

Article

Quinoa Whole Plant: A Promising Nutrient-Rich Alternative Forage in the U.S. Midwest

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Abstract

Quinoa (*Chenopodium quinoa* Willd) is a nutrient-rich multipurpose crop. Its grains are used as a cereal, green leaves as a vegetable for humans, and the whole green plant as an alternate forage for livestock. Recently, whole-plant quinoa forage has been evaluated in several countries in Asia and Europe for its potential use as an alternative forage for livestock; however, this has not been performed in the United States. We investigated forage yield and related agronomic traits, nutritional composition, and feed quality-related traits in 60-day-old quinoa whole plants of four quinoa lines over a two-year period. The goal was to evaluate the feasibility of quinoa forage production in Missouri, a drought-prone midwestern state of the USA. Morphological traits (height and fresh and dry weight per plant), chemical composition (fiber contents), and nutritive quality (digestible nutrient contents) of forages were affected by quinoa genotype and year of planting. The crude protein content of quinoa forage averaged 16.23% and fiber 22.08%, which was similar to the values reported in Asia and Europe, but was slightly lower than that of alfalfa. Calcium (1.26%) and phosphorus (0.47% dry weight) were significantly higher than those reported in published quinoa forage results and are comparable to those in published alfalfa minerals. Lysine (0.98%) and methionine (0.25%) were higher than the published results for quinoa and alfalfa. Neutral detergent fiber (34.10%) and acid detergent fiber (25.01%) were lower than those of alfalfa, indicating better digestibility of the quinoa forage. The calculated digestible dry matter (69.40%), dry matter intake (3.56%), relative food value (192%), and total digestible nutrient (70.33%) were higher than those of alfalfa and comparable with published results for quinoa forage. Our preliminary results indicate that the quinoa lines evaluated in this study have excellent potential to be used as a non-traditional alternative forage, especially in environmentally stressed areas where the production of other forage crops is limited. Further research should explore the full multipurpose benefits of quinoa, including its use as grains, leafy green, and whole-plant forage.

Keywords: quinoa; whole plant; ruminants; nutrients; alternate forage; forage quality; sustainability



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1. Introduction

Climate change can negatively affect crop yields and livestock production and threaten food and nutrition security. There is an urgent need to transform agriculture and livestock

farming towards more sustainable production methods [1–5]. Climate change can affect livestock production directly through increased heat stress and indirectly through impacts on the quantity and quality of forage and crop-based feeds, and on feeding lands and water availability. Global crop production, including forage, is at high risk due to more frequent and intense abiotic stress caused by heat, cold, drought, salt, and flood. Croplands and grazing areas are decreasing due to rapid climate change, with productive lands turning into less productive and/or unproductive ones. Among various abiotic stresses, drought (water stress) and heat (high temperature) are the two major factors limiting crop production.

Forage is plant material grazed directly by livestock, like hay or silage. Forage includes a wide range of species, including cool- and warm-season grasses (i.e., tall fescue and bluegrass), legumes (i.e., alfalfa, vetches, and clovers), forbs (i.e., buckwheat and amaranth), and grain crops (i.e., corn, sorghum, soybean, and small grains). Alfalfa is one of the largest forage crops in the U.S. and the world. Other common forages are clover, vetch, pea, corn, sorghum, and small grains. Historically, hay production in the U.S. has decreased over the last two decades, from approximately 158.10 million tons in 2004 to 122.50 million tons in 2024. Over the years, prices of different forages have also increased significantly as demand increased and total production decreased [6,7]. According to Agrilife Today [8], hay supply is at a nearly 50-year low, and the price is a record high in the United States. Drought, poor range and pasture conditions, and higher feed costs have all combined to work against animal producers. Forage also plays an important role in small ruminant (such as goat and sheep) production systems as they can be grazed or harvested to feed later, such as hay or silage. Forages contain carbohydrates in the form of cellulose that can be digested by rumen bacteria. Feeding nutrient-rich non-conventional forage such as quinoa whole plant as an alternative to common feedstuffs can be used as a ruminant feed [9–11].

Quinoa (*Chenopodium quinoa* Willd.) grains are consumed worldwide as a nutrient-rich gluten-free food. It contains high quantities and qualities of protein, essential amino acids, and essential minerals and vitamins. Although it has been cultivated for more than a thousand years in South America, its importance has been rediscovered most recently and is now grown in over 100 countries worldwide [12–15]. Quinoa has extensive adaptability to different agro-ecological conditions, from sea level to mountainous areas, and is tolerant of drought, salinity, and cold, and suitable for cultivation in less fertile soil with a minimum amount of water supply. Based on quinoa's unique qualities, it undoubtedly holds a position in sustainable agricultural systems. In addition to quinoa grains, the green leaves of quinoa are consumed as leafy vegetables, and more recently, entire green plants are used as a non-conventional forage for livestock, which makes quinoa a multipurpose crop. Earlier, the quinoa plant was used as a forage in the Netherlands [16] and Mexico [17–19]. Recently, whole-plant quinoa forage has also been evaluated in many countries for its potential use as a forage crop due to its high nutritional composition, which is suitable for livestock [10,20–26]. However, such evaluations have not yet been conducted in the United States. To our knowledge, Lincoln University of Missouri, USA, is the only institution that has initiated a feasibility study on utilizing the entire quinoa plant as forage, particularly for small ruminants. Other institutions of the United States have focused their research primarily on quinoa grains for human consumption.

