CROP QUALITY & UTILIZATION

Forage Nutritive Value of Various Amaranth Species at Different Harvest Dates

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ABSTRACT

Complete information on forage quality characteristics of amaranth is unavailable. This study evaluated the forage quality of various amaranth accessions at different harvest dates. Seven accessions from the North Central Plant Introduction Station were established in June 1997 and June 1998 near Boone, IA. Subplots were harvested six times at 2-wk intervals beginning 42 d after planting (DAP). In vitro dry matter digestibility (IVDMD), neutral detergent fiber (NDF), crude protein (CP), nitrate-nitrogen, acid detergent fiber (ADF), acid detergent lignin (ADL), protein and fiber digestion, and undegradable intake protein (UIP) were determined. Averaged over accessions, IVDMD decreased ($P < 0.05$) from 780 g kg^{-1} at 42 DAP to 680 g kg^{-1} at 112 DAP. Digestibility ranged from 590 to 790 g kg^{-1}. Averaged over accessions at 42 DAP, CP was 270 g kg^{-1} then decreased to 100 g kg^{-1} at 112 DAP. Neutral detergent fiber increased from 310 g kg^{-1} at 42 DAP to 430 g kg^{-1} at 112 DAP. Averaged over harvest date, *Amaranthus cruentus* (Zimbabwe) had the highest NDF (390 g kg^{-1}), and *A. hybrid* (Puebla, Mexico) had the lowest (330 g kg^{-1}). *Amaranthus cruentus* (Zimbabwe), *A. cruentus* (Rwanda), and *A. hybrid* (Puebla, Mexico) had UIP averaging 25, 22, and 16%, respectively, of total crude protein after 16 h of digestion. Forage quality of the accessions at most harvest dates was consistent with what would be expected for relatively good quality forage, although high nitrate levels are a concern.

The potential of amaranths as forage has not been fully studied. Most of literature relates to human use of grain or vegetable amaranths. Some amaranth cultivars, however, are highly prized as forage crops because of their rapid growth rate and high protein content. In China, *Amaranthus hypochondriacus* L. and *A. hybridus* L. are being cultivated solely for use as forage for cattle (Kauffman, 1992). Amaranth is widely grown as a leafy vegetable in tropical and subtropical Africa, Asia, the Pacific Islands, the Caribbean, and Central America, but there are few reports of its potential as a forage or silage crop (Cervantes, 1986).

Environmental hardiness, utility as a grain and/or vegetable resource, and efficient water use has led to the recent resurgence in amaranth production. These are qualities essential for the survival of any modern crop because of diminishing water supply and limited land resources in many areas of the world (Saunders and Becker, 1984).

Several studies (Stordahl et al., 1999; Lehmann, 1990; Pond and Lehmann, 1989; Senft, 1979; Cheeke and Bronson, 1979; Odwongo and Mugerwa, 1980; Yue et al., 1987) have shown that amaranth nutritional qualities are superior to those of the common cereals and forage crops. Arguably, the most important nutritional quality of a grain is its protein content and quality. Amaranth protein levels range from 13 to 19% in the grain (Lehmann, 1990; Pedersen et al., 1987) and from 12 to 27% for the whole plant (Stordahl et al., 1999; Mugerwa and Bwabye, 1974; Marten and Andersen, 1975). The protein quality of amaranth grain combined with its productivity (Stordahl et al., 1999; Campbell and Abbott, 1982; Clark and St. Jean, 1984) compares favorably with more commonly used grains. The proteins of wheat, corn, and rice are deficient in the essential amino acid lysine and the sulfur-containing amino acids methionine and cysteine. Amaranth, however, is rich in both lysine (Bressani et al., 1987) and sulfur-containing amino acids (Senft, 1979).

Cheeke and Bronson (1979) found that amaranth leaves and stems were higher in hemicellulose and ash and lower in acid detergent fiber (ADF) than alfalfa (*Medicago sativa* L.). They also found a greater amount of protein bound to the cell wall constituents in amaranth than in alfalfa and comfrey (*Symphytum officinale* L.). This suggests that amaranth may have a higher bypass protein value. Bypass protein or rumen undegraded intake protein (UIP), if available in the lower gut, can be of great value in livestock production because rumen microbes may degrade high-quality protein and escape protein is more efficiently used in postruminal digestion as long as it contains essential amino acids (Van Soest, 1994). Increasing the UIP percentage in the diets of growing heifers improves feed efficiency and increases body weight gain (Tomlinson et al., 1997) and milk yield (Vagnoni and Broderick, 1997).

