

Article

Nutritional Composition and Geographic Variation of *Elaeagnus angustifolia* Fruit from the Alxa Region, China

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Abstract

The nutritional composition of *Elaeagnus angustifolia* fruits from the Alxa Region, China, remains poorly understood. To address this gap, *E. angustifolia* fruits were collected from four sites (Tonggunaoer, Barunbieli, Chaertan, Jilantai) in the Alxa Region, Inner Mongolia. Morphological traits, basic nutrients (protein, fat, soluble sugar, titratable acid, crude fiber), mineral elements (Ca, Mg, Fe, Zn, Cu, Mn), and bioactive compounds (tannin, total flavonoids) were analyzed using standard methods. Significant geographic variation was observed. Chaertan fruits were the smallest (0.42 g), while Jilantai had the highest protein (7.49%). Barunbieli had the highest Ca (1721.20 µg/g), Fe (36.31 µg/g), and Zn (4.38 µg/g). Correlation analysis revealed a trade-off between organic nutrients and mineral elements (particularly Mg, Ca, Mn, and Cu) in larger fruits, and principal component analysis (PCA) explained 72.59% of the total variance. These preliminary findings provide a basis for germplasm conservation and functional food development of *E. angustifolia*.

Keywords: *Elaeagnus angustifolia*; Alxa Region; nutritional components; mineral elements; geographic variation

1. Introduction

Elaeagnus angustifolia is a small deciduous tree or shrub extensively distributed throughout the arid and semi-arid regions of Northwest China, where it serves as a key ecological and economic species [1]. Its notable tolerance to drought, salinity, and poor soil conditions enables significant contributions to windbreaks, sand fixation, soil and water conservation, and soil amelioration [2]. The fruit of *E. angustifolia* is rich in carbohydrates, proteins, fats, vitamins, and minerals and can be consumed fresh or processed into products such as jam, fruit wine, and beverages, offering considerable prospects for further development and utilization [3].

The Alxa Region in western Inner Mongolia features an arid desert environment with fragile ecosystems, yet it constitutes one of the natural habitats of *E. angustifolia*. The region's complex topography and climatic diversity are likely to promote geographic differentiation in local germplasm morphology and quality traits. Geographic variation in fruit traits represents an important adaptive strategy for plants in heterogeneous environments. Understanding such variation is crucial for germplasm conservation and identification of elite accessions [4].

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Most studies examining the fruit quality of *E. angustifolia* have focused on inter-province or varietal comparisons [5,6] and aspects of processing and utilization [7]. Meanwhile, comprehensive evaluations of the nutritional constituents of *E. angustifolia* fruit in the Alxa Region remain limited. In particular, there is limited information on variability in morphological attributes, basic nutritional components, mineral content, and bioactive compounds across geographic populations, as well as on their interrelationships.

To address these gaps, the primary aim of the current study was to analyze geographic variation in morphological traits and nutritional components of *E. angustifolia* fruits collected from four sampling sites—Tonggunaoer, Barunbieli, Chaertan, and Jilantai, in the Alxa Region, Inner Mongolia—and to explore correlations among these indicators. The specific contributions of this study are threefold. First, it provides the first integrated dataset combining fruit morphology, basic nutrients (protein, fat, soluble sugar, titratable acid, crude fiber), mineral elements (Ca, Mg, Fe, Zn, Cu, Mn), and bioactive compounds (tannin, total flavonoids) for multiple *E. angustifolia* populations within the Alxa Region. Second, it identifies populations with distinct nutritional and mineral profiles that may serve as candidate resources for germplasm conservation and functional food development. Third, it documents preliminary trait associations (e.g., between fruit size, macronutrients, and specific minerals) that may provide useful reference points for future selection and breeding efforts.