Ebeid et al. [10] reported that quinoa's nutritional value and fermentation characteristics are comparable to clover hay as a ruminant feed. Abarghuei and Boostani [20] stated that quinoa forage harvested at the budding (45 days after planting) and 10% flowering (95 days after planting) stages exhibits no problems with digestibility and has the potential to decrease the production of methane, carbon dioxide, and nitrous oxide gases, thereby

mitigating environmental pollution. Also, quinoa has higher water-use efficiency compared to alfalfa.

The objective of this study was to determine the feasibility of producing the whole plant quinoa as an alternative and sustainable feed in the United States, especially in the Midwest, where climate extremes exist. To our knowledge, no other study has been conducted in the United States investigating the yield and nutritional values of quinoa forage at the flowering stage. We compared this result with published results on quinoa forage outside the United States and on alfalfa worldwide.

2. Materials and Methods

2.1. Plant Materials

A subset of four quinoa germplasm lines, namely, PI614885, PI614887 (both originating from Chile), PI614927 (Bolivia), and PI698769 (USA), were selected in this study from a larger set of 10 lines reported earlier [27]. These lines were selected based on their early vegetative growth, yield of leafy greens, and grains. Seeds of these lines were collected from the USDA-ARS, GRIN-North Central Research Plant Introduction Station, Ames, IA, USA.

2.2. Field Location, Experimental Design, Planting, and Field Management

The study was conducted at Lincoln University’s Carver Farm (38.52° N latitude, 92.14° W longitude, and elevation 170 m), located near Jefferson City, MO, USA, over two consecutive growing seasons in the summers of 2023 and 2024. The soil had a well-drained, moderately permeable texture, classified as silt loam with 20% clay, 0.8% organic matter, and a pH range of 6.5 to 6.8. The experimental design, field preparation, fertilizer application, planting, irrigation, and weed control were managed following the methodology described by Pathan et al. [27,28].

2.3. Data Collection—Agronomical Traits, Sample Collection, and Climate Data

During the anthesis stage (at 50% flowering, BBCH code 6), about 60 days after seed germination (maturity about 90 days), three randomly selected plants from each replication were harvested about 12–15 cm above ground (Figure 1). Different agronomic traits, such as plant height and fresh and dry weight, were recorded from those plants. Harvested samples were dried at 40 °C for three days and ground to a fine powder using a Foss CT193 Cyclotec grinder and stored in a cool place (at 5 °C) for nutritional and forage quality analysis. Mean air temperature (with minimum and maximum), rainfall, and relative humidity (RH) (June to August, 2023 and 2024) of the experimental field were obtained from the USDA-NRCS National Weather and Climate Center (NWCC) Soil Climate Analysis Network (SCAN) site #2223 located at George Washington Carver Farm in Jefferson City, MO, USA (<https://wcc.sc.egov.usda.gov/nwcc/site?sitenum=2223>, accessed in 11 February 2025) (Table 1).

Table 1. Average temperature (with minimum and maximum), relative humidity (RH), and total rainfall during quinoa growing season, 01 June–07 August 2023 and 2024.

Month	2023 Temperature (°C)			Temperature °C 2024			Rainfall (cm)		RH (%)	
	Maximum	Minimum	Mean	Maximum	Minimum	Mean	2023	2024	2023	2024
June	36.20	7.70	23.06	36.50	11.10	24.55	2.72	10.54	91.53	90.32
July	39.80	13.00	26.01	35.00	14.00	24.27	6.65	18.59	86.48	93.19
Aug (first 7 days)	31.20	20.70	24.87	35.60	18.70	26.77	17.45	0.00	90.83	93.57
							Σ 26.82	Σ 29.13	̄x 89.61	̄x 92.36



Figure 1. Quinoa forage harvesting stage (60 days after seed germination during anthesis).

2.4. Nutritional and Forage Quality Analysis

The proximate composition, i.e., crude protein (CP; nitrogen content $\times 6.25$), ether extract (EE), crude fiber (CF), ash, and moisture as well as amino acid and mineral contents were analyzed at the Agricultural Experiment Station Chemical Laboratories (AESCL) of the University of Missouri, Columbia, MO, United States. Proximate analysis of quinoa grains was executed following the procedures described by the AOAC [29]. The Kjeldahl method, applying the AOAC method 984.13 (A–D), determined the total nitrogen content in the grains. The moisture, EE, and CF contents were determined using the AOAC method 934.01, 920.39 (A), and 978.10, respectively.