The concentration of UIP in different forages has been reported (Merchen and Satter, 1983; Mathers and Miller, 1981; Rooke et al., 1983; Charmley and Veira, 1990; Glenn et al., 1989; Beever et al., 1987). Mitchell et al. (1997) reported UIP for switchgrass (*Panicum virgatum* L.) and smooth bromegrass (*Bromus inermis* L.) as 230 to 310 and 110 to 180 g kg^{-1} of total crude protein, respectively, and that warm-season grasses generally had greater UIP because of their C_4 anatomy. Amaranth, being a C_4 plant, could potentially be a good source of UIP.

Pond and Lehmann (1989) cited *Amaranthus cruentus*

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Abbreviations: ADF, acid detergent fiber; ADL, acid detergent lignin; CP, crude protein; DAP, days after planting; DM, dry matter; IVDMD, in vitro dry matter digestibility; NDF, neutral detergent fiber; NIRS, near infrared reflectance spectra; TD, true digestibility; UIP, undegradable intake protein.

L. (Zimbabwe cultivar PI 482049) as a potential feed resource for ruminants based on its high protein content, low cellulose, and the absence of toxic substances in the vegetative fractions of the plant. However, some amaranth can have toxic levels of nitrates and oxalates (Cheeke and Bronson, 1979). Toxicity can result from nitrates in forages. Poisoning may result from accumulation of nitrates and/or oxalates in plants growing under stress, especially if drought conditions occur during a period of heavy nitrate uptake by the plant. Dietary nitrate is converted to nitrite, then ammonia by rumen bacteria. Toxicity occurs when the rate of conversion of nitrate to nitrite is higher than the conversion of nitrite to ammonia. Once absorbed into the blood, nitrite will bind to hemoglobin, forming methemoglobin. Since methemoglobin is less efficient in oxygen transport, animals will literally suffocate (Vough et al., 1991).

Adams et al. (1992) reported that nitrate content above 1 to 3% on a dry matter basis can cause acute toxicity in animals. However, Vough et al. (1991) reported that toxicity usually occurs when cattle consume large amounts of forage containing 1.76% or more nitrate ion on a dry matter basis.

Our objective was to evaluate the forage nutritive value of different amaranth species from various geographical areas with different morphological characteristics at different harvest dates.

MATERIALS AND METHODS

Plant Material

Seven amaranth accessions were chosen from the USDA North Central Regional Plant Introduction Station based on their general morphology, growth habit, and probable suitability as a forage crop as well as to reflect a broad geographic and genetic spectrum. The accessions evaluated were *Amaranthus cruentus* (Mexico, PI 477913), *A. cruentus* (Zimbabwe, PI 482049), *A. cruentus* (Rwanda, PI 527570), *A. hybrid* (Puebla Mexico, Ames 22667), *A. hybridus* (Greece, Ames 5531), *A. hybridus* (Zambia, PI 500249), and *A. hypochondriacus* (Colorado, PI 584523). *Amaranthus hybrid* (Puebla, Mexico) and *A. hybridus* (Greece) are vegetable-type amaranths, and the others are grown primarily for grain.

Plant Establishment

Seeds of each accession were allowed to imbibe and then chilled at 6°C for 30 d. The seeds were then grown in the greenhouse under 16 h of light and day and night temperatures of 29 and 24°C, respectively. Plants were grown for 3 wk in the greenhouse and then transplanted 1 June 1997 and 1 June 1998 at the Iowa State University Sorenson Research Farm near Boone, IA (42°N, 93°W), on a Webster-Nicolet (fine-loamy, mixed, superactive, mesic, Typic Endoaquoll). Mean air temperature for 1 May to 30 September was 20°C and 21°C for 1997 and 1998, respectively, and mean monthly precipitation for the same period in 1997 and 1998 was 65.38 mm and 110.74 mm, respectively. Plots were 7.6 × 7.6 m, with plants placed in 76-cm rows. Border rows were established around each plot and subplot to reduce border effects. In both years, ammonium nitrate was applied at 45 kg ha^{-1} to each plot. Irrigation was provided as needed for the first 2 wk after transplanting.

The experimental design was a randomized complete block with a split-split plot arrangement with three replications and seven plots per replication.