2. Materials and Methods

2.1. Plant Materials

In October 2025, *E. angustifolia* fruits were collected from four sampling sites within Alxa Left Banner, Inner Mongolia: Tonggunaoer (105°22′53.40″ E, 38°45′56.27″ N), Barunbieli (105°36′9.21″ E, 38°37′14.60″ N), Chaertan (105°41′50.08″ E, 39°18′05.55″ N), and Jilantai (105°43′30.00″ E, 39°43′04.80″ N) (Figure 1). These sites exhibit a typical temperate continental arid climate, characterized by annual precipitation ranging from 50 to 150 mm, high evaporation rates, abundant sunshine, pronounced diurnal temperature variation, and soils primarily composed of gray desert and aeolian sandy substrates.

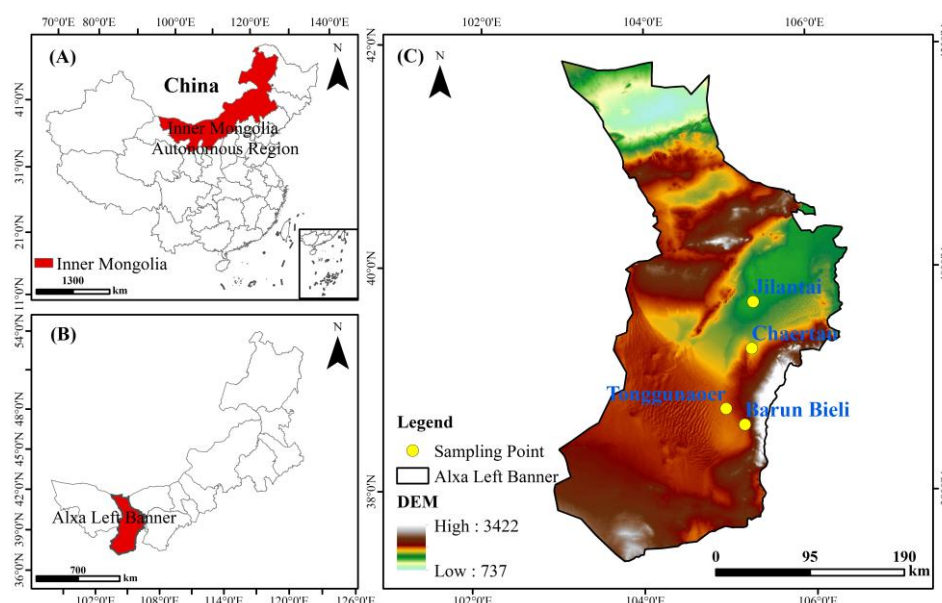


Figure 1. Location map of *Elaeagnus angustifolia* fruit sampling sites in the Alxa Region. (A) Map of China, with the Inner Mongolia Autonomous Region highlighted in red; (B) map of Inner Mongolia, with Alxa Left Banner highlighted in red; (C) map of Alxa Left Banner, showing the four sampling sites (Tonggunaoer, Barunbieli, Chaertan, and Jilantai).

At each site, 15 adult trees of similar age with normal growth and no visible pest or disease symptoms were selected, with a minimum spacing of 50 m between individuals to ensure sample representativeness. Approximately 2 kg of mature fruit were randomly harvested from all four canopy directions—east, south, west, and north—of each tree. Immediately following collection, all fruit samples were placed in breathable bags and transported to the laboratory.

Morphological measurements were conducted on all 60 trees (4 sites × 15 trees). Due to budgetary limitations, nutritional composition analysis—including assessment of basic nutrients, mineral elements, and bioactive compounds—was performed on fruit from five randomly selected trees per site (20 trees total). A portion of the samples was utilized for morphological evaluation (fresh material), while the remaining fruit was pitted, chopped, homogenized, and stored at −20 °C for nutritional analysis. Prior to analysis, frozen pulp samples were freeze-dried to constant weight and ground to a fine powder.

2.2. Morphological Measurements

Morphological measurements were conducted on all 15 trees selected from each sampling site. From each tree, 30 mature, intact, and undamaged fruits were randomly collected for analysis.