The carbohydrate content was estimated using the following equation:

$$\text{Carbohydrate (\%)} = 100\% - \% (\text{CP} + \text{EE} + \text{ash} + \text{moisture})$$

The amino acid contents were determined using the AOAC official method 982.30E (a, b). The mineral concentrations were determined using the AOAC official method 985.01 (A, B, D) via Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES).

The neutral detergent fiber (NDF) and acid detergent fiber (ADF) contents were determined using the AOAC methods 2002.04 and 973.18 [30], respectively. The feeding value of quinoa forage was estimated as a percentage (%) using the value of NDF and ADF as follows: total digestible nutrients (TDN) = $82.38 - (0.7515 \times \text{ADF})$; dry matter intake (DMI) = $120/\text{NDF}$; digestible dry matter (DDM) = $88.9 - 0.779 \times \text{ADF}$; relative feed value (RFV) = $\text{DMI} \times \text{DDM}/1.29$; and relative forage quality (RFQ) = $\text{DMI} \times \text{TDN}/1.23$ [31].

2.5. Statistical Analysis

A standard statistical procedure was used to evaluate quinoa genotypes grown across two years for agronomic traits, such as plant height, shoot fresh weight, shoot dry weight, and nutritional composition (proximate, amino acid, mineral, NDF, and ADF), and relative feed qualities (DDM, DMI, RFV, and TDN). Data were analyzed using SAS (version 9.3) statistical software (GLM) with the model containing genotype, year, and their interaction for forage yield, agro-morphological traits, and nutritional values [32]. Tukey's honest significance difference (HSD) test was used at the $p \leq 0.05$ significance level to determine

differences among the genotypes and between years. Pearson's correlation analysis was performed using the metan package in R software (R 4.4.3).

3. Results

The analysis of variance (ANOVA) results for quinoa line, year, and the interaction between lines for agronomic traits, proximate components, forage quality traits, amino acids, and minerals are presented in Supplementary Table S1.

3.1. Weather and Agronomic Traits

Monthly temperature, rainfall, and relative humidity (RH) during the quinoa growing period (1 June to 7 August 2023 and 2024) at Carver Farm, MO, USA, are presented in Table 1. During the crop-growing period in both years, all variables were very similar except for monthly rainfall. In June and July of 2024, total rainfall was 29.1 cm, but it was only 9.37 cm in 2023.

The plant height of PI698769 was lower ($p < 0.05$) than that of the other three genotypes, and height was higher in 2023 (Table 2). Also, there was a substantial difference in fresh weight (FW) among the genotypes ($p < 0.05$) but not between the years ($p > 0.05$). The fresh weight per plant was lower for PI698769 compared with PI614885 and PI614927. In contrast, no difference in dry weight (DW) was found among the genotypes, but a difference was observed between the years ($p < 0.05$; 2024 > 2023). There was a significant difference in the FW to DW ratio between the genotypes (PI698769 > PI614887, and the years 2024 > 2023).

Table 2. The least square means of plant height and fresh and dry weight, and their ratios of four quinoa lines during anthesis grown in 2023 and 2024.

Variables ¹	Quinoa Lines				Mean	Year		SEM
	PI614885	PI614887	PI614927	PI698769		2023	2024	
Height (cm)	150.58 a	153.67 a	153.96 a	128.01 b	146.55	152.18 a	139.06 b	2.08
FW/plant (g)	71.22 a	59.53 ab	70.22 a	50.87 b	62.96	65.92	59.02	2.87
DW/plant (g)	14.58	11.94	14.94	11.53	13.25	11.27 b	15.88 a	0.64
FW to DW ratio	21.36 ab	20.33 b	21.36 ab	22.93 a	21.49	17.25 b	27.16 a	0.32

¹ Height = plant height; FW = fresh weight; DW = dry weight; SEM = standard error of mean. Letters a, b, and ab-values in a row within a grouping denoted with different letters differ significantly by Tukey HSD test ($p < 0.05$).

3.2. Proximate Components

Among the four quinoa lines tested over the two years (2023 and 2024), there was no significant ($p > 0.05$) genotype difference in CP, ash, EE, and carbohydrate content except for CF content (Table 3).

However, the year's effect was significant ($p < 0.05$) for all the traits mentioned above. CP and ash content were significantly higher in 2023, and the rest of the traits (CF, EE, and carbohydrates) were higher in 2024. Crude protein did not show a significant difference among genotypes (ranging from 15.48 to 17.02%, with a mean of 16.23% DW); however, it varied significantly between years (12.64% and 18.92%). There was a significant difference in CF among the genotypes (ranging from 20.60 to 23.40%, with a mean of 22.08%), and between the years (21.05 and 23.50%). Also, there was no significant difference in carbohydrate among the genotypes (ranging from 56.47 to 58.39%, with a mean of 57.43% DW), while showing a significant difference between the years (53.09 and 63.22). Similarly, ash (ranging from 16.19 to 17.22%, mean 16.33%) and EE (ranging from 2.90 to 3.47%, mean 3.29%) showed no significant differences among genotypes, but both differed significantly between years (ash: 15.58 and 17.43%; EE: 3.08 and 3.56%).