Forage Quality

In each plot, subplots representing harvest dates were marked. Plants were harvested at 14-d intervals starting 42 d after planting (DAP) in the field. Subplots were hand-harvested at a height of 7.5 cm, weighed, and dried in a forced-air dryer at 60°C for 48 h. Dried samples were ground to pass through a 1-mm mesh screen by using a UDY cyclone mill (UDY Manufacturing, Fort Collins, CO). Near infrared reflectance spectra (NIRS) were acquired for all samples by using a scanning monochromator (NIRS Systems, Silver Springs, MD). All samples from replications one and three for 1997 and 1998, respectively, were chosen as calibration samples and analyzed for IVDMD, CP, NDF, and ADL, and rumen bypass protein. All samples for both years were analyzed for nitrate-nitrogen. NIRS prediction equations were developed by using modified partial least squares regression to predict the values of IVDMD, NDF, CP, ADF, and ADL. The R^2, standard error of calibration, and standard error of cross validation for prediction equations are shown in Table 1.

The IVDMD procedure followed the NC-64 Marten and Barnes (1980) direct acidification system based on the Tilley and Terry (1963) in vitro method. Neutral detergent fiber and ADF were determined with the ANKOM 200 Fiber Analyzer (ANKOM Technology, Fairport, NY) as described by Vogel et al. (1999). The NDF procedure was modified by adding 4 mL of heat-stable α-amylase (ANKOM Technology #FAA) to the NDF solution before extraction. Acid detergent lignin was determined by using the procedure for lignin determination in the Daisy^{II} Incubator (ANKOM Technology, Fairport, NY). Crude protein was determined by obtaining the Kjeldahl N value for each sample and multiplying by 6.25 (Bremner and Breitenbeck, 1983). A modified version of the Gelderman and Beegle (1998) method for determining soil nitrate-nitrogen was used to obtain nitrate-nitrogen values for the samples. The modification was simply to change the amount of sample material used to 0.50 g of dried ground plant material instead of the 10 g used for soil samples.

The accessions *A. cruentus* (Zimbabwe), *A. cruentus* (Rwanda), and *A. hybrid* (Puebla, Mexico) were selected to be analyzed for fiber and protein digestion characteristics. Fermentation times were 4, 16, and 48 h and a zero time (NDF nitrogen) sample was used as a standard. Samples were digested in vitro in nylon bags for the prescribed time, then NDF determinations were done on the residues by using the ANKOM 200 Fiber Analyzer. After NDF analysis, total nitrogen was determined for each sample as previously described and used to estimate degradable intake protein and undegraded intake protein and their associated digestion parameters:

$$\text{Degraded Intake Protein} = CP_s + CP_d\,(1 - e^{-kt})$$

Table 1. Near infrared reflectance spectroscopy prediction calibration statistics for in vitro dry matter digestibility (IVDMD), neutral detergent fiber (NDF), crude protein (CP), acid detergent fiber (ADF), and acid detergent lignin (ADL).

Variable	*n*†	Terms	Mean	SEC†	R^2†	SECV†	1-VR†
IVDMD	79	7	71.28	1.16	0.96	1.56	0.93
NDF	79	6	37.42	1.17	0.97	1.42	0.96
CP	77	8	14.45	0.41	0.99	0.58	0.99
ADF	78	8	24.71	0.51	0.99	0.87	0.98
ADL	83	8	3.54	0.24	0.97	0.41	0.93

† *n*, number of samples; SEC, standard error of calibration; R^2, coefficient of determination; SECV, standard error of cross validation; 1-VR, validation coefficient of determination.

$$\text{Undegraded Intake Protein} = CP_d \times \frac{K_p}{K_d + K_p} + CP_U$$

Where

CP_s = Soluble protein = (Total N − NDFN)6.25

CP_d = Degradable protein = (NDFN − residual N)6.25

kt = Rate of digestion multiplied by duration of incubation

K_p = Estimated passage rate = 0.05

K_d = Rate of digestion = $[\ln(C_4 - C_{48}) - \ln(C_{16} - C_{48})]/[16 - 4]$

CP_u = Undegradable protein = (residual N)6.25

True digestibility (TD) was estimated by a modified version of the method reported by Redfearn et al. (1999) and partitioned into cell solubles (C_S), digestible fiber (C_D), and their associated digestion parameters:

$$TD = C_S + C_D\,[1 - e^{-k(t-L)}]$$

$$C_S = 1000 - NDF = 1000 - C_0$$

$$C_D = \text{Initial NDF} - (\text{residual NDF at 48 h}) = C_0 - C_{48}$$

Where

C_0 = NDF concentration (grams of NDF kg^{-1} initial DM)

