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Research Article

Effect of Plant Spacing on Agronomic Performance and Fodder Quality of Four Tepary Bean (*Phaseolus acutifolius* A. Gray) Cultivars

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Tepary bean is gaining interest around the world as a dryland field crop. A two-year field experiment was conducted to determine the effect of plant spacing on the agronomic performance and fodder quality of the crop. A split-plot design was used with three replications, four cultivars (GK010, GK011, GK012, and Motsumi) were assigned to main plots, while subplots were three intrarow plant spacing (10 cm, 20 cm, and 30 cm). Four agronomic variables and eight chemical compositions, including *in vitro* dry matter digestibility (IVDMD) of husk, stem, and leaf, were measured. Spacing significantly ($P < 0.05$) influenced plant biomass, pod yield, harvest index, and seed yield, while cultivar affected only pod yield and seed yield. Plant biomass increased with plant spacing where 10 cm produced 936 kg/ha; 20 cm, 750 kg/ha; and 30 cm, 611 kg/ha for 2015–2016 while 10, 20, and 30 cm were observed for 1568 kg/ha, 1135 kg/ha, and 889 kg/ha, respectively, in 2016–2017 season. These trends are attributed to the higher plant population in the narrow row spacing. GK012 consistently outperformed other cultivars for plant biomass, pod yield, and seed yield and has a potential for further selection. Fodder nutritive qualities were not affected by cultivar, while spacing only influenced IVDMD. The three plant parts were significantly ($P < 0.05$) different for all the nutritive qualities. Leaves had significantly ($P < 0.05$) lower values of ADF, CF, and NDF compared to those of stem and husk an indication of relatively higher digestibility of the leaf. Acid detergent fiber (40%), neutral detergent fiber (53.65%), crude fiber (35.45%), ash content (12.29%), dry matter (93.09%), and IVDMD (70.66%) were recorded. This study revealed that tepary bean forage has good nutritional content, except for the low phosphorus level. For higher agronomic performance, tepary cultivars should be planted at a spacing of 10 cm without compromising forage quality.

1. Introduction

Legumes are key components in mixed crop-livestock systems; they provide nutritious grains for food and haulms for fodder and improve soil fertility through nitrogen fixation [1].

Tepary bean (*Phaseolus acutifolius*) originally from the arid and semiarid environments of northwestern Mexico and the southwestern United States of America is an important legume crop [2, 3]. It possesses novel genes for abiotic and biotic stress tolerance useful in breeding its sister species common bean and other related species [4–6]. It has prospects in crop diversification by ensuring food availability in areas with common drought occurrence and in marginal areas [5, 7]. The crop produces nutritious, high-protein seeds and has gained interest around the world as a dryland field crop [8, 9].

In Africa, the crop is grown mainly by subsistence farmers under harsh environmental conditions (Shisanya, [10]), but as an underutilized crop, it has received limited research work especially in sub-Saharan Africa [11]. Tepary bean is a crop that is seriously promoted for the semiarid Botswana, especially since there is almost no production of common bean (*Phaseolus vulgaris*) in the country [12]. There is a need to conduct some scientific research on the agronomic performance and nutritional quality of the crop as an initiative to promote the crop further. Among several good agricultural practices that can contribute to the attainment of yield potential, plant spacing is critical, as it affects the growth and development of crops through modifying the canopy light interception and interplant competition for water and nutrients [13, 14]. A dense plant population may have limited availability of nutrients, moisture, solar radiation, and air temperature; hence, it is necessary to determine the optimum plant spacing to obtain maximum economic yields [15]. Planting pattern in tepary bean has been found to remarkably influence the yield of the crop in research conducted in semiarid Iran [16]. However, studies of plant spacing under rain-fed conditions of Botswana have not been explored, to optimize the suitable row planting pattern for tepary beans. In other legumes, intrarow spacing was reported to affect several yields and yield-related characters significantly such as lablab [17], cowpeas [18], soybean [19], and faba bean [20].

Generally, there is a lack of information on the nutritional fodder quality of tepary beans [21], including in Botswana. This fodder quality study is useful mainly for a country that is heavily dependent on the livestock industry. Botswana agriculture contributes approximately 2% of Gross Domestic Products (GDP), and livestock production, especially cattle, contributes an estimated 80% to the agricultural GDP and beef is the principal agricultural product for export [22]. However, a high mortality rate usually attributed to severe drought in the country leads to a significant reduction in the number of cattle [23]. Natural pastures are the most economical feed resource available to the majority of livestock farmers [24]. However, crop residues can be used during the dry season to augment the feed resources. Although some crop residues are low in nutritive value, they can be processed and used in animal diets [25]. There is a need to look for unconventional feed resources to supplement grazing livestock during the dry season when the nutrient content of natural pastures is limiting in quantity and quality. Tepary bean could be a useful feed source; as indicated, it compares well to those of alfalfa, peanut, soybean, and guar (Bhardwaj, [26, 27]); it could be explored for use as fodder like other legumes [28, 29]. Currently, there is a paucity of information about its use as fodder in Botswana livestock feeding systems. Additionally, the agronomic performance of the crop has not been fully investigated; hence, this study was conducted. In this context, the objective of the study was to determine the agronomic performance and fodder quality of four cultivars, based on three different row spacings, to identify appropriate sowing density to maximize yields and good quality fodder.