Table 3. The least square means of nutritional values of four quinoa lines grown in 2023 and 2024.

Variables ¹ (% DM)	Quinoa Lines				Mean	Year		SEM	Published Results (Range)	
	PI614885	PI614887	PI614927	PI698769		2023	2024		Quinoa ²	Alfalfa ³
CP	15.80	17.02	16.61	15.48	16.23	18.92 a	12.64 b	0.36	15.4–26.0	15.3–24.7
CF	22.09 ab	23.40 a	20.60 b	22.25 ab	22.08	21.05 b	23.50 a	0.43	11.6–18.4	25.3–35.7
Ash	16.19	16.79	17.22	16.33	16.33	17.43 a	15.58 b	0.23	9.07–14.9	8.6
EE	3.38	2.90	3.43	3.47	3.29	3.08 b	3.56 a	0.10	2.2–3.4	1.4–2.1
Carb	58.39	57.19	56.47	57.68	57.43	53.09 b	63.22 a	0.52	54.6–62.2	67.9–74.4
NDF	33.68 ab	35.76 a	32.25 b	34.70 ab	34.10	31.95 b	36.96 a	0.56	32.7–46.4	36.7–43.8
ADF	25.11 ab	26.26 a	23.44 b	25.25 ab	25.01	25.14	24.86	0.45	21.4–29.1	22.5–33.0
DDM	69.34 ab	68.44 b	70.65 a	69.23 ab	69.42	69.32	69.55	0.35	66.3–72.2	63.2–71.4
DMI	3.60	3.42	3.74	3.49	3.56	3.77 a	3.28 b	0.06	2.6–3.7	2.7–3.3
RFV	193.99	181.77	205.04	187.58	192.10	202.92 a	177.65 b	4.00	138.2–207.8	134.3–182.7
TDN	70.27 ab	69.46 b	71.43 a	70.17 ab	70.33	70.24	70.45	0.31	60.6–67.2	57.6–65.5
Ca	1.26	1.31	1.22	1.23	1.26	1.35 a	1.13 b	0.04	1.0–1.1	1.3–1.6
P	0.47	0.48	0.47	0.47	0.47	0.45	0.50	0.01	0.3	0.3–0.4
Fe (mg/kg)	69.26	69.60	99.60	94.70	75.80	79.15	71.34	0.47	100.0	104.0

¹ DM = dry matter; CP = crude protein; CF = crude fiber; EE = ether extract; Carb = carbohydrate; NDF = neutral detergent fiber; ADF = acid detergent fiber; DDM = digestible dry matter; DMI = dry matter intake; RFV = relative feed value; TDN = total digestible nutrient; Ca = calcium; P = phosphorus; Fe = iron; Lys = lysine; Met = methionine; SEM = standard error of mean. ² [10,20–26,28,33,34]. ³ [20,26,35–40]. ^{a,b} Different letters within a grouping suggest significant differences among means within a column indicated by Tukey's HSD test at $p \leq 0.05$.

3.3. Forage Quality Traits

Forage quality traits, such as NDF, ADF, calculated DDM, DMI, RFV, and TDN of the tested quinoa lines over the two years are presented in Table 3. The quinoa lines displayed a significant ($p < 0.05$) difference in NDF, ADF, DDM, and TDN, but not in DMI and RFV. The year was significant ($p < 0.05$) for NDF, DMI, and RFV. However, there was no difference between the years for the rest of the traits. NDF and ADF showed significant differences among genotypes (PI614887 > PI614927, with other genotypes being similar). NDF also differed significantly between years (32.0% in 2023 and 37.0% in 2024), whereas ADF did not (25% in both 2023 and 2024). There was no significant difference ($p > 0.05$) in RFV among the genotypes, with a mean of 192, but years showed a significant difference (178 in 2024 and 203% in 2023). Correspondingly, there was a significant difference ($p < 0.05$) among the genotypes for traits like DDM (PI614927 > PI614887) and TDN (PI614927 > PI614887), but not years. However, DMI showed no differences among genotypes, but differed significantly between years (2023 > 2024).

3.4. Amino Acids

The essential amino acids (AAs) content in the tested quinoa lines over the two years are presented in Table 4. Eight out of nine essential AAs displayed no significant ($p > 0.05$) difference, except for one amino acid, tryptophan (Trp) which showed a difference among the genotypes (PI614927 > PI614885). There was a significant ($p < 0.05$) year effect for all nine essential AAs. The concentration of all AAs was always better in 2023 than in 2024.