C_{48} = residual NDF concentration (grams of NDF kg^{-1} initial DM) following 48 h of in vitro incubation

Rate of fiber digestion (k) and digestion lag time (L) were then calculated as follows:

$$k = [\ln(C_4 - C_{48}) - \ln(C_{16} - C_{48})]/[4 - 16]$$

$$L = \{\ln(C_0 - C_{48}) - 0.5\,[\ln(C_4 - C_{48})(C_{16} - C_{48}) - k\,(4 + 16)]\}/k$$

DM = dry matter

t = duration of incubation

Statistical Analysis

Statistical analysis was performed with the General Linear Model and Regression procedures of Statistical Analysis Systems (SAS, 1985). Mean comparisons were made by using an F-protected LSD (Steele and Torrie, 1980). Single degree of freedom contrasts were made between the vegetable- and grain-type accessions. The significance level for all comparisons was $P \leq 0.05$ unless otherwise noted.

Table 2. Mean nitrate concentration for seven amaranth accessions at different harvest dates. Results are averaged over years.

Accessions	Days after planting					
	42	56	70	84	98	112
	g kg^{-1} DM†					
A. cruentus (Mexico)	96	96	57	30	17	1.3
A. cruentus (Zimbabwe)	73	77	33	21	17	8.7
A. cruentus (Rwanda)	62	87	46	31	18	5.6
A. hybrid (Puebla, Mexico)	58	57	35	21	21	6.3
A. hybridus (Greece)	55	36	36	12	19	2.7
A. hybridus (Zambia)	78	89	43	47	31	10
A. hypochondriacus (Colorado)	92	96	66	42	29	18

LSD 0.05 = 1.4.
† DM, dry matter.

RESULTS AND DISCUSSION

An interaction of accession and harvest date was observed for all variables studied except CP. Tables 2 to 8 illustrate the interaction between accession and harvest date for the variables studied.

Years

Neutral detergent fiber was higher in 1997 (400 g kg^{-1} DM) than in 1998 (330 g kg^{-1} DM). Also, nitrate levels at 42 and 56 DAP in 1997 were greater than the highest nitrate level for 1998. This observation may be explained by transient stress conditions, which included high temperature, moisture stress, heavy rain, and low sunlight experienced during the first 3 to 4 wk of field growth. The CP concentrations are encouraging because it suggests that CP concentration is likely to be constant between years even though there were differences in the environment. More research needs to be done over several seasons to make a conclusion on that matter.

Accession

Nitrate concentration was affected by harvest date and harvest date–accession interaction (Table 2). As the season progressed, there were observable differences in stage of development among accessions at each harvest date. Some were vegetative while others had started the reproductive stage. Adams et al. (1992) reported that nitrate concentrations >1 to 3% on a dry matter basis can cause acute toxicity in animals. With this in mind, the observed nitrate levels in fresh forage were too high to be fed to livestock until 84 DAP for all accessions except *A. hybridus* (Zambia) and *A. hypochondriacus* (Colorado), which did not get below 3% nitrate concentration until after 98 DAP.

Accession and accession–harvest date interactions were significant for NDF concentration (Table 3). Single degree of freedom contrasts of vegetable- versus grain-type accessions were not significant. Observed NDF values were lower than those reported for some cool-season grasses (Sleugh et al., 2000).

Although NDF is known to increase with the age of plants, Walters et al. (1988) showed that leaf NDF of several amaranth accessions declined linearly with increasing nitrogen fertilizer application levels. This could be a management option to improve the forage quality

Table 3. Mean neutral detergent fiber (NDF) concentration for seven amaranth accessions at different harvest dates. Results are averaged over years.

Accessions	Days after planting					
	42	56	70	84	98	112
	g kg^{-1} DM†					
A. cruentus (Mexico)	310	300	360	350	380	380
A. cruentus (Zimbabwe)	310	310	370	450	440	470
A. cruentus (Rwanda)	320	300	340	380	430	440
A. hybrid (Puebla, Mexico)	260	280	310	350	370	380
A. hybridus (Greece)	290	290	350	390	430	450
A. hybridus (Zambia)	310	300	350	410	440	450
A. hypochondriacus (Colorado)	330	330	350	390	400	400

LSD 0.05 = 50.
† DM, dry matter.

of amaranth fed to livestock. However, excess nitrogen fertilization could lead to lodging, nitrate poisoning, and increased stem NDF.