2. Materials and Methods

2.1. Study Site. A field experiment was conducted under rain-fed conditions for two consecutive seasons of 2015-2016 and 2016-2017 at Sebele, Gaborone. The experimental area is in Sebele Agricultural Research Station (24°35'S; 25°56'E) at 991 m above sea level, in the South-eastern, South of Botswana. The climate is semiarid with an average annual rainfall of 500 mm, the rains generally start in October and end in April, and most rains are received during November to March. Rains are not evenly distributed both spatially and temporally with long dry spells within the season. The average temperatures, relative humidity, and rainfall received during the 2015-2016 and 2016-2017 seasons are provided in Table 1. The soil in the experimental site is Eutric and Cambisols consisting of medium to coarse sandy and sandy loam soils [30]. The transect method was used to collect samples before the establishment of experiment soil at 15–20 cm depth using spade (or auger), the soil samples were thoroughly mixed and homogenized to make a composite sample for the complete site, and chemical analysis was conducted at Botswana National Soil and Plant Laboratory (BNSPL) [31]. The properties of the soil were sandy loam texture with a pH of 5.05, organic matter of 0.29%, P content of 0.19 cmol/kg, Ca content of 1.89 cmol/kg, Mg content of 0.53 cmol/kg, and K content of 0.39 cmol/kg.

2.2. Agronomic Management. Four tepary bean varieties GK010, GK011, GK012, and Motsumi were obtained from the National Plant Genetic Resources Centre (NPGRC), Botswana. The varieties have relatively high yield and agronomic characters and are suitable for planting in Southern Botswana [32]. The site was plowed and disc harrowed to level the soil and prepare the seedbed for planting. Sowing was done on the 3^{rd} week of December in the 2015-2016 and 2016-2017 seasons, according to the specifications of the experimental design. Two seeds were sown per hole and thinning was done 21 days after sowing. No fertilizer was applied as it is done in low-input farming systems, especially in legumes. However, manual weeding was conducted through the growth stage of the crop when necessary, and harvesting was done at physiological maturity of the crop on the 3^{rd} week of March in both seasons which is approximately 86 days after planting.

2.3. Experimental Design. The experiment was conducted in a split-plot, randomized complete block design (RCBD), replicated three times. Four tepary bean cultivars (GK010, GK011, GK012, and Motsumi) were used as the main factor and three plant spacings (0.75×10 cm, 0.75×20 cm, and 0.75×30 cm) as a subplot; grouping experimental units into blocks allows for experimental error minimization. The three intrarow spacings of 10 cm, 20 cm, and 30 cm, and a standard space between a row of 75 cm provide plant population estimates of 200,000, 100,000, and 66,600, respectively. The main plot size was $8\,m \times 6\,m$ ($48\,m^2$); the distance between main plots and blocks was 1 m and 2 m, respectively.

Table 1: Climatic data in the 2015-2016 and 2016-2017 season experimental periods.

	Average temperature (°C)		Relative humidity		Rainfall (mm)	
Months/years	2015-2016	2016-2017	2015-2016	2016-2017	2015-2016	2016-2017
December	28.5	26.4	37.5	46.1	22.8	60.4
January	27.7	24.3	40.7	60.5	33.0	167.6
February	27.9	22.7	38.9	75.3	29.4	307.6
March	23.5	22.4	56.5	60.7	103.6	46.2
Mean/total	26.9	23.95	43.4	60.65	188.8	581.4