Table 4. The least square means of essential amino acids (% DM) of four quinoa lines grown in 2023 and 2024.

Variables ¹ (% DM)	Quinoa Lines				Mean	Year		SEM	Published Results (Range)	
	PI614885	PI614887	PI614927	PI698769		2023	2024		Quinoa ²	Alfalfa ³
Histidine	0.31	0.34	0.34	0.34	0.33	0.41 a	0.24 b	0.005	0.23	0.31
Isoleucine	0.68	0.75	0.74	0.74	0.73	0.92 a	0.48 b	0.013	0.55	0.88
Leucine	1.06	1.17	1.17	1.16	1.14	1.43 a	0.74 b	0.001	1.01	1.13
Lysine	0.92	0.99	0.99	1.00	0.98	1.18 a	0.70 b	0.016	0.51	0.54

Table 4. Cont.

Variables ¹ (% DM)	Quinoa Lines				Mean	Year		SEM	Published Results (Range)	
	PI614885	PI614887	PI614927	PI698769		2023	2024		Quinoa ²	Alfalfa ³
Methionine	0.24	0.26	0.26	0.26	0.25	0.32 a	0.17 b	0.005	0.22	0.07
Phenylalanine	0.73	0.80	0.81	0.79	0.78	0.97 a	0.53 b	0.015	0.65	0.88
Threonine	0.57	0.63	0.6	0.62	0.61	0.74 a	0.43 b	0.011	0.63	0.71
Tryptophan	0.19 b	0.22 ab	0.23 a	0.22 ab	0.21	0.28 a	0.12 b	0.006	0.06	-
Valine	0.77	0.85	0.74	0.84	0.83	1.03 a	0.56 b	0.015	0.64	1.03

¹ DM = dry matter; SEM = standard error of mean; amino acid values are expressed as the mean of 28 samples.

² [24] (studied young vegetative quinoa of about 44 days old) ³ [41]. a,b,ab- Different letters within a grouping suggest significant differences among means within a row indicated by Tukey's HSD test at $p \leq 0.05$.

3.5. Minerals

The tested results of calcium (Ca), phosphorus (P), and iron (Fe) of quinoa lines over the two years are presented in Table 3. There was no significant ($p > 0.05$) difference in Ca among the genotypes (ranging from 1.22 to 1.31% DW, with a mean of 1.26), but a substantial difference between the years (1.13 and 1.35%). Additionally, there was no significant difference in P among the genotypes (ranging from 0.47% to 0.48%, with a mean of 0.47), but a substantial difference between the years (0.45% and 0.50%). There was no significant difference in Fe among the genotypes (ranging from 69.3 to 99.6 with a mean of 75.8 mg kg⁻¹), but not between the years (71.34 and 79.15 mg kg⁻¹ DM).

3.6. Trait Correlation and Principal Component Analysis (PCA)

The correlation between nutritional and forage quality traits of quinoa is shown in Figure 2. Figure 3 exhibits the grouping pattern of different nutritional and forage quality traits of quinoa assessed by principal component analysis (PCA). The first two components of PCA explained about 97% of the total variation (PC1 and PC2).