In vitro dry matter digestibility was significantly affected by accession (Table 4). Single degree of freedom contrast of vegetable- versus grain-type accession indicated that vegetable-type accessions consistently had greater IVDMD concentrations than grain-type accessions at all harvest dates. The increased digestibility of the vegetable-type accessions may have been due to the presence of a greater number of leaves and stems observed and they were visibly more succulent than the stems of the grain-type accession, especially earlier in the season. Some amaranth forage has nearly equal proportions of leaves and stem when they are in the vegetative stages (Stordahl et al., 1999).

Acid detergent fiber concentration was affected by accession (Table 6). *Amaranthus hybrid* (Puebla, Mexico) had the lowest (210 g kg^{-1}) ADF concentration when averaged over harvests. Surprisingly, the other vegetable-type accession, *A. hybridus* (Greece) had the third highest ADF concentration (244 g kg^{-1}). Another surprise was that *A. cruentus* (Mexico), a visibly stemmy and woody plant in the latter part of the season, still had the second lowest (225 g kg^{-1}) ADF when averaged over harvest date. This was unexpected because Stordahl et al. (1999) reported a decline in whole plant quality with maturity associated with an increase in stem NDF and ADF concentration.

These ADF concentrations are encouraging when compared with data reported by Marten and Andersen (1975) for alfalfa and oat (*Avena sativa* L.), 237 and 340 g kg^{-1}, respectively. All accessions except *A. cruentus* (Mexico) and *A. cruentus* (Zimbabwe) had ADF concentrations lower than 237 g kg^{-1} until up to 70 DAP. However, nitrate levels were too high for safe feeding until 2 wk later. The ADF concentration in *A. hybrid* (Puebla, Mexico) was 227 g kg^{-1} at 84 DAP (Table 6). Cherney and Marten (1982) reported ADF values for wheat (*Triticum aestivum* L.), oat, triticale (*Triticum durum* Desf. X *Secale cereale* L.), and barley (*Hordeum vulgare* L.) that were higher than the average values for all amaranth accessions evaluated. Acid detergent lignin for all accessions except *A. cruentus* (Zimbabwe) was lower than for the crops studied by Cherney and Marten (1982).

Concentration of ADL was significantly influenced by accession (Table 7). Averaged over harvest date, *A. cruentus* (Zimbabwe) had the highest ADL (48 g kg^{-1}) followed by *A. hypochondriacus* (Colorado), *A. cruentus* (Mexico), and *A. cruentus* (Rwanda) with similar ADL of 35, 35, and 33 g kg^{-1}, respectively. *Amaranthus hybridus* (Zambia), *A. hybrid*us (Greece), and *A. hybrid* (Puebla, Mexico) were not different and had ADL concentrations of 29, 28, and 26 g kg^{-1}, respectively.

Marten and Andersen (1975) reported that high-quality alfalfa had 60 g kg^{-1} ADL and oat had an ADL of 36 g kg^{-1}. The results obtained for these amaranth accessions at various harvest dates are substantially less than that reported by Marten and Andersen (1975) for alfalfa and could prove to be a positive indication for the use of amaranth as forage.

Harvest Date

The effect of accession on nitrate concentration was not significant when plants were at a similar maturity stage. Variations in nitrate levels are presented in Table 2. Nitrate concentration decreased from an average of 7.7% at 42 DAP to 0.94% at 112 DAP. The greatest nitrate concentration in grain-type accessions averaged 58% higher than the greatest average nitrate concentration of the vegetable-type accessions.

Neutral detergent fiber increased with harvest date (Table 3), similar to that reported by Walters et al. (1988) and Stordahl et al. (1999). The greatest change (550 g kg^{-1}) in NDF from 42 DAP to 112 DAP was observed in *A. hybridus* (Greece) and the lowest (210 g kg^{-1}) in *A. hypochondriacus* (Colorado).

