harris-Coble, 2021). Natural pastures and crop residues, which constitute over 94% of the national feed supply, are characterized by low crude protein (32–72 g/kg DM) and high fiber content (NDF: 595–792 g/kg DM), resulting in suboptimal digestibility and metabolizable energy values (Feyisa et al., 2022). The escalating costs of commercial concentrates further limit their accessibility to resource-poor farmers, necessitating the exploration of alternative, cost-effective feed resources (Bediye et al., 2018).

Water hyacinth (*Eichhornia crassipes*) has emerged as a promising unconventional feed resource due to its prolific growth, high biomass production, and nutritional profile. This invasive aquatic weed can produce up to 220 kg of biomass per hectare per day under optimal conditions (Bayrakci et al., 2023), with crude protein content ranging from 10–20% DM, making it comparable to many conventional forages (Hossain et al., 2015;

Mekuriaw et al., 2018). Its utilization as livestock feed addresses two critical challenges simultaneously: mitigating the environmental impacts of water hyacinth infestation and alleviating feed shortages (Su et al., 2018; Nega et al., 2021).

The browser/grazer dichotomy represents a fundamental difference in feeding behavior and digestive physiology between small ruminant species (Ketshabile, 2008). Goats (browsers) are adapted to select and process woody plant materials, possessing superior ability to digest fibrous feeds and detoxify secondary compounds compared to sheep (grazers), which are optimized for grass consumption (Lamy et al., 2011; Kijas et al., 2012). These species-specific adaptations may influence their capacity to utilize water hyacinth, which contains moderate levels of fiber and potential anti-nutritional factors such as calcium oxalate crystals (Krajda et al., 2023).

Previous studies have demonstrated the potential of water hyacinth as a feed ingredient for ruminants. Mekuriaw et al. (2018) reported that wilted water hyacinth leaves could effectively substitute up to 75% of concentrate mix in Washera sheep diets without compromising growth performance. Van Thu (2016) found that ensiled water hyacinth could replace up to 30% of Para grass in sheep diets, promoting growth without negative effects on rumen health. However, limited research has simultaneously evaluated the comparative responses of sheep and goats to water hyacinth-based diets under controlled conditions, particularly concerning nutrient utilization efficiency and economic viability.

The objectives of this study were to: (1) evaluate the effects of graded levels of water hyacinth inclusion on nutrient intake, digestibility, and growth performance in Doyogena sheep and Woyito-Guji goats; (2) compare species-specific responses to water hyacinth-based diets; and (3) assess the economic feasibility of incorporating water hyacinth into small ruminant feeding systems. We hypothesized that moderate inclusion of water hyacinth would improve nutrient utilization and growth performance, with species-specific differences influenced by the browser/grazer dichotomy, and that water hyacinth-based diets would offer economic advantages over conventional concentrate feeding.

2. Materials and Methods

2.1 Study Area

The experiment was conducted from October 2021 to February 2022 at the Arba Minch University Livestock Research Farm, Kulfo Campus, southern Ethiopia (6°2'21"N latitude, 37°34'24"E longitude; 1,285 m above sea level). The area has an average annual temperature of 29°C and receives 892 mm of rainfall annually (Ayda et al., 2024).

2.2 Experimental Animals and Management

Twenty-four intact yearling males comprising 12 Doyogena sheep (20.78 ± 0.40 kg initial body weight) and 12 Woyito-Guji goats (19.23 ± 0.30 kg initial body weight) were used in the experiment. Prior to the commencement of the study, animals were quarantined for four weeks, treated against internal and external parasites, vaccinated against common infectious diseases, and gradually adapted to the experimental diets. Animals were quarantined and acclimatized for four weeks, during which they received broad-spectrum

anthelmintic (albendazole), acaricide (diazinon) treatment, and vaccination against anthrax and pasteurellosis. Animals were gradually introduced to experimental diets to facilitate rumen microbial adaptation. Following acclimatization, animals were weighed after overnight fasting on two consecutive days, ear-tagged, and housed individually in 1.5 × 1.0 m metabolic pens. Feed was provided in equal portions twice daily (08:00 and 14:00 h), with clean water and mineralized salt licks available *ad libitum*.