2.4. Data Collection. At harvest at plant maturity approximately 86 days after sowing, data recorded include plant biomass (kg/ha), plant height (cm), pod yield (kg/ha), harvest index, and seed yield (kg/ha), collected within the middle rows of each plot. Plant height was measured from 10 randomly selected plants as the height from the ground level to the tip of the plant. Plant biomass (shoot dry weight) was measured by collecting the biomass (upper ground stems plus the leaves) while pod yield and seed yield were measured from the harvest from two middle rows and calculated per kg/ha. The harvest index (%) was calculated by dividing seed weight over plant biomass multiplied by 100. This yield attribute is a useful indicator of the efficacy with which assimilates are portioned into an economically useful component of the crop. The composition of tepary bean fodder quality was calculated from three traits of (husk, leaf, and stem) plant parts. Fodder samples from each treatment were collected in paper bags at grain maturity and oven-dried. The dried samples were ground to pass through a 2 mm mesh, and only data obtained from the second year was computed. Forage dry matter (DM) was determined by drying in an oven at 60°C for 24 hrs. Neutral detergent fiber (NDF) and acid detergent fiber (ADF) were determined as described by [33] using ANKOM 200 Fiber analyzer (model D2001, New York, USA). Crude fiber (CF) was determined using the procedures and equipment by ANKOM [34]. In vitro dry matter digestibility (IVDMD) was determined by a Daisy incubator (ANKOM technology corp) following procedures of [35]. Calcium was determined using atomic absorption spectrophotometer (280FSAA) while phosphorus (P) concentration was determined using a spectrophotometer (UV160PC UV visible spectrometer, ILSA Pty Ltd.) by the Association of Official Analytical Chemists (AOAC) methods [36]. Ash content of the feeds was determined according to the Kjeldahl method (AOAC) [36].

2.5. Statistical Analysis. The data obtained was analyzed using Genstat version 18. The design was a split-plot considering cultivar and spacing as main plot factor and subplot factor, respectively. Analysis of variance (ANOVA) was conducted to study the significance of all effects and their interactions; it was performed on yield and yield attributes and on the nutritional attributes of tepary bean. Since the year effect was significant for almost all growth and yield parameters, the results from each year were presented separately. The least significant difference (LSD) was used at 5% significance to compare the mean significant effect.

Model used:

$$Y_{ijk} = m + a_i + b_j + (ab)_{ij} + g_k + (ag)_{ik} + e_{ijk}$$

3. Results

3.1. Agronomic Performance of the Crop. The difference between the two seasons influenced the performance of tepary beans possibly due to the temperature and precipitation effects. The weather data indicate that during the 2015-2016 growing season a higher average temperate (26.9°C) and lower rainfall (188.8 mm) were observed compared to relatively lower temperatures of 23.9°C and higher precipitation (581.4 mm) during the 2016-2017 growing season (Table 1). Rains are not evenly distributed both spatially and temporally with long dry spells within the season, for example, during the 2015-2016 season, December, January, and February received less than 50 mm rainfall each, while more than 100 mm was received during March. On the other hand, for the 2016-2017 season during March, less than 50 mm of rain was recorded. The year highly ($P < 0.001$) affected plant biomass, pod yield, harvest index, and seed yield, indicating the presence of variation among the tested seasons (Table 2). The results of the analysis of variance for the spacing, cultivar, and their interactions for both seasons are provided in Table 2. Our findings revealed that plant spacing significantly ($P < 0.001$) influenced plant biomass, pod yield, harvest index, and seed yield, while cultivar significantly ($P < 0.01$) affected pod yield and seed yield. The interaction between spacing and cultivar did not affect any character, while interaction between spacing and year only affected harvest index (Table 2), indicating a lack of stability on the index.

The effect of cultivar and spacing on yield and yield attributes assessed in both seasons is summarized in Table 3. Generally, there was a higher agronomic performance during 2016-2017 compared to 2015-2016; for example, there was an increase of 36% for biomass and 41% for seed yield. Plant spacing indicated that a narrow spacing of 10 cm produced higher plant biomass, pod yield, and seed yield, followed by the medium spacing of 20 cm and least on the wider plant spacing of 30 cm, which was observed in both years (Table 3). For example, there was an increase in plant biomass with an increase in plant spacing where 10 cm produced 1568 kg/ha; 20 cm, 1135 kg/ha; and 30 cm, 889 kg/ha in 2016-2017, which is attributed to the higher plant population in the narrow row spacing. Similarly, higher pod yield was realized in the narrow spacing of 10 cm (882 kg/ha), preceded by the medium spacing of 20 cm with 634 kg/ha and lower in the 30 cm spacing (471 kg/ha). Spacing also had a significant effect ($P < 0.01$)

Table 2: Mean square variances from combined analysis of variance for yield and related components for four tepary bean cultivars evaluated for three plant spacings over two seasons (2015-2016 and 2016-2017).