Fresh fruit weights were determined using an electronic balance with a precision of 0.001 g. Longitudinal and transverse diameters of each fruit were measured with a digital Vernier caliper (precision: 0.01 mm), and the fruit shape index was calculated as the ratio of longitudinal to transverse diameter. The pulp was manually removed to isolate the stones, which were then weighed (fresh weight) and measured for longitudinal and transverse diameters using identical procedures.

For each tree, mean values for all morphological traits were calculated from the data obtained for 30 fruits, serving as the morphological profile for that tree. Subsequently, the mean value derived from 15 trees per site was used as the representative value for each sampling site in subsequent comparative analyses.

2.3. Analysis of Basic Nutritional Components

Nutritional analyses were performed on five randomly selected trees at each sampling site, yielding a total of 20 trees. Each sample was measured in triplicate, with mean values per tree used for subsequent analyses. Data are reported as percentages of dry weight.

Soluble sugar content was assessed using the copper reduction-iodometric method according to the Chinese standard NY/T 1278-2007 [8].

Titrateable acid content was measured by acid–base titration following the Chinese national standard GB 12456-2021 [9].

Protein content was quantified using the Kjeldahl method according to the Chinese national standard GB 5009.5-2016 [10], with a nitrogen-to-protein conversion factor of 6.25.

Fat content was determined by Soxhlet extraction in accordance with the Chinese national standard GB 5009.6-2016 [11].

Crude fiber content was analyzed using the acid–base digestion–gravimetric method per the Chinese national standard GB/T 5009.10-2003 [12].

2.4. Analysis of Mineral Elements

Calcium (Ca) and magnesium (Mg) levels were measured using atomic absorption spectrometry (AAS). Samples were digested with a 4:1 (v/v) mixture of nitric acid and perchloric acid and analyzed using an iCE 3000 atomic absorption spectrometer (Thermo Fisher Scientific, Waltham, MA, USA).

The iron (Fe), zinc (Zn), copper (Cu), and manganese (Mn) contents were determined using inductively coupled plasma optical emission spectrometry (ICP-OES). The samples

were digested following the same procedure, and measurements were performed using an ICP-OES spectrometer (iCAP 7200, Thermo Fisher Scientific, Waltham, MA, USA).

For quality assurance and quality control (QA/QC), reagent blanks were prepared and analyzed alongside each batch of samples, and sample values were corrected by subtracting blank values where applicable. External calibration curves were constructed using standard solutions prepared from certified reference materials, with calibration ranges of 0–5 mg/L for Ca, 0–2 mg/L for Mg, 0–5 mg/L for Fe, 0–2 mg/L for Zn, 0–2 mg/L for Cu, and 0–2 mg/L for Mn; all calibration curves had correlation coefficients (R^2) exceeding 0.999. The limits of detection (LOD) and limits of quantification (LOQ) for each element (in $\mu\text{g/g}$) were as follows: Ca (0.25/0.85), Mg (0.10/0.35), Fe (0.15/0.50), Zn (0.08/0.25), Cu (0.05/0.15), and Mn (0.06/0.20).

Analytical accuracy was verified using a certified reference material (GBW10015 [13]) and spike recovery tests, with average recoveries ranging from 95.2% to 103.7% for all elements. The relative standard deviations (RSDs) for triplicate determinations were consistently below 5% for all elements, indicating good analytical precision.

All mineral contents are reported on a dry-weight basis. Moisture content was determined by drying a separate portion of the freeze-dried pulp samples at 105 °C to constant weight, and dry matter was calculated accordingly.

2.5. Analysis of Bioactive Components

The tannin content was quantified employing the Folin–Denis method. Sample extraction was prepared, and absorbance was measured at 760 nm with gallic acid serving as the calibration standard. The results are expressed as gallic acid equivalents (mg GAE/g dry weight).