2.3 Experimental Design and Dietary Treatments

The study employed a randomized 2×4×4 crossover design comprising two animal species, four dietary treatments, and four feeding periods. The study was conducted using a 2 × 4 crossover arrangement involving two animal species and four dietary treatments. The experiment consisted of four feeding periods. Each period lasted 22 days, comprising 15 days of dietary adaptation and 7 days of measurement and sample collection. The dietary treatments were:

- **T1**: 0% water hyacinth (WH) + 100% commercial concentrate (CC)
- **T2**: 25% WH + 75% CC
- **T3**: 50% WH + 50% CC
- **T4**: 75% WH + 25% CC

All treatments were supplemented with natural grass hay as the basal diet, offered *ad libitum*. The ratio of supplement to basal diet was maintained at 1:1 across all treatments. Animals were fed at 50 g DM/kg live body weight daily, formulated to provide a minimum of 8.36 MJ/kg metabolizable energy and 70 g CP/kg DM (NRC, 2007). Feed allowance was adjusted weekly based on body weight measurements.

2.4 Feed Ingredients and Chemical Analysis

Feed samples of water hyacinth, natural grass hay, commercial concentrate, refusals, and feces were analyzed for dry matter (DM), ash, and nitrogen according to AOAC (2019) procedures. Crude protein (CP) was calculated as nitrogen × 6.25, while organic matter (OM) was determined as the difference between dry matter and ash content. Neutral detergent fiber (NDF), acid detergent fiber (ADF), and acid detergent lignin (ADL) were analyzed according to Van Soest et al. (1991).

Digestible crude protein (DCP), total digestible nutrients (TDN), digestible energy (DE), metabolizable energy (ME), gross energy (GE), and non-fiber carbohydrates (NFC) were estimated using published prediction equations (Hvelplund et al., 1995; Sniffen et al., 1992; Ranjhan, 2001).

2.5 Data Collection

2.5.1 Feed Intake and Nutrient Digestibility

Daily feed intake was determined as the difference between feed offered and feed refused. During the collection phase of each experimental period, total fecal output was measured for digestibility determination. Approximately 20% of the daily fecal output was sampled, pooled by animal within period, and oven-dried at 60°C for 72 h. Apparent nutrient digestibility coefficients were calculated as:

Digestibility (%) = [(Nutrient intake − Nutrient excreted) / Nutrient intake] × 100

2.5.2 Body Weight and Growth Performance

Animals were weighed at the beginning and end of each experimental period after overnight feed withdrawal. Average daily gain (ADG) was calculated as the difference between final and initial body weight divided by the number of feeding days. Feed conversion efficiency (FCE) was calculated as the ratio of average daily gain to average daily dry matter intake. Calculations followed were indicated below:

1. ADG (g/day) = (Final BW - Initial BW) / Feeding days
2. Feed conversion efficiency (FCE) was calculated as:
3. FCE = ADG / Average daily feed intake (ADFI)

2.5.3 Economic Analysis

Partial budget analysis was conducted following Upton (1979) methodology. Variable costs included feed (hay: 10.71 ETB/kg; concentrate: 24 ETB/kg; water hyacinth: 6.94 ETB/kg), labor, and medication. Animals were valued at purchase and sale prices determined by local market experts. Net income (NI), change in net income (ΔNI), and marginal rate of return (MRR) were calculated as:

NI = Total Returns (TR) - Total Variable Costs (TVC)

ΔNI = ΔTR - ΔTVC

MRR = ΔNI / ΔTVC

2.6 Statistical Analysis

Data were analyzed using the MIXED procedure of SAS version 9.4. The statistical model included the fixed effects of species, dietary treatment, and their interaction, while experimental period and animal within species were considered random effects. The model was:

$Y_{ijkl} = \mu + S_i + T_j + (S \times T)_{ij} + P_k + Al(i) + \varepsilon_{ijkl}$

Where:

Y_{ijkl} = dependent variable;

μ = overall mean;

S_i = effect of species (sheep or goat);

T_j = effect of dietary treatment;

$(S \times T)_{ij}$ = interaction between species and treatment;

P_k = random effect of period;

Al(i) = random effect of animal nested within species;

ε_{ijkl} = residual error.

Normality of residuals was assessed using the Shapiro–Wilk test and homogeneity of variance using Levene's test. Means were separated using Tukey's multiple comparison procedure, and differences were declared significant at $P < 0.05$. Pearson correlation analysis was performed to evaluate relationships among nutrient intake, digestibility, and growth performance variables.

2.7 Ethics Statement

All experimental procedures were approved by the Animal Research Ethics Committee of Arba Minch University (Ref. No. AMU/AREC/4/2016) and conducted in accordance with European Union Directive 2010/63/EU guidelines for the care and use of animals for scientific purposes.

3. Results

3.1 Chemical Composition of Experimental Feedstuffs

The chemical composition and estimated energy values of water hyacinth (WH), grass hay, commercial concentrate (CC), and the experimental diets are presented in Table 1. Water hyacinth contained 923.4 g/kg DM, 891.2 g/kg OM, 54.2 g/kg EE, 109.1 g/kg DCP, 303.3 g/kg TDN, and 4.72 MJ/kg ME. Commercial concentrate contained greater DCP (164.2 g/kg DM), TDN (419.4 g/kg DM), and ME (6.60 MJ/kg DM) than water hyacinth. As the proportion of WH increased from T1 to T4, dietary DCP, EE, TDN, DE, ME, and GE decreased, whereas ash and ADL contents increased.

Table 1
Chemical composition and energy values of feed ingredients and treatment diets (g/kg DM)

Parameter	WH	Hay	CC	T1	T2	T3	T4
DM	923.4	922.3	901.7	912.0	914.7	917.4	920.1
OM	891.2	910.6	931.5	921.1	916.0	911.0	905.9
EE	54.2	37.8	79.0	58.4	55.3	52.2	49.1
DCP	109.1	50.2	164.2	107.2	100.3	93.4	86.5
CHO	71.7	81.6	67.3	74.4	75.0	75.5	76.1
NFC	19.3	15.3	28.8	22.0	20.8	19.7	18.5
TDN	303.3	212.5	419.4	315.9	301.4	286.9	272.4
Ash	108.8	89.4	68.5	78.9	84.0	89.0	94.1
DE (MJ/kg)	5.76	3.86	8.04	5.95	5.67	5.38	5.10
ME (MJ/kg)	4.72	3.17	6.60	4.89	4.65	4.42	4.18
GE (MJ/kg)	17.17	16.79	18.70	17.75	17.55	17.36	17.17
ADL	72.3	115.7	68.9	92.3	92.7	93.2	93.6

WH: Water hyacinth; CC: Commercial concentrate; DM: Dry matter; OM: Organic matter; EE: Ether extract; DCP: Digestible crude protein; CHO: Carbohydrates; NFC: Non-fiber carbohydrates; TDN: Total digestible nutrients; DE: Digestible energy; ME: Metabolizable energy; GE: Gross energy; ADL: Acid detergent lignin

3.2 Nutrient and Energy Intake

Nutrient and energy intake are presented in Table 2. Species significantly affected all measured intake parameters ($P < 0.001$), with sheep consuming greater amounts of DM, OM, DCP, TDN, and ME than goats. Treatment effects were significant for DCP, TDN, and ME intake ($P < 0.001$), while DM and OM intake showed a tendency to differ among treatments.