Source of variation	Df	Biomass (kg/ha)	Plant height (cm)	Pod yield (kg/ha)	Harvest index	Seed yield (kg/ha)
Cultivar	3	107262 ns	36.56 ns	72552**	14.99 ns	25500**
Spacing	2	1541762***	1.90 ns	443358***	72.27***	243778***
Spacing × cultivar	6	23225 ns	5.02 ns	6676 ns	11.59 ns	5260 ns
Year	1	3355633***	25.83 ns	1196354***	109.02**	912049***
Spacing × year	2	197414 ns	0.97 ns	121933 ns	97.88**	81671 ns
Cultivar × year	3	33886 ns	54.00 ns	11687 ns	10.68 ns	2228 ns
Spacing × cultivar × year	6	21156 ns	9.69 ns	13253 ns	18.96 ns	5213 ns
Residual	24	180146	33.42	93003	23.55	41878
Mean		981.0	24.56	534.0	44.06	434.0
CV%		20.20	4.4	23.2	0.8	21.8

CV: coefficient of variation; ***significant at $P < 0.001$; **significant at $P < 0.01$.

Table 3: Main effect of cultivar and plant spacing on yield and yield attributes of tepary bean during 2015-2016 and 2016-2017 growing season.

	Biomass (kg/ha)		Plant height (cm)		Pod yield (kg/ha)		Harvest index		Seed yield (kg/ha)	
Treatments	2015-2016	2016-2017	2015-2016	2016-2017	2015-2016	2016-2017	2015-2016	2016-2017	2015-2016	2016-2017
Cultivar										
GK010	634	1170	20.23	25.58	306	613	42.95	43.58	264.3	511
GK011	706	1151	22.51	25.21	359	651	43.24	46.21	300.5	538
GK012	891	1216	27.07	24.9	501	698	41.72	45.99	370.1	567
Motsumi	832	1252	26.02	24.94	453	689	43.39	45.37	351	570
LSD	465.5	453.7	12.13	3.29	345.9	291.6	4.59	4.13	190.8	220.2
Spacing										
10	936	1568	23.79	25.08	468	882	38.89	45.8	365	718
20	750	1135	23.58	25.13	410	634	43.29	44.74	321	518
30	611	889	24.5	25.26	453	471	46.3	45.33	279	404
LSD	103.2	245	3.42	2.88	85.2	176.9	4.24	3.14	47.5	128.9
Mean	765	1197	23.96	25.16	405	662	42.83	45.29	321	547
CV%	15.6	19	16.5	13.3	24.3	30.9	11.5	8	17.1	27.3

LSD: least significant difference; CV: coefficient variation.

on seed yield, 10 cm spacing produced (718 kg/ha), medium spacing 20 cm (518 kg/ha), and wider spacing 30 cm (404 kg/ha) (Table 3). Even though higher values were recorded in the narrow spacing of 10 cm, preceded by medium 20 cm followed by those in the wider plant spacing (30 cm), significant differences were largely observed only between the 10 cm and the 30 cm plant spacing (Table 2).

However, the narrow spacing (10 cm) had an advantage of higher agronomic values. Harvest index was significantly ($P < 0.01$) influenced by spacing by year interaction but was not influenced by cultivar (Table 2). Conversely, a higher harvest index was identified among wider spacing of 30 cm (45.8), preceded by medium spacing 20 cm (44.01), and was lower in the narrow spacing of 10 cm (42.35), an indication that higher biomass in the narrow row spacing could not compensate for the seed yield production.

There was no significant difference in the amount of plant biomass produced by the four cultivars (Table 3), but the highest biomass was recorded on GK012 (1053 kg/ha) and lowest on GK010 (942 kg/ha). Similarly, pod yield was higher on GK012 (599 kg/ha) and lower on GK010 (459 Kg/ha). Seed yield was significantly different ($P < 0.01$) among the four cultivars, with significant variation noted between the highest yielder GK012 (468 kg/ha) and lowest producer GK010 (388 kg/ha). GK012 consistently outperformed other cultivars for plant biomass, pod yield, and seed yield and has a potential for further selection. Plant height was consistent between the two seasons and was not significantly different among the selected cultivars and even between three plant spacings. Our tepary bean cultivars have lower sizes with an average plant height of 24.56 cm (Table 2). There was a lack of spacing × cultivar × year for the plant height, an indication that this trait was not affected by the environmental changes.

3.2. Fodder Quality of Husk, Leaf, and Stem. The results on proximate composition, digestibility, and mineral content from tepary bean parts (husk, leaf, and stem) are summarized in Tables 4 and 5. Cultivar did not affect all the eight assessed nutritive qualities, which is an indication of lack of differentiation on the selected cultivars. Except for IVDMD, the three plant spacing did not influence all the nutritive qualities. In addition, cultivar × spacing interaction significantly ($P < 0.05$) affected only IVDMD, which implies a lack of stability on this character (Table 4). The three plant parts (husk, leaf, and stem) were significantly ($P < 0.05$) different for all the eight nutritive qualities (Tables 4 and 5). There was, however, no significant interaction between

Table 4: Mean square analysis of variance of eight nutritive qualities in three traits of husk, stem, and leaf of four tepary bean cultivars.