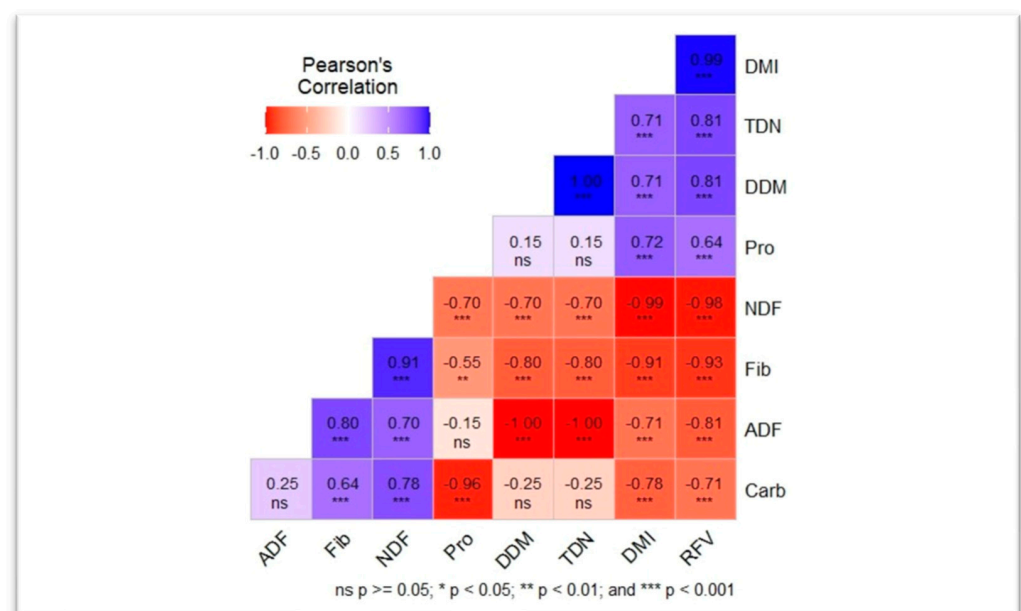


Figure 2. Pearson's correlation coefficient (r) shows the relationship between nutritional and forage quality traits of quinoa forage (ADF = acid detergent fiber; Fb = crude fiber; NDF = neutral detergent fiber; Pro = crude protein; DDM = digestible dry matter; TDN = total digestible nutrient; DMI = dry matter intake; RFV = relative food value; Carb = carbohydrate).

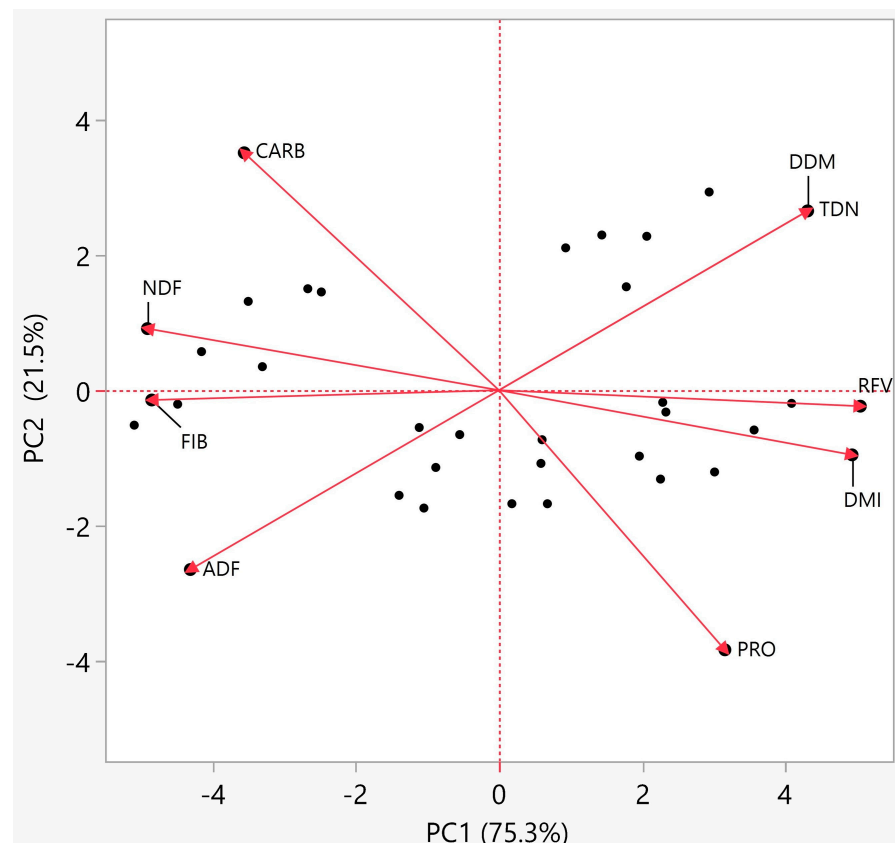


Figure 3. Principal component analysis (PCA) biplot illustrating forage quality traits: PRO = protein, CARB = carbohydrate, FIB = fiber, NDF = neutral detergent fiber, ADF = acid detergent fiber, DDM = digestible dry matter, DMI = dry matter intake, RFV = relative feed value, and TDN = total digestible nutrients.

4. Discussion

4.1. Weather and Agronomic Traits

During June and July of 2024, the total rainfall (29.1 cm) was three-fold higher than the same period in 2023 (9.37 cm). Average temperature during the same period was 24.54 and 24.41 °C in 2023 and 2024, respectively (Table 1). Quinoa is a drought-tolerant crop, preferring a relatively dry environment for growth and development.

In agreement with the previous report of Pathan et al. [27], these findings also cannot be directly compared to other published results due to substantial variations in agronomic and forage quality-related traits found in different countries, as well as the use of different genotypes, test locations, soil, weather variables (temperature, rainfall, and humidity), irrigation intensity, growth duration, and management practices. The growth and maturation of the quinoa plant vary widely worldwide, and the ages of the plants for forage collection are varied. In this study, the period from anthesis was approximately 60 days. It was about 70 days for anthesis and 116 days for maturation in China [25], 70–80 days for full blooms in Turkey [23,42] hay was harvested 112 days after seed sowing and 155 days after crop maturation in Israel [21], and around 95 days for crop maturation in the United States [27].