For sheep, DM intake increased from 718 g/day in T1 to 879 g/day in T2 and subsequently declined in T3 and T4. In goats, DM intake ranged from 606 to 659 g/day. Digestible crude protein intake declined progressively with increasing WH inclusion in both species, reaching the lowest values in T4 (74.5 and 57.0 g/day for sheep and goats, respectively). Significant species × treatment interactions were observed for most intake parameters, indicating differential responses of sheep and goats to increasing WH inclusion levels.

Table 2
Nutrient and energy intake of sheep and goats fed varying levels of water hyacinth

Parameter		Treatments, Mean					P-value		
	Animal Species	T1	T2	T3	T4	SEM	S	T	S×T
DM (g/day)	S	718[1]	879[1]	786[1]	793[1]	**12.7**	< 0.001	0.079	0.003
	G	659[2]	626[2]	649[2]	606[2]				
OM (g/day)	S	725[1]	880[1]	780[1]	780[1]	**12.7**	< 0.001	0.059	0.003
	G	666[2]	627[2]	644[2]	596[2]				
DCP (g/day)	S	84.4[1]	96.3[1]	80.0[1]	74.5[1]	**1.47**	< 0.001	< 0.001	0.002
	G	77.5[2]	68.6[2]	66.1[2]	57.0[2]				
TDN (g/day)	S	249[1]	290[1]	246[1]	235[1]	**4.27**	< 0.001	< 0.001	0.002
	G	228[2]	206[2]	203[2]	179[2]				
ME (MJ/day)	S	3.85[1]	4.47[1]	3.78[1]	3.59[1]	**0.07**	< 0.001	< 0.001	0.003
	G	3.53[2]	3.18[2]	3.13[2]	2.75[2]				

S: Sheep; G: Goats; DM: Dry matter; OM: Organic matter; DCP: Digestible crude protein; TDN: Total digestible nutrients; ME: Metabolizable energy; S: Species; T: Treatment; S×T: Species × treatment interaction. Means with different superscript letters within rows differ significantly (P < 0.05); superscript numbers indicate species differences within columns (P < 0.05).

3.3 Nutrient Digestibility

Apparent nutrient digestibility coefficients are shown in Table 3. Species and treatment effects were significant (P < 0.001) for all digestibility parameters evaluated. Goats exhibited higher digestibility coefficients than sheep across treatments for OM, DM, CP, NDF, and ADF digestibility.

Digestibility decreased progressively with increasing dietary WH inclusion. The highest digestibility values were recorded in T1, whereas the lowest values occurred in T4. Crude protein digestibility declined from 82.6% to 66.4% in sheep and from 85.7% to 69.4% in goats between T1 and T4. No significant species × treatment interactions were detected (P > 0.05), indicating a similar pattern of digestibility reduction in both species as WH inclusion increased.

Table 3
Apparent nutrient digestibility (%) in sheep and goats fed varying levels of water hyacinth

Parameter		Treatments, Mean					P value		
	Animal Species	T1	T2	T3	T4	SEM	S	T	S×T
OM	S	75.6[a²]	70.4[b²]	68.0[c]	63.7[d²]	1.16	< 0.001	< 0.001	0.638
	G	80.2[a¹]	77.0[b¹]	72.1[c]	66.8[d¹]				
DM	S	73.5[a²]	68.8[b²]	66.4[c]	62.4[d²]	1.14	< 0.001	< 0.001	0.552
	G	78.5[a¹]	75.3[b¹]	70.4[c]	65.1[d¹]				
CP	S	82.6[a²]	80.7[b]	73.2[c]	66.4[d²]	1.38	< 0.001	< 0.001	0.682
	G	85.7[a¹]	82.7[b]	74.9[c]	69.4[d¹]				
NDF	S	74.5[a²]	71.4[b²]	68.3[c²]	65.4[d]	0.76	< 0.001	< 0.001	0.995
	G	76.6[a¹]	73.6[b¹]	70.6[c¹]	67.5[d]				
ADF	S	60.6[a]	58.5[b²]	56.6[c]	54.2[d]	0.57	< 0.001	< 0.001	0.618
	G	62.7[a]	60.3[b¹]	57.8[c]	55.4[d]				