Total flavonoid content was assessed using the aluminum nitrate–sodium nitrite colorimetric assay. Ethanol was used for sample extraction, and absorbance was measured at 510 nm, using rutin as the reference standard. Data are presented as rutin equivalents (mg RE/g dry weight). All bioactive component analyses were performed in triplicate, with RSDs below 5% for both tannin and total flavonoid measurements.

2.6. Statistical Analysis

All data were expressed as mean $\pm$ standard deviation (SD). Statistical analyses were performed using SPSS 26.0 software. One-way analysis of variance (ANOVA), followed by Tukey's honest significant difference (HSD) test, was used to assess statistically significant differences among sampling sites for each indicator ($p < 0.05$). Morphological trait comparisons were made based on 15 trees per site ($n = 15$), while nutritional comparisons utilized five trees per site ($n = 5$).

Pearson's correlation analysis was performed to investigate the relationships between morphological traits (six indicators) and nutritional components (13 indicators) using data from 20 trees. Principal component analysis (PCA) was subsequently applied to visualize the overall differences among the four sampling sites, utilizing nutritional data from 20 trees (13 indicators).

Prior to ANOVA, normality was checked using the Shapiro–Wilk test, and homogeneity of variances was checked using Levene's test for each trait. Where assumptions were violated, data were log-transformed before analysis. Given the exploratory nature of this study, multiple comparison corrections (e.g., false discovery rate) were not applied; instead, findings should be interpreted with caution, and p -values are presented with this exploratory context in mind.

For correlation analyses, Spearman correlations were used for variables that deviated from normality or contained outliers. Pearson correlations were used for normally distributed variables. Because trees were sampled from four distinct sites, some correlations may

partially reflect site-level differences rather than within-site relationships. This limitation should be considered when interpreting the correlation results.

PCA was performed on standardized variables using the correlation matrix, as the 13 nutritional indicators are measured in different units (% , $\mu\text{g/g}$, mg/g).

3. Results

3.1. Geographic Variation in Fruit Morphological Traits

ANOVA revealed significant differences in the morphological traits of *E. angustifolia* fruits from the four sampling sites ($p < 0.05$; Table 1). Tukey's HSD post hoc test further identified specific differences among the sites, indicating pronounced geographic variation in fruit morphology in the Alxa Region.

Table 1. Comparison of *Elaeagnus angustifolia* fruit morphological traits from four sampling sites in the Alxa Region.

Trait	Tonggunaoer	Barunbieli	Chaertan	Jilantai
Individual fruit fresh weight (g)	0.68 ± 0.10 a	0.54 ± 0.09 b	0.42 ± 0.10 c	0.63 ± 0.16 ab
Fruit transverse diameter (mm)	10.96 ± 0.83 a	10.55 ± 0.86 a	9.62 ± 0.78 b	11.31 ± 0.76 a
Fruit longitudinal diameter (mm)	14.92 ± 1.16 a	14.23 ± 1.11 a	12.22 ± 0.99 b	13.99 ± 1.68 a
Fruit shape index	1.36 ± 0.10 a	1.35 ± 0.09 a	1.27 ± 0.08 ab	1.24 ± 0.16 b
Stone fresh weight (g)	0.25 ± 0.05 a	0.23 ± 0.03 a	0.17 ± 0.02 b	0.26 ± 0.04 a
Stone transverse diameter (mm)	5.07 ± 0.36 a	5.18 ± 0.45 a	3.92 ± 0.23 b	5.28 ± 0.54 a
Stone longitudinal diameter (mm)	14.73 ± 1.32 a	13.26 ± 1.30 b	11.61 ± 0.80 c	13.27 ± 1.14 b

Different letters in the same row indicate significant differences (Tukey's HSD test, $p < 0.05$).