Source of variation	Df	ADF	DM	IVDMD	NDF	ASH	CF	Ca	P
Cultivar	3	13.27 ns	1.78 ns	74.16 ns	9.58 ns	33.10 ns	82.52 ns	1.49 ns	0.00023 ns
Spacing	2	2.76 ns	0.24 ns	81.99***	3.85 ns	26.06 ns	100.34 ns	1.04 ns	0.000014 ns
Spacing × cultivar	6	17.42 ns	0.25 ns	36.82**	17.77 ns	7.65 ns	58.26 ns	0.82 ns	0.000646 ns
Traits (husk, stem, leaf)	2	2890.19***	8.22***	1804.46***	5343.16***	1888.19***	4684.10***	28.77***	0.00278***
Spacing × traits	4	26.41 ns	0.16 ns	7.49 ns	34.14 ns	22.51 ns	29.72 ns	1.70 ns	0.00019 ns
Cultivar × traits	6	5.73 ns	0.23 ns	29.08 ns	6.90 ns	40.27**	80.63 ns	0.81 ns	0.00017 ns
Spacing × cultivar × traits	12	8.94 ns	0.27 ns	17.05 ns	22.43 ns	15.37 ns	30.50 ns	0.759 ns	0.00042 ns
Residual	48	723.36	0.166	17.62	27.08	16.49	52.08	1.43	0.0042
Mean		40	93.09	70.66	53.65	12.29	35.45	1.57	0.00401

ADF: acid detergent fiber, DM: dry matter, IVDMD: in vitro dry matter digestibility, NDF: neutral detergent fiber, CF: crude fiber, Ca: calcium, and traits (husk, stem, and leaf).

Table 5: Effect of plant spacing and cultivar on acid detergent fiber, dry matter, in vitro dry matter digestibility, and neutral detergent fiber on the husk, leaf, and stem of four tepary bean cultivars.

		ADF			DM			IVDMD			NDF		
Spacing	Cultivar	Husk	Leaf	Stem	Husk	Leaf	Stem	Husk	Leaf	Stem	Husk	Leaf	Stem
10	GK010	42.79	25.81	48.39	92.75	92.66	93.33	67.73	75.99	67.45	61.82	34.69	63.98
	GK011	40.63	30.52	50.53	93.01	93.42	93.9	71.84	73.94	56.92	55.22	39.54	64.52
	GK012	41.19	30.12	49.28	92.87	93.39	93.89	67.63	74.29	58.51	59.85	36.72	62.37
	Motsumi	40.68	31.61	52.14	92.35	92.77	93.81	71.63	78.47	62.92	57.99	39.68	64.94
20	GK010	39.69	31.53	44.83	92.38	92.47	93.27	75.48	78.37	69.44	57.5	44.26	59.47
	GK011	40.48	29.66	49.41	92.35	93.7	94.25	70.34	75.26	60.74	58.29	38.18	64.16
	GK012	37.07	28.54	49.31	92.69	92.67	93.37	75.03	81.28	67.26	53.39	37.37	62.25
	Motsumi	41.97	32.85	51.85	92.47	93.03	93.48	70.76	77.36	59.86	60.61	40.92	65.91
30	GK010	40.34	31.61	47.07	92.46	93.1	93.68	73.08	80.23	65.29	58.3	43.1	63.64
	GK011	39.42	32.96	47.14	93.07	93.18	94.06	71.25	75.52	60.91	57.28	43.07	61.35
	GK012	41.50	33.84	48.85	93.27	92.92	93.15	77.67	72.74	63.63	59.66	40.79	63.35
	Motsumi	40.69	30.34	45.33	92.43	92.57	93.13	73.02	79.33	62.67	59.42	39.76	58.6
	Mean	40.54	30.78	48.68	92.67	92.99	93.61	72.12	76.90	62.97	58.23	39.84	62.88
	LSD		1.84			0.19			1.98			2.46	
	CV %		4.9			0.3			2.8			4.4	

LSD: least significant difference; CV: coefficient of variation.

cultivar × traits for most of the qualities except for ash content. In addition, cultivar × spacing × traits did not affect any of the assessed nutritive qualities.

The selected quality measures are key in the assessment of the nutritive value of the crop for fodder quality. For instance, ADF, NDF, and CF measure the cellulose and lignin in the cell wall of plants. Acid detergent fiber (ADF) as expected was higher on the stem (48.68%) and then husk (40.5%) and least in the leaves (30.7%) with an average ADF content of 40% (Table 5). Similarly, NDF was higher on the stem (62.88%), followed by the husk (58.23%) and the least on the leaves (39.84%). Likewise, the DM was relatively higher on the stem (93.61%), followed by leaf (92.99%) and husk (92.67%). And so was in the CF, where the stem contained more CF (44.88%), preceded by the husk (38.7%), and was least on the leaves (22.7%) with an average of 35.45%.