S: Sheep; G: Goats; OM: Organic matter; DM: Dry matter; CP: Crude protein; NDF: Neutral detergent fiber; ADF: Acid detergent fiber; S: Species; T: Treatment; S×T: Species × treatment interaction. Means with different superscript letters within rows differ significantly (P < 0.05); superscript numbers indicate species differences within columns (P < 0.05).

3.4 Growth Performance and Feed Conversion Efficiency

Growth performance and feed conversion efficiency are presented in Table 4. Initial and final body weights differed between species (P < 0.001), with sheep maintaining greater body weights than goats throughout the study.

Average daily gain (ADG) and body weight gain (BWG) were significantly affected by species (P = 0.028) and treatment (P < 0.001). Sheep achieved greater ADG and BWG than goats. The highest ADG was recorded in sheep receiving T1 (88.1 g/day), whereas the lowest value was observed in goats receiving T4 (36.1 g/day). Similarly, BWG declined as WH inclusion increased in both species.

Feed conversion efficiency was significantly affected by treatment (P < 0.001) but not by species (P = 0.792). The highest FCE values were recorded in T1 (0.11 for both species), while the lowest values occurred in T4 (0.07 for sheep and 0.06 for goats). No significant species × treatment interactions were observed for growth performance variables.

Table 4
Body weight change and feed conversion efficiency in sheep and goats fed varying levels of water hyacinth

Parameter		Treatments, Mean					P-value		
	Animal Species	T1	T2	T3	T4	SEM	S	T	S×T
IBW (kg)	S	22.1¹	23.1¹	22.6¹	22.9¹	0.32	< 0.001	0.884	0.938
	G	19.1²	19.1²	19.1²	19.9²				
FBW (kg)	S	24.5¹	24.7¹	24.0¹	24.1¹	0.31	< 0.001	0.059	0.554
	G	20.7²	20.5²	20.4²	20.7²				
ADG (g/day)	S	88.1	77.0	67.9	58.7¹	4.28	0.028	< 0.001	0.815
	G	75.4	67.5	59.9	36.1²				
BWG (kg)	S	1.85	1.62	1.43	1.23¹	0.09	0.028	< 0.001	0.815
	G	1.58	1.41	1.26	0.76²				
FCE	S	0.11	0.08	0.07	0.07	0.005	0.792	< 0.001	0.625
	G	0.11	0.10	0.08	0.06				

IBW: Initial body weight; FBW: Final body weight; ADG: Average daily gain; BWG: Body weight gain; FCE: Feed conversion efficiency; Animal Species: Species; T: Treatment; S×T: Species × treatment interaction. Means with different superscript letters within rows differ significantly (P < 0.05); superscript numbers indicate species differences within columns (P < 0.05).

3.5 Correlations among Nutrient Utilization and Growth Performance Traits

Pearson correlation coefficients among nutrient intake, digestibility, and growth performance variables are presented in Table 5. Average daily gain was strongly and positively correlated with DCP intake (r = 0.82; P < 0.001), ME intake (r = 0.78; P < 0.001), and TDN intake (r = 0.76; P < 0.001). Body weight gain showed similar positive relationships with nutrient intake variables.

Feed conversion efficiency was positively associated with DCP intake (r = 0.72; P < 0.001), ME intake (r = 0.68; P < 0.001), and CP digestibility (r = 0.74; P < 0.001). Water hyacinth inclusion level was negatively correlated with ADG, BWG, FCE, CP digestibility, NDF digestibility, DCP intake, ME intake, and TDN intake. The strongest negative association was observed between WH inclusion and CP digestibility (r = − 0.61; P < 0.001).