The highest mean fruit fresh weight was detected in Tonggunaoer specimens (0.68 g), which did not differ significantly from that in Jilantai (0.63 g); however, both were markedly higher than those observed in Barunbieli (0.54 g) and Chaertan (0.42 g) samples. The weight of Chaertan fruit was the lowest, representing a 38.2% reduction compared with Tonggunaoer. The fruit transverse diameter was largest in Jilantai fruit (11.31 mm), followed by Tonggunaoer (10.96 mm) and Barunbieli (10.55 mm), with no significant differences among these three sites. Nevertheless, each demonstrated significantly larger diameters than Chaertan (9.62 mm). A comparable pattern emerged for longitudinal diameter, with Tonggunaoer (14.92 mm), Barunbieli (14.23 mm), and Jilantai (13.99 mm) specimens all displaying significantly higher values than Chaertan (12.22 mm); no significant differences were observed among the former three sites.

Regarding the fruit shape index, the highest values were recorded for Tonggunaoer (1.36) and Barunbieli (1.35) fruits, with no significant difference between them. Jilantai had the lowest fruit shape index (1.24), which did not differ significantly from Chaertan (1.27). The indices for Tonggunaoer and Barunbieli had significantly higher values than Jilantai, indicating that fruits from Tonggunaoer and Barunbieli were more elongated, whereas those from Jilantai were relatively rounded.

Stone traits mirrored patterns observed in the fruit. Stone fresh weight was relatively high in Tonggunaoer (0.25 g), Barunbieli (0.23 g), and Jilantai (0.26 g) specimens, with no significant differences among them, but all were significantly higher than that of Chaertan (0.17 g). The stone transverse diameter was also the smallest in Chaertan (3.92 mm), significantly lower than the other sites (5.07–5.28 mm), with no significant differences among Tonggunaoer, Barunbieli, and Jilantai. The stone longitudinal diameter demonstrated the most pronounced differences: Tonggunaoer (14.73 mm) was significantly greater than Barunbieli (13.26 mm) and Jilantai (13.27 mm), with both latter sites exceeding Chaertan (11.61 mm); there was no significant difference between Barunbieli and Jilantai.

In summary, the data suggest pronounced geographic variation in fruit morphology among the sampling sites, with fruits from Chaertan consistently smaller than those from Tonggunaoer, Barunbieli, and Jilantai.

3.2. Geographic Variation in Nutritional Components

3.2.1. Basic Nutritional Components

Significant differences were not observed in the fat content of fruits collected from Tonggunaoer (4.31%), Barunbieli (4.33%), and Jilantai (4.42%); however, these three were markedly higher than in Chaertan (3.66%; Table 2).

Table 2. Basic nutritional components of *E. angustifolia* fruits from four sampling sites in the Alxa Region.

Trait	Tonggunaoer	Barunbieli	Chaertan	Jilantai
Fat (%)	4.31 ± 0.25 a	4.33 ± 0.15 a	3.66 ± 0.25 b	4.42 ± 0.15 a
Protein (%)	6.59 ± 0.28 b	6.33 ± 0.33 b	3.86 ± 0.55 c	7.49 ± 0.14 a
Soluble sugar (%)	35.80 ± 0.90 a	23.71 ± 3.08 b	35.15 ± 1.53 a	34.80 ± 1.40 a
Titrateable acid (%)	2.61 ± 0.28 a	2.53 ± 0.17 a	2.72 ± 0.13 a	2.42 ± 0.27 a
Crude fiber (%)	5.98 ± 0.13 b	6.44 ± 0.21 a	6.50 ± 0.30 a	6.46 ± 0.23 a

Different letters in the same row indicate significant differences (Tukey's HSD test, $p < 0.05$).

Jilantai had the highest protein content at 7.49%, significantly exceeding the levels found in fruit from the other three locations. Tonggunaoer (6.59%) and Barunbieli (6.33%) followed, showing no significant difference between them but both having notably higher values than Chaertan (3.86%), which had the lowest protein content, 48.5% lower than Jilantai.

Soluble sugar content did not differ significantly among Tonggunaoer (35.80%), Chaertan (35.15%), and Jilantai (34.80%), but the fruit from these three sites had significantly higher concentrations than Barunbieli (23.71%). Meanwhile, titrateable acid content did not differ significantly among the sampling sites, ranging from 2.42% to 2.72%.