On the other hand, the IVDMD value as expected was higher ($P < 0.05$) on the leaves (76.90%) compared to the husk (72.12%) and stem (62.97%). In addition, a significant ($P < 0.05$) effect of plant spacing on IVDMD was detected, with the narrow plant spacing recording (68.94%) significantly lower compared to 20 cm spacing with 71.76% and 30 cm with 71.28% (Table 5). This high digestibility suggests that the rumen microbes can have enough nitrogen and other nutrients from the substrates during fermentation.

The analysis of the ash and mineral composition revealed that there was a significant ($P < 0.05$) difference between the three plant organs; however, the higher values were instead observed in the leaf structure. For example, ash content was higher on the leaf (20.63%), compared to the husk (8.55%) and lower on the stem (7.68%), with an average of 12.29%. The higher ash content on the leaf was more pronounced on cultivar GK012 (28.30%) (Table 6). As for Ca, significantly ($P < 0.05$) higher values were also on the leaf (2.55%), followed by the stem (1.24%) and least in the husk (0.84%) (Table 6), with an average of 1.57% (Table 6). Similarly, phosphorus content (P) was significantly ($P < 0.05$) higher on the leaf (0.046%) than on stem (0.044%) and husk (0.0299%) (Table 6), with an average of 0.04% (Table 6). This led to a Ca : P ratio of approximately 28 : 1, 51 : 1, and 31 : 1 for husk, leaf, and stem, respectively (Table 6).

4. Discussion

4.1. Plant Growth Performance. As shown in Table 1, year two received good rains accompanied by slightly cooler ambient temperatures which promoted better plant growth

Table 6: Effect of plant spacing and cultivar on ASH, CF, Ca, and P on the husk, leaf, and stem of tepary bean cultivars.

		ASH			CF			Ca			P		
Spacing	Cultivar	Husk	Leaf	Stem	Husk	Leaf	Stem	Husk	Leaf	Stem	Husk	Leaf	Stem
10	GK010	6.66	21.88	8.05	44.46	17.82	41.33	0.71	4.91	1.59	0.032	0.058	0.061
	GK011	11.8	19.30	7.88	30.60	24.93	38.67	0.53	2.15	0.86	0.029	0.046	0.045
	GK012	6.76	28.30	7.64	35.76	16.11	47.30	1.12	2.22	1.32	0.022	0.045	0.046
	Motsumi	8.66	23.52	7.35	38.08	21.79	49.49	0.64	3.17	0.73	0.013	0.041	0.034
20	GK010	7.35	15.71	8.01	39.81	26.62	40.09	0.98	1.33	1.51	0.025	0.048	0.037
	GK011	8.33	15.29	8.21	39.00	30.08	48.45	0.77	1.96	0.76	0.061	0.052	0.039
	GK012	9.51	19.76	7.38	37.41	23.29	48.22	1.36	2.22	1.27	0.027	0.047	0.049
	Motsumi	5.95	25.12	6.77	39.24	23.43	50.41	0.45	2.22	1.33	0.022	0.034	0.041
30	GK010	12.00	17.16	6.73	43.94	25.61	45.79	0.75	2.89	1.41	0.019	0.042	0.033
	GK011	7.49	16.97	7.18	38.65	22.83	45.69	0.85	2.19	0.97	0.031	0.043	0.049
	GK012	10.07	24.94	9.60	35.39	14.42	39.75	1.10	2.28	1.60	0.035	0.048	0.049
	Motsumi	8.04	19.66	7.32	42.50	26.35	43.36	0.83	3.06	1.50	0.044	0.047	0.045
	Mean	8.55	20.63	7.68	38.71	22.71	44.88	0.84	2.55	1.24	0.0299	0.046	0.0442
	LSD		1.92			3.42			0.56			0.0097	
	CV%		16.1			13.0			23.2			30.4	

and development as reflected by improved plant biomass, pod yield, harvest index, and seed yield (Table 3). Low rainfall and rainfall variability and high-temperature extremes are the main factors driving vulnerability in semiarid Botswana [37]. The yield performance of grain legumes can be influenced by the environmental conditions [38]; previous observation on tepary beans revealed that lower moisture would lead to reduced agronomic performance such as lower plant biomass and reduced seed weight [12]. The 2015-2016 and 2016-2017 growing season differences were demonstrated by a lower average yield in the first year (321 kg/ha) compared to that (547 kg/ha) realized in the second year, which still indicates the generally low performance of tepary bean cultivars grown in Botswana. Tepary beans as an underutilized crop have not yet been improved; therefore, reports of low yields due to abiotic stress susceptible cultivars are rife in sub-Saharan Africa [39].