Averaged over accessions, CP was highest at 42 DAP (270 g kg^{-1}) and declined steadily over the season (Table 5). The CP concentration at 42, 56, and 70 DAP (270, 210, and 150 g kg^{-1}, respectively) were significantly different but were similar at 84, 98, and 112 DAP (120, 120, and 100 g kg^{-1}, respectively). The relationship between CP and harvest date was best described by an equation with a quadratic effect and had a strong negative correlation ($R^2 = 0.99$). The 42 DAP CP concentration (270 g kg^{-1}) is close to the results reported by Mugerwa and Bwabye (1974), who found 277 g kg^{-1} CP in *A. hybridus* subs. *incurvatus* at 38 DAP.

Harvest date and the accession–harvest date interaction affected IVDMD (Table 4). In vitro dry matter

Table 4. Mean in vitro dry matter digestibility (IVDMD) concentration for seven amaranth accessions at different harvest dates. Results are averaged over years.

Accessions	Days after planting					
	42	56	70	84	98	112
	g kg^{-1} DM†					
A. cruentus (Mexico)	760	760	710	710	680	670
A. cruentus (Zimbabwe)	760	770	730	640	630	590
A. cruentus (Rwanda)	780	790	770	720	670	630
A. hybrid (Puebla, Mexico)	790	780	790	770	740	720
A. hybridus (Greece)	780	780	750	720	670	650
A. hybridus (Zambia)	750	760	740	690	640	630
A. hypochondriacus (Colorado)	790	740	720	700	670	670

LSD 0.05 = 60.
† DM, dry matter.

Table 5. Mean crude protein (CP) concentration for seven amaranth accessions at different harvest dates in 1997 and 1998.

Accessions	Days after planting					
	42	56	70	84	98	112
	g kg^{-1} DM†					
A. cruentus (Mexico)	275	220	160	140	110	120
A. cruentus (Zimbabwe)	280	225	160	120	110	100
A. cruentus (Rwanda)	270	210	160	125	90	100
A. hybrid (Puebla, Mexico)	260	190	140	110	95	90
A. hybridus (Greece)	270	190	140	110	90	80
A. hybridus (Zambia)	260	210	140	110	90	85
A. hypochondriacus (Colorado)	285	220	180	150	130	120

LSD 0.05 = 20.
† DM, dry matter.

Table 6. Mean acid detergent fiber (ADF) concentration for seven amaranth accessions at different harvest dates. Results are averaged over years.

Accessions	Days after planting					
	42	56	70	84	98	112
	g kg^{-1} DM†					
A. cruentus (Mexico)	170	183	240	234	264	260
A. cruentus (Zimbabwe)	170	200	257	324	326	354
A. cruentus (Rwanda)	176	190	212	252	306	312
A. hybrid (Puebla, Mexico)	150	170	193	227	246	265
A. hybridus (Greece)	168	185	228	263	298	323
A. hybridus (Zambia)	193	203	230	284	319	329
A. hypochondriacus (Colorado)	191	208	229	256	270	281

LSD 0.05 = 48.
† DM, dry matter.

digestibility decreased significantly over the season from a high of 790 g kg^{-1} for *A. cruentus* (Rwanda) and *A. hybrid* (Puebla, Mexico) at 42 and 56 DAP, respectively, to a low of 630 g kg^{-1} for *A. cruentus* (Zimbabwe) at 112 DAP. The vegetable-type, *A. hybrid* (Puebla, Mexico), consistently had the greatest IVDMD concentration at all harvest dates except 56 DAP when *A. cruentus* (Rwanda) had a greater concentration. These consistently high IVDMD concentrations agree with those reported by Mugerwa and Bwabye (1974) for *A. hybrid* subsp. *incurvatus*. They observed whole plant IVDMD values of 820 g kg^{-1} at 38 DAP and 725 g kg^{-1} at 66 DAP.

Harvest date and the accession–harvest date interaction affected ADF (Table 6). However, ADF concentration was not different after 84 DAP. At 112 DAP, *A. hybridus* (Greece) and *A. hybridus* (Zambia) had the greatest ADF concentrations, averaging 326 g kg^{-1}. Lowest concentrations were observed for *A. hybrid* (Puebla, Mexico) at 150 g kg^{-1}.

Harvest date and the accession–harvest date interaction influenced ADL (Table 7). In this study, ADL increased quadratically with harvest date and had a strong positive correlation ($R^2 = 0.97$) with harvest date. Acid detergent lignin levels varied from a low of 17.6 g kg^{-1} for *A. hybridus* (Greece) at 42 DAP to a high of 73.7 g kg^{-1} in *A. cruentus* (Zimbabwe) at 112 DAP. The greatest increase over the season was observed in *A. cruentus* (Zimbabwe) and *A. hybridus* (Greece), with 196 and 163% change in ADL between 42 DAP and 112 DAP, respectively.