Table 5
Pearson correlation coefficients among nutrient intake, digestibility, and growth performance parameters

Parameter	ADG	BWG	FCE	CP Dig.	NDF Dig.	DCP Int.	ME Int.	TDN Int.	WH%
ADG	1.00								
BWG	0.98***	1.00							
FCE	0.89***	0.87***	1.00						
CP Dig.	0.72***	0.70***	0.74***	1.00					
NDF Dig.	0.58***	0.56***	0.61***	0.83***	1.00				
DCP Int.	0.82***	0.80***	0.72***	0.76***	0.62***	1.00			
ME Int.	0.78***	0.76***	0.68***	0.71***	0.58***	0.94***	1.00		
TDN Int.	0.76***	0.74***	0.66***	0.69***	0.56***	0.92***	0.98***	1.00	
WH%	-0.49**	-0.48**	-0.42*	-0.61***	-0.55***	-0.51***	-0.48**	-0.46**	1.00

**ADG: Average daily gain; BWG: Body weight gain; FCE: Feed conversion efficiency; CP Dig.: Crude protein digestibility; NDF Dig.: Neutral detergent fiber digestibility; DCP Int.: Digestible crude protein intake; ME Int.: Metabolizable energy intake; TDN Int.: Total digestible nutrient intake; WH%: Water hyacinth inclusion level. Significance: *P < 0.05; **P < 0.01; **P < 0.001*

3.6 Economic evaluation of water hyacinth inclusion in sheep and goat diets

The economic analysis is summarized in Table 6. Increasing WH inclusion reduced total variable costs in both species. Total variable costs declined from 514.8 ETB in T1 to 376.3 ETB in T4 for sheep and from 461.0 ETB to 332.6 ETB for goats.

Net income increased progressively with increasing WH inclusion level. The highest net income was obtained in T4, reaching 1323.7 ETB for sheep and 1067.4 ETB for goats. Relative to T1, T4 increased net income by approximately 34.4% in sheep and 44.4% in goats.

Marginal rate of return (MRR) was greatest in T2 for both species (2.00 for sheep and 1.34 for goats) and declined with further increases in WH inclusion. Nevertheless, the highest overall net income was achieved under T4 due to reduced feeding costs.

Table 6
Economic parameters (Birr/head) of sheep and goats fed varying levels of water hyacinth

Parameter	Species	T1	T2	T3	T4
Initial Price	S	2500	2500	2500	2500
	G	2100	2100	2050	2000
Selling Price	S	4000	4100	4200	4200
	G	3300	3400	3400	3400
Total Returns (TR)	S	1500	1600	1700	1700
	G	1200	1300	1350	1400
Total Variable Cost (TVC)	S	514.8	481.6	422.5	376.3
	G	461.0	418.2	375.2	332.6
Net Income (NI)	S	985.2	1118.5	1277.5	1323.7
	G	739.0	881.8	974.8	1067.4
Change in NI (ΔNI)	S	-	133.3	292.3	338.5
	G	-	142.8	235.8	328.4
MRR	S	-	2.00	1.17	0.78
	G	-	1.34	0.75	0.56
MRR: Marginal rate of return; 1 Birr ≈ 0.018 USD at time of study					

4. Discussion

4.1 Nutrient Composition and Intake

The chemical composition of water hyacinth in this study (CP: 109.1 g/kg DCP; NDF: 523.8 g/kg; ADL: 72.3 g/kg) falls within the range reported in previous studies (Hossain et al., 2015; Mako et al., 2011; Mekuriaw et al., 2018). The observed variations in nutrient composition can be attributed to differences in harvesting season, water quality, and biomass density at collection sites (de Vasconcelos et al., 2016; Shafy et al., 2016). The lower CP and higher fiber content of WH compared to commercial concentrate explains the declining nutrient quality observed from T1 to T4, consistent with findings by Mekuriaw et al. (2018) who reported decreased CP and increased NDF with higher WH inclusion.