In this study, plant spacing significantly ($P < 0.05$) influenced plant biomass, pod yield, harvest index, and seed yield (Table 2), since narrow spacing recorded higher plant biomass, pod yield, and seed yield. These results are in accordance with those of [40, 41] who observed that narrow row spacing out yielded the wider spacing. For instance, on tepary bean studies conducted in Swaziland, a comparison was made between an intrarow spacing of 40 cm, 20 cm, 10 cm, and 5 cm; there was an increase in seed yield with a decrease in spacing at 644 kg/ha, 1176 kg/ha, 1383 kg/ha, and 1867 kg/ha, respectively [42].

The plant biomass is an important component useful for the feed of livestock [43] and a key factor in the crops-livestock mixed cropping. Marginal significance ($P = 0.07$) between cultivars was recorded, and the highest biomass was on GK012 (1053 kg/ha) and was higher on the spacing of 10 cm (1252 Kg/ha). These biomass values are lower than those for tepary bean grown in Cali-Columbia with an average of 2160 kg/ha [44], 4400 kg/ha reported by Bhardwaj [26], and 8130 kg/ha recorded by [27] in the USA. The differences could be attributed to environmental factors, and our selected cultivars are determinate and of lower stature. Tepary bean in this study produced a comparatively similar seed yield to forage cowpeas grown in Botswana with 141–691 kg/ha, but lower biomass of 2700–4300 kg/ha was reported by [28].

The planted tepary bean cultivars had an average plant height of 25.16 cm and are considered dwarf type; therefore, they would generally have a lower number of nodes and few branches and this would lead to lower yields [42]. However, the plant height estimate between the two seasons was not significantly different among the four cultivars and was also nonsignificant between the three plant spacings. Our findings are in accordance with those reported by Mureithi [40], who found that increasing intrarow spacing from 10 to 20 to 30 cm did not affect the plant height of French beans (*Phaseolus vulgaris*).

In contrast to other characters, the harvest index indicated a higher value (45.8) on a wider spacing of 30 cm, preceded by a medium spacing of 20 cm and a lower narrow spacing of 10 cm. Similar findings were reported on *Medicago sativa*, where the highest index was recorded in the wider spacing of 100 cm compared to 25 cm spacing [45]. The average harvest index (44.5) was relatively similar to approximately 40 observed among the nine lines assessed in a semiarid environment of Iran by Adibzadeh [46]. Cultivar only influenced two traits (pod yield and seed yield) among the selected characters in Table 2, which implied that there is relatively lower diversity among the cultivars. The outstanding cultivar was GK012, which consistently produced higher values than others but was only significantly different from the least performing cultivar GK010. The marginal differences among the cultivars are possibly due to the generally low diversity [32, 47] among the tepary beans.

4.2. Fodder Nutritive Value of Husk, Leaf, and Stem Plant Parts. The spacing effect was nonsignificant on proximate composition, mineral content, and digestibility of tepary beans (Table 4). As an indication of the cell wall content based on intrarow space differences, similarly [27] reported a lack of effect of ADF, on the maturity of tepary bean stems, compared to those of soybean and guard crops. Contrary to our findings, [19] reported a higher forage quality on CP, NDF, and ADF in 18 cm row spaced soybean plants than those spaced at 76 cm, which had higher fiber components (NDF and ADF) attributed to increased stem diameter.

There was a significant difference ($P < 0.05$) among the three traits for all the eight nutritive traits (Tables 4–6). The neutral detergent fiber was higher on the stem (62.88%) and relatively lower on the husk (58.23%) followed by the leaves (39.84%). Similar observations were reported on tepary nutrition analysis by Baath [27]), when comparing the stem and leaf of the crop. Forages with NDF within the range of 45% to 65% are classified as average in quality according to [48]; therefore, tepary bean cultivars in the present study are of "average" quality with respect to NDF content (with a range of 39.8%–62.84%). Stems have a greater cell wall content than leaves; thus, stems are generally lower in digestibility than leaves [49]. Forages with low NDF content tend to have a high dry matter intake thereby supplying host animals with the energy needed for growth and development. Our findings revealed that tepary bean leaf is highly digestible and has low NDF and therefore can be used as supplementary forage to dairy goats as an example. Our finding revealed that the leaves were significantly ($P < 0.05$) superior in forage quality due to lower ADF, CF, and NDF compared to both stem and husk (Tables 5 and 6).