There was a difference in total rainfall during June and July (the first 60 days of the cropping season) between the two years. During this period, total rainfall was 9.37 and 29.1 cm in 2023 and 2024, respectively (Table 1). Subsequently, plant height was significantly different between the two years, 139 cm in 2024 and 152 cm in 2023. Shorter plant height in 2024 was due to excessive rain and soil saturation during the crop-growing season. Temperature and relative humidity were similar between the months and years.

Based on agronomic traits, two genotypes, PI614885 and PI614927, performed better than the other two genotypes in terms of both fresh and dry weight (Table 2).

4.2. Proximate Components

The mean CP content of 60-day-old quinoa forage was 16.2% DM, which was within the reported range of 15.4–26.0 DM% reported outside the United States [20,23,25,43] (Table 3). According to Shah et al. [25], the CP of quinoa was like that of alfalfa but higher than oat forage when harvested both at the anthesis (~70 days) and grain filling (~90 days) stages. The CP content of the quinoa forage depends on the time of harvest (i.e., the stages of the crop growth). Higher CP content of 23% and 33% were reported in 44- and 30-day-old quinoa leaves, respectively [24,28]. Quinoa leaves are rich in protein and their stems are poor in protein [44]. The CP percentage decreases with the progression of harvesting time (delayed harvesting) [16,45]. Shah et al. [25] found higher CP content during anthesis (24.3%) than grain filling (23%). Abarghuel and Boostani [20] reported lower CP content in alfalfa than quinoa forage, and CP content decreased with the increase in quinoa plant ages. The CP value of alfalfa forage ranges between 15.3% and 24.7% [20,26,35–37]. The CF content of this study (21–28%) was higher than that reported for quinoa (12–18%) but lower than that for alfalfa forage (25–35%). Carbohydrate contents were similar to published quinoa forage results (54–62%), but much higher in alfalfa forage (68–74%) [39].

4.3. Forage Quality Traits

The two crucial fiber quality traits, NDF and ADF, measure the composition of forage's cell wall fiber. The NDF quantifies total fiber content, including hemicellulose, cellulose, and lignin, whereas ADF computes less digestible fiber, specifically cellulose and lignin. Low NDF and ADF levels lead to better digestibility of the forage, whereas high levels decrease digestibility [46].

The average NDF was 34.1%, placing it within the lower range of published quinoa forage results (32.7–46.4%) and outside the lower range of alfalfa forage (36.7–43.8%). Similarly, the average ADF was 25.0%, placing it within the lower ranges of published quinoa (21.4–29.1%) and alfalfa forage (22.5–33.0%) (Table 3). Both the NDF and ADF levels were low compared to the published papers. Baskota and Islam [46] mentioned that low NDF and ADF values help better digestibility of the fodder, while high values of NDF and ADF decrease digestibility. Both NDF and ADF levels of quinoa forage increased from the flowering to the grain-filling stages [25]. Abarghuel and Boostani [20] evaluated quinoa forage at four different growth stages: 45 (budding), 95 (10% flowering), 125 (before milk stage), and 145 (milk stage) days after planting. They found that both NDF and ADF increased with increasing plant age. Additionally, they reported that CP had a negative correlation with forage ages, meaning that CP decreased with an increase in forage age (from 20.0 to 11.2%). They also compared alfalfa and quinoa forages. CP content was higher in quinoa forage at harvests of 45 and 95 days after planting than in alfalfa forage. Additionally, the NDF and ADF content in quinoa forage was lower when harvested at 45 and 95 days after planting compared to the NDF and ADF content in alfalfa forage. Our NDF and ADF levels align with the previous results of Shah et al. [25] at the flowering stage and Abarghuel and Boostani [20] at 95 days after planting.

The mean RFV of this study was 192, which was higher than the reported value of alfalfa, 182.7. Additionally, the mean value of TDN (70.3%) was higher than that of reported for quinoa and alfalfa forage, at 67.2% and 65.5%, respectively. The DDM, DMI, RFV, and TDN were equal to or higher than the reported values for quinoa and alfalfa forage. Lower values of NDF and ADF, along with higher values of other quality traits, indicate a better quality of quinoa forage.

4.4. Amino Acids

Quinoa forage, like quinoa grains, contains high-quality protein and all essential amino acids [24,28]. In this study, quinoa forage includes a substantial quantity of all essential amino acids (Table 4). Our findings are superior to the earlier report on young vegetative quinoa and alfalfa hay [24,41], specifically in terms of histidine, leucine, lysine, methionine, and tryptophan. Angeli et al. [9] also reported that quinoa forage contains considerable amounts of lysine, threonine, and methionine.