Crude fiber content was comparatively high in Chaertan (6.50%), Jilantai (6.46%), and Barunbieli (6.44%), with no significant differences among them; however, all three were significantly higher than in Tonggunaoer (5.98%).

3.2.2. Mineral Elements

Significant differences were observed for all mineral elements across the *E. angustifolia* sampling sites, reflecting notable geographic variation (Table 3).

Table 3. Comparison of *E. angustifolia* fruit mineral element contents from four sampling sites in the Alxa Region.

Trait	Tonggunaoer	Barunbieli	Chaertan	Jilantai
Mg (µg/g)	528.60 ± 19.55 c	552.40 ± 29.36 c	851.80 ± 57.93 a	651.00 ± 25.97 b
Ca (µg/g)	427.80 ± 27.89 c	1721.20 ± 133.98 a	1512.00 ± 123.35 b	460.00 ± 31.73 c
Mn (µg/g)	4.82 ± 0.11 b	7.63 ± 0.20 a	8.01 ± 0.40 a	3.57 ± 0.27 c
Cu (µg/g)	2.19 ± 0.13 b	3.88 ± 0.15 a	3.44 ± 0.31 a	1.68 ± 0.31 c
Fe (µg/g)	15.43 ± 0.89 c	36.31 ± 2.04 a	22.51 ± 2.05 b	23.07 ± 2.88 b
Zn (µg/g)	2.84 ± 0.20 b	4.38 ± 0.31 a	2.28 ± 0.23 c	1.52 ± 0.36 d

Different letters in the same row indicate significant differences (Tukey's HSD test, $p < 0.05$).

Mg content was highest in Chaertan fruit (851.80 µg/g) and significantly greater than in the fruit from all other sites. Jilantai followed with 651.00 µg/g, whereas Tonggunaoer (528.60 µg/g) and Barunbieli (552.40 µg/g) recorded the lowest levels. In contrast, Ca con-

tent was highest in Barunbieli fruit (1721.20 µg/g), markedly exceeding that in Chaertan (1512.00 µg/g), and both were significantly higher than in Tonggunaoer (427.80 µg/g) and Jilantai (460.00 µg/g).

Mn and Cu demonstrated similar spatial distribution, with Chaertan (Mn: 8.01 µg/g, Cu: 3.44 µg/g) and Barunbieli (Mn: 7.63 µg/g, Cu: 3.88 µg/g) presenting significantly elevated levels compared with Tonggunaoer (Mn: 4.82 µg/g, Cu: 2.19 µg/g) and Jilantai (Mn: 3.57 µg/g, Cu: 1.68 µg/g). Fe content was highest in Barunbieli (36.31 µg/g), considerably higher than the other sites, with Chaertan (22.51 µg/g) and Jilantai (23.07 µg/g) following, and Tonggunaoer exhibiting the lowest levels (15.43 µg/g). Zn content displayed the most pronounced site-specific variation, with concentrations as follows: Barunbieli (4.38 µg/g), Tonggunaoer (2.84 µg/g), Chaertan (2.28 µg/g), Jilantai (1.52 µg/g).

3.2.3. Bioactive Components

Regarding the bioactive component contents of *E. angustifolia* fruits, significant differences were detected for tannin and total flavonoid content among the sampling sites, revealing distinct geographic distribution patterns (Table 4).

Table 4. Comparison of *E. angustifolia* fruit bioactive components from four sampling sites in the Alxa Region.

Trait	Tonggunaoer	Barunbieli	Chaertan	Jilantai
Tannin (mg/g)	3.35 ± 0.27 a	2.46 ± 0.20 b	1.52 ± 0.32 c	1.43 ± 0.16 c
Total flavonoid (mg/g)	0.24 ± 0.04 b	0.13 ± 0.01 c	0.62 ± 0.02 a	0.15 ± 0.02 c

Different letters in the same row indicate significant differences (Tukey's HSD test, $p < 0.05$).