Fodder quality traits that reveal good attributes to livestock nutrition are expected to have higher values for IVDMD, while the fiber fractions should have low values (NDF, ADF, and CF) [50]. The current findings (Table 4) on DM, ADF, NDF, CF, IVDMD, and ash are within the range of values reported by Bhardwaj [26, 27]. Similarly, these are in accordance with findings from [51] among eight *Lablab purpureus* varieties, for NDF (46.6%), ADF (33.6%), and IVDMD (70.9%) in Kenya. Yetimwork [52] reported similar results on ADF (32.2%–38.2%) and NDF (35.6%–46.4%) in faba beans (*Vicia faba*) among eight genotypes in Ethiopia, an indication that tepary bean is a good quality fodder like other pulses.

The higher digestibility values for leaves, husk, and stem (Table 5) suggest that the rumen microbes can have enough nitrogen and other nutrients from the substrate during fermentation. Van Soest [53] has stated that the minimum nitrogen required by microbes to digest feed efficiently in the rumen ranges from 1% to 1.2%. However, in the current study, crude protein was not determined, but it can be inferred that adequate nitrogen was availed to rumen microbes to digest tepary bean forage. Our IVDMD findings are comparable to digestibility results reported on cowpeas by Ravhuhali [28, 29] and on field pea (*Pisum sativum)* by Yetimwork [48]. The findings also indicated a significant ($P < 0.01$) effect of plant spacing on IVDMD, and these results are in accordance with those obtained by Ghadimian [16], who reported that tepary bean planting patterns can influence the protein and carbohydrates contents on crop parts. This could be attributed to temporal adaptation of tepary bean crop; in particular, given the low yielding growing condition, the study was undertaken.

Ash content was higher on the leaf (20.63) than on husk (8.55) and on the stem (7.68), and the higher ash content on the leaf was more pronounced on cultivar GK012 (28.30) and lower on GK011 (15.29) (Table 6). There was, however, no significant interaction between cultivar × traits for most of the qualities except for ash content, an indication of lack of stability of this particular character. According to Mirzaei [54], forages normally contain 3% to 12% ash on a dry matter basis. The leaves of the tepary bean had a relatively higher ash content at an average of 20%, which is attributable to the leaves being a storage organ of the plant.

Calcium content (Ca) ranged from higher values of 2.55 in the leaf to lower values of 1.24 on the stem and 0.84 on the husk (Table 6). The requirements for calcium in ruminants range from 0.2% to 0.6% [54]; therefore, our results show that the selected tepary bean crop residue has the potential to supplement calcium in other feed ingredients. Phosphorus content (P) ranged from higher values in the leaf with 0.046 to lower values in the husk with 0.029. This phosphorus level is inadequate for ruminant requirements for growth and development [49]. Phosphorus and calcium are very important in skeletal growth and development [55]. According to [56], the desirable calcium : phosphorus ratio is often between 2 : 1 and 1 : 1; however, our findings revealed that the calcium : phosphorus ratio is imbalanced in leaves, husk, and stems. The noticeably low levels of phosphorus would imply that feeding of tepary bean should be done as total mixed ration (TMR) or as sole feeding with a mineral lick to supplement phosphorus. Karachi and Lefofe [28] also reported phosphorus deficiency and high calcium and phosphorus ratio in cowpea forage grown in Botswana. The high calcium and phosphorus ratio in the current study could be attributable to soils in Botswana being inherently poor in phosphorus [57]. Castro-Montoya et al. [58] demonstrated that legume crop residues improve dry matter intake in dairy cattle than sorghum silage when fed in total mix ration. Legume forages have a higher nutritive value when compared to grasses especially during the dry season [59, 60]. In semiarid environments, seasonal-constant changes in the nutritional quality of natural pastures compromise livestock quality and lead to the inclusion of leguminous plants as supplements [61]. Tepary bean could be useful as a good quality forage for the growth or milk yield in livestock.

5. Conclusions

Tepary bean produces nutritious, high protein seeds and is gaining interest around the world, but as an underutilized crop, it has received limited research work especially in sub-Saharan Africa. This study showed that plant spacing influences the agronomic performance and fodder quality of the crop. For the crop to realize higher agronomic performance, it can be cultivated at a spacing of 10 cm without compromising forage quality. The outstanding cultivar was GK012, which consistently produced higher values than others; marginally differences among cultivars were generally due to lower diversity. This would call for a concerted effort to improve the diversity of Botswana's tepary germplasm. The result may prove particularly important as it also provided evidence that tepary bean forage has the potential to provide ruminants with nutrients needed for growth especially during the dry season when natural pastures are having poor quality. However, it is very important to supplement phosphorus when feeding tepary bean forage since it is lower than the requirements for ruminants.

Data Availability

The dataset that supports the findings in the study is available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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