4.5. Minerals

In this study (Table 3), Ca content (1.26%) was higher than earlier reports (ranging from 1.00 to 1.10%) on quinoa forage [23,28], but was lower than alfalfa (1.29–1.59%). Also, P content (0.47%) aligns with the published results of quinoa forage (0.34–0.62%) but was higher than alfalfa forage (0.30–0.42%) [23,26,28,47]. Both Ca and P are the most essential minerals in the development and maintenance of skeletal tissue in animals [48]. Quinoa leaves are rich in Ca, K, and Fe, which is an advantage for animal feeding [48,49]. For animals' normal growth, the ranges of Ca content in feeds should be 0.14–0.70% of dry matter for sheep and 0.20–1.10% for cattle. The ranges mentioned above lead to rapid growth in livestock, while the lower range causes growth retardation and lower animal product yields [50]. About 0.25% of P content in forage dry matter is sufficient for livestock needs [48,51]. The presence of a considerable amount of Ca, P, and Fe supports the use of quinoa forage for animal feeding.

4.6. Trait Correlation

In this study, NDF showed a significant positive correlation with ADF ($r = 0.70$), carbohydrate ($r = 0.78$), crude fiber ($r = 0.91$), and similar associations have also been reported in alfalfa and quinoa forages. Also, the NDF showed a significant negative correlation with RFV ($r = -0.98$), DMI ($r = -0.99$), TDN, DDM and Pro (all $r = -0.70$). Our RFV had a highly significant negative association with NDF ($r = -0.98$) and ADF ($r = -0.98$) (Figure 2), which also supports previous reports [25,52]. Also, RFV showed a positive correlation with DDM ($r = 0.81$), DMI ($r = 0.99$), and TDN ($r = 0.81$). CP showed a significant positive association with RFV ($r = 0.64$) and a negative association with NDF ($r = -0.70$), which aligns with the findings of Cacan et al. [52]. CP showed a significant negative correlation with carbohydrates ($r = -0.96$).

4.7. Principal Component Analysis (PCA)

The first two components of PCA explained 96.8% of the total variance, with PC1 (75.3%) and PC2 (21.5%) capturing the significant variation among forage quality traits (Figure 3). PC1 was strongly associated with digestibility- and intake-related traits, including DDM, TDN, DMI, and RFV, which loaded positively, while fiber fractions (ADF, NDF, and lignin) loaded negatively. This indicates that high fiber content was inversely related to forage digestibility and intake potential. The PC2 mainly separated samples based on protein and carbohydrate content, indicating a compositional balance between nitrogenous and carbon-based components. Positive associations among DDM, TDN, and RFV suggest that these traits jointly define quinoa forage quality, whereas ADF and NDF contribute to the reduced nutritive value. Overall, the PCA highlights that fiber digestibility and protein concentration are the main drivers of forage quality, and that lowering ADF and NDF while maintaining high protein and digestibility levels would improve the overall feeding value of the forage.

5. Conclusions

This study demonstrated that quinoa can be successfully grown as a whole plant forage crop in the United States, particularly in the Midwest. Among the four genotypes evaluated, PI614885 and PI614927 exhibited superior performance in both fresh and dry matter yield, confirming the adaptability to regional growing conditions. The chemical composition and nutritional values of quinoa varied across genotypes and years. When harvested at the flowering stage (60 days after sowing), quinoa forage has the potential to serve as an alternative feed resource for small ruminants, particularly goats and sheep. Our results are consistent with previously published reports from Asia, Europe, and Latin America, where quinoa forage showed crude protein contents ranging from 15 to 26%, lower fiber concentrations than alfalfa, and superior digestibility parameters (DDM, DMI, TDN, and RFV). The alignment of our U.S. results with these international findings confirms quinoa's global reliability as a nutrient-dense and climate-resilient forage crop. In addition, the high lysine (0.98%) and methionine (0.25%) contents, along with the favorable mineral composition ($\text{Ca} \approx 1.26\%$, $\text{P} \approx 0.47\%$) observed in our samples, reinforce the suitability of quinoa as a high-quality feed component. Based on the current findings and a team with diverse backgrounds and experiences, a federally funded project is ongoing to assess the nutritional quality of quinoa forage using both in vivo and in vitro trials, focusing on rumen degradation and feed value for small ruminants. The project's outcomes will be disseminated to producers through field demonstrations, workshops, and scientific publications, promoting on-farm adoption of quinoa as a dual-purpose grain-and-forage crop. Overall, this study bridges a critical knowledge gap by providing the first U.S. dataset on quinoa forage performance and quality, comparable to or exceeding international benchmarks. Continued multi-location and multi-year studies, including diverse genotypes, environments, and management systems, will be essential to optimize quinoa's contribution to sustainable livestock production in the United States and beyond.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agronomy15112618/s1>, Table S1. The analysis of variance (ANOVA) of agronomic traits, proximate components, forage qualities, amino acids, and minerals.

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

Abbreviations

The following abbreviations are used in this manuscript:

FW	fresh weight
DW/DM	dry weight/dry matter
CP	crude protein
CF	crude fiber
EE	ether extract
AA	amino acid
NDF	neutral detergent fiber
ADF	acid detergent fiber
DDM	digestible dry matter
DMI	dry matter intake
RFV	relative food value
TDN	total digestible nutrient

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