Tonggunaoer fruit exhibited the highest tannin content (3.35 mg/g), significantly higher than that of fruit from the other three sites. Barunbieli (2.46 mg/g) ranked second, significantly higher than Chaertan (1.52 mg/g) and Jilantai (1.43 mg/g), with no significant difference between Chaertan and Jilantai. Meanwhile, the total flavonoid content was highest in Chaertan fruit (0.62 mg/g), significantly surpassing the levels observed in the fruits from the other sites. Tonggunaoer (0.24 mg/g) ranked second, significantly higher than Barunbieli (0.13 mg/g) and Jilantai (0.15 mg/g).

3.3. Correlation Analysis Between Morphological Traits and Nutritional Components

Pearson correlation analyses were performed to assess relationships among the morphological and nutritional data from 20 *E. angustifolia* fruit samples (Figure 2).

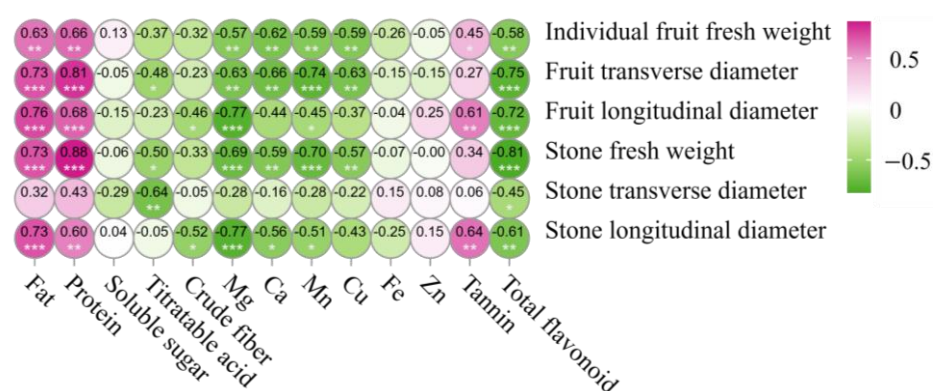


Figure 2. Correlation heatmap between morphological traits and nutritional components of *E. angustifolia* fruits. Note: Pink indicates a positive correlation, green indicates a negative correlation, and darker colors represent stronger correlations. The values in the cells represent correlation coefficients (r). * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; $n = 20$.

Fruit fresh weight, transverse diameter, and longitudinal diameter, as well as stone fresh weight and longitudinal diameter, all exhibited positive correlations with fat content ($r = 0.63\text{--}0.76$) and protein content ($r = 0.60\text{--}0.88$). Notably, the strongest correlation was observed between stone fresh weight and protein content ($r = 0.88$).

In contrast, soluble sugar content exhibited weak correlations with all morphological traits ($|r| < 0.3$), with no statistically significant relationships detected. Titratable acid content demonstrated a moderate negative correlation with stone transverse diameter ($r = -0.64$); its association with other morphological traits was weak. Crude fiber content showed a moderate negative correlation with stone longitudinal diameter ($r = -0.52$) and weak correlations with other traits.

All morphological traits were negatively correlated to varying degrees with Mg, Ca, Mn, and Cu. The most pronounced negative correlations were observed between fruit and stone longitudinal diameter and Mg content ($r = -0.77$). Additionally, fruit transverse diameter showed significant negative correlations with Ca, Mn, and Cu content ($r = -0.66$, -0.74 , and -0.63 , respectively). Stone fresh weight was also significantly negatively correlated with Mn content ($r = -0.70$). Both Fe and Zn exhibited only weak correlations with all assessed morphological traits ($|r| < 0.3$), with no significant associations detected. These results suggest a tendency for larger fruits to have lower concentrations of Mg, Ca, Mn, and Cu.

The per-tree values of all 13 nutritional indicators used in these analyses are provided