The higher nutrient intake observed in sheep compared to goats aligns with their grazing behavior and greater feed consumption capacity (Salim et al., 2002; Candyrine et al., 2019). Sheep, as grazers, typically consume a wider variety of forage and have higher voluntary intake than goats, which are selective browsers (Bahtti, 2013). The peak nutrient intake observed in T2 (25% WH) for both species suggests an optimal inclusion level that balances palatability and nutrient density. The decline in intake beyond T2 may be attributed to increased

fiber content and potential anti-nutritional factors at higher WH levels, which can reduce feed palatability and intake (Mako and Ikusika, 2020; Krajda et al., 2023).

4.2 Nutrient Digestibility

The higher digestibility coefficients observed in goats compared to sheep across all treatments support the browser/grazer dichotomy hypothesis (Lamy et al., 2011; Kijas et al., 2012). Goats possess superior capacity to digest fibrous feeds and utilize poor-quality roughages due to more efficient rumen function, higher feed retention time, and greater microbial activity (Kechero et al., 2016). The digestion coefficients for CP, NDF, and ADF in this study (65–86%) were within the range reported by Mekuriaw et al. (2018) for Washera sheep fed WH-based diets (DM: 55–68%; CP: 60–78%; NDF: 65–75%).

The progressive decline in nutrient digestibility with increasing WH inclusion reflects the higher fiber and lignin content, which negatively affects rumen microbial activity and fiber degradation (Van Soest et al., 1991). The reduction in CP digestibility from T1 to T4 (16% in both species) is particularly noteworthy, as it may limit protein availability for growth. The negative correlation between WH inclusion and CP digestibility (r = -0.61) supports the contention that high-fiber feeds may reduce protein digestibility through increased rumen outflow rate or reduced microbial protein synthesis (de Vasconcelos et al., 2016; Mengistu et al., 2020).

4.3 Growth Performance

The superior growth performance of sheep compared to goats is consistent with their higher nutrient intake and utilization efficiency (Candyrine et al., 2019). The ADG values for sheep in this study (58.7–88.1 g/day) are comparable to those reported for Washera sheep (60–89 g/day) by Mekuriaw et al. (2018) and for Arsi-Bale sheep (62–88 g/day) by Girma et al. (2014). The ADG for goats (36.1–75.4 g/day) are similar to those reported for Borana goats (55–78 g/day) by Kumsa et al. (2019) but higher than the 30 g/day observed in local goats fed low-quality forage (Tilahun et al., 2013).

The decline in ADG and BWG with increasing WH inclusion reflects the reduced nutrient intake and digestibility at higher WH levels. The strong positive correlations between ADG and DCP intake (r = 0.82), ME intake (r = 0.78), and TDN intake (r = 0.76) emphasize the importance of protein and energy supply for growth performance. The species differences in growth response to WH inclusion (sheep maintained higher ADG than goats at all inclusion levels) suggest that sheep may be better adapted to utilizing WH-based diets, possibly due to their grazing habits and more efficient utilization of high-fiber feeds.

4.4 Feed Conversion Efficiency

The similar FCE between sheep and goats (0.06–0.11) indicates comparable efficiency in converting feed to body weight gain, despite species differences in intake and digestibility. This finding is consistent with Candyrine et al. (2019), who reported similar feed efficiency between sheep and goats despite differences in growth rate and feed intake. The decline in FCE with increasing WH inclusion (from 0.11 in T1 to 0.06–0.07 in T4) reflects the lower nutrient quality and reduced digestibility at higher WH levels. The strong positive correlation between FCE and DCP intake (r = 0.72) and ME intake (r = 0.68) underscores the importance of dietary protein and energy density for feed efficiency (Khalid et al., 2012).