Table 7. Mean acid detergent lignin (ADL) concentration for seven amaranth accessions at different harvest dates. Results are averaged over years.

Accessions	Days after planting					
	42	56	70	84	98	112
	g kg^{-1} DM†					
A. cruentus (Mexico)	29	26	33	36	41	45
A. cruentus (Zimbabwe)	24	27	31	64	67	73
A. cruentus (Rwanda)	24	23	21	31	44	53
A. hybrid (Puebla, Mexico)	19	24	24	29	29	32
A. hybridus (Greece)	17	22	22	28	34	46
A. hybridus (Zambia)	25	23	25	32	36	36
A. hypochondriacus (Colorado)	22	26	26	25	49	52

LSD 0.05 = 19.
† DM, dry matter.

Table 8. Soluble crude protein, degradable crude protein, undegraded crude protein, undegraded intake protein, and rate of digestion of degradable protein for three amaranth accessions at different harvest dates.

Days after planting	Total CP†	CP_S†	CP_D†	CP_U†	UIP†	K_d†
	g kg^{-1} DM‡					h^{-1}
A. cruentus (Zimbabwe)						
42	287	197	63	27	48	0.09
56	226	171	38	17	30	0.10
70	175	120	40	13	26	0.11
84	118	61	27	30	43	0.06
98	110	62	21	27	37	0.05
112	94	48	19	27	36	0.06
A. cruentus (Rwanda)						
42	270	170	67	33	61	0.08
56	192	137	37	18	32	0.08
70	136	99	29	8	15	0.14
84	109	68	29	12	21	0.11
98	77	42	18	17	25	0.06
112	90	51	20	19	27	0.07
A. hybrid (Puebla, Mex.)						
42	256	207	37	12	23	0.12
56	198	153	31	14	25	0.09
70	143	99	31	13	24	0.10
84	111	74	23	14	23	0.07
98	92	62	19	11	19	0.07
112	74	47	18	9	15	0.08
LSD 0.05	20	43	14	16	21	0.07

† CP, crude protein; CP_S, soluble crude protein; CP_D, degradable crude protein; CP_U, undegradable crude protein; UIP, undegradable intake protein; K_d, rate of digestion.
‡ DM, dry matter.

Fiber and Protein Degradation

Crude protein digestion parameters are presented in Table 8. Undegraded intake protein (UIP), as a percentage of total crude protein, increased with harvest date and was generally higher for the grain-type accessions *A. cruentus* (Zimbabwe) and *A. cruentus* (Rwanda) at each harvest date (Table 9). At 84 DAP, an average of

Table 9. Means of cell solubles, digestible fiber, indigestible fiber, true digestibility, rate of fiber digestion, and digestion lag time for three amaranth accessions at different harvest dates.

Days after planting	C_S†	C_D†	C_I†	TD†	*k*†	*L*†
	g kg^{-1} DM‡				h^{-1}	h
A. cruentus (Zimbabwe)						
42	640	289	71	929	0.08	11.8
56	566	255	178	821	0.08	11.1
70	608	219	172	827	0.09	10.0
84	573	280	145	853	0.06	10.1
98	546	248	205	794	0.07	7.9
112	681	224	94	905	0.07	8.5
A. cruentus (Rwanda)						
42	650	243	106	893	0.06	13.5
56	652	171	176	823	0.08	11.7
70	641	228	130	869	0.08	10.6
84	587	247	165	834	0.06	12.0
98	646	275	78	921	0.06	9.0
112	665	205	129	870	0.07	7.3
A. hybrid (Puebla, Mex.)						
42	602	191	206	793	0.09	8.5
56	524	238	237	762	0.11	7.4
70	652	166	181	818	0.08	9.7
84	620	211	168	831	0.08	10.7
98	682	234	83	916	0.08	10.3
112	604	230	165	834	0.04	13.2
LSD 0.05	214	143	243	243	0.06	7.7

† C_S, cell solubles; C_D, digestible fiber; C_I, indigestible fiber; TD, true digestibility; *k*, rate of fiber digestion; and *L*, digestion lag time.
‡ DM, dry matter.

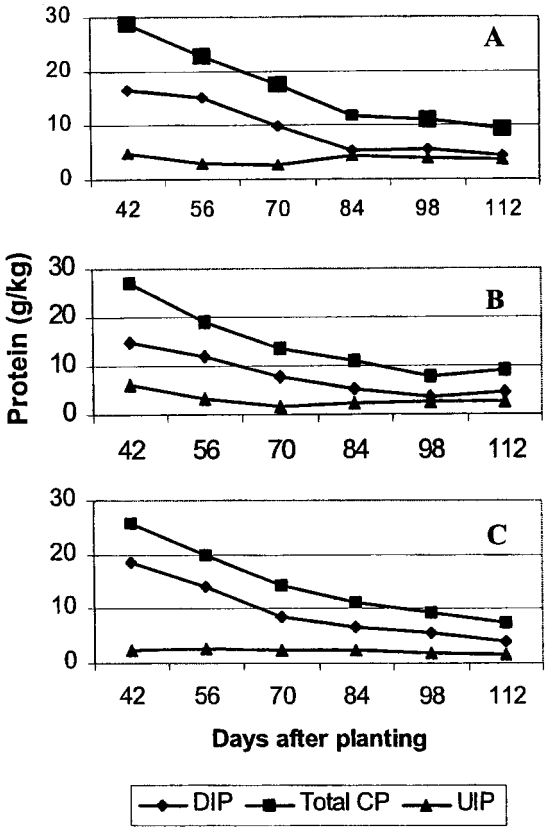

Fig. 1. Variation of degradable intake protein (DIP), total crude protein (total CP), and undegraded intake protein (UIP) with maturity of three amaranth accession, *A. cruentus* (Zimbabwe) [A], *A. cruentus* (Rwanda) [B], and *A. hybrid* (Puebla, Mexico) [C].

19 and 36%, respectively, of the total crude protein of *A. cruentus* (Rwanda) and *A. cruentus* (Zimbabwe) was UIP. After 70 DAP, *A. cruentus* (Zimbabwe) had greater average UIP (36%) than the UIPs reported for alfalfa (Merchen and Satter, 1983; Charmley and Veira, 1990) and perennial ryegrass (Rooke et al., 1983; Rooke et al., 1987; Dawson et al., 1988). The percentage of UIP reported for white clover (*Trifolium repens*) (Beever et al., 1987) is also lower than that of *A. cruentus* (Zimbabwe) and *A. cruentus* (Rwanda) after 70 DAP. The comparison across species should be noted with some caution since these species were evaluated under different environmental conditions. The variation of UIP, degradable intake protein, and total crude protein with harvest date is illustrated in Figure 1. Undegraded intake protein remained constant until 84 DAP, then declined for *A. hybrid* (Puebla, Mexico), while more fluctuations were observed for *A. cruentus* (Zimbabwe) and *A. cruentus* (Rwanda).

The rate of protein digestion was unaffected by accession or by the accession–harvest date interaction, but was affected by harvest date ($P < 0.01$). By the end of the season, the average rate of digestion had decreased from a high of 0.11 h^{-1} at 70 DAP to 0.06 h^{-1} at 98 and 112 DAP. It is uncertain as to why the rate was highest at 70 DAP and not at a harvest date when the plants were less mature.

Differences in TD and digestible fiber were observed over harvest dates (Table 9) but digestible fiber deceased with maturity for each accession. Up to 56 DAP the early maturing *A. cruentus* (Zimbabwe) had the greatest TD, but thereafter the greatest TD was observed for *A. hybrid* (Puebla, Mexico). Rate of fiber digestion was similar for all accessions and at all harvest dates except for *A. hybrid* (Puebla, Mexico) at 56 and 112 DAP. Digestion lag times were not different across accessions and harvest.

CONCLUSIONS

The forage nutritive value of amaranth is equal to or better than commonly used forages in NDF, ADF, ADL, IVDMD, CP, and UIP. Of all the quality parameters evaluated, nitrate concentration remains a major concern. The observed nitrate concentrations may be too high for these accessions to be used as fresh forage for livestock before 84 DAP. Ensiling the forage may be an alternative for reducing nitrate concentration and improving its digestibility (Cervantes, 1990).

When most of the forage quality parameters studied are taken together, it can be concluded that amaranth has good to excellent forage quality at certain stages of development. There is a concern, however, about the high nitrate levels in some accessions at early harvest dates. More work is needed with intake studies to get a full picture of amaranth forage quality since we cannot exclude animals when making decisions about forage quality.

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