4.5 Correlation Analysis

The correlation matrix provides valuable insights into the relationships between dietary composition, nutrient utilization, and growth performance. The strong positive correlations between nutrient intake and digestibility (r = 0.45–0.58) suggest that increased intake of nutrients is associated with improved digestibility, reflecting the positive effects of balanced nutrition on rumen function (McGrath et al., 2018). The negative correlations between WH inclusion and CP digestibility (r = -0.61) and NDF digestibility (r = -0.55) confirm the negative impact of high-fiber feeds on nutrient utilization.

The positive correlations between growth performance (ADG, BWG, FCE) and digestibility parameters (CP digestibility: r = 0.72; NDF digestibility: r = 0.58) indicate that improved nutrient digestibility directly translates to better growth performance. The moderate correlation between WH inclusion and ADG (r = -0.49) suggests that while increasing WH reduces growth, the effect is not as severe as the impact on digestibility, possibly due to compensatory mechanisms or adaptation of rumen microbes to higher fiber diets over time.

4.6 Economic Implications

The partial budget analysis demonstrates that WH-based diets offer economic advantages for smallholder farmers, particularly in feed-scarce regions where conventional concentrates are expensive or unavailable. The reduction in feed costs with increasing WH inclusion (up to 37.2% in sheep) reflects the lower cost of WH compared to commercial concentrate. The highest net income achieved in T4 for both species (sheep: 1,323.68 ETB; goats: 1,067.36 ETB) indicates that despite lower growth rates, the cost savings from reduced feed costs more than compensate for the lower weight gain.

The declining MRR with increasing WH inclusion (from 2.00 to 0.78 in sheep, 1.34 to 0.56 in goats) suggests diminishing economic returns at higher inclusion levels. This pattern is consistent with the biological response, where the negative impact on growth performance outweighs the cost savings beyond a certain inclusion threshold. The MRR values above 1.0 for T2 and T3 indicate profitable investments, while T4 (MRR < 1.0) may represent a less attractive investment despite the lowest feed costs and highest net income.

The species-specific economic differences (higher MRR for sheep than goats) reflect the better growth performance and nutrient utilization of sheep on WH-based diets. This suggests that sheep may be more suitable for WH-based feeding programs, while goats may require additional protein supplementation to achieve comparable growth rates and economic returns.

Conclusion

This study demonstrates that water hyacinth can effectively replace up to 75% of commercial concentrate in diets for small ruminants, offering a cost-effective feeding strategy during feed-scarce periods. Key findings include:

1. **Species-specific responses**: Sheep exhibited superior nutrient intake, digestibility, and growth performance compared to goats across all WH inclusion levels, indicating better adaptability to WH-based diets.
2. **Optimal inclusion level**: Moderate WH inclusion (25%, T2) provided the highest nutrient and energy intake for both species, while higher inclusion levels (50–75%) resulted in progressively lower growth performance.

3. **Digestibility patterns**: Goats showed consistently higher nutrient digestibility than sheep, supporting the browser/grazer dichotomy hypothesis.
4. **Growth and efficiency**: Growth performance and feed conversion efficiency declined with increasing WH inclusion, with strong positive correlations between nutrient intake and growth parameters (r = 0.58–0.82).
5. **Economic viability**: The T4 regimen (75% WH) achieved the highest net income for both species, reducing feed costs by 37% compared to the control diet.
6. **Recommendation**: The 75% WH inclusion level (T4) is recommended for maximizing economic returns, particularly for sheep production, while moderate inclusion (25–50%) may be preferred for goats or when higher growth rates are desired.

These findings contribute to the development of sustainable feeding strategies that utilize invasive aquatic plants while reducing production costs and improving profitability for smallholder farmers in tropical regions. Future research should investigate long-term effects of WH-based diets on animal health, reproductive performance, and product quality, as well as strategies to improve WH digestibility through processing or supplementation.

Declarations

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Conflict of Interest

The authors declare no conflicts of interest.

Data Availability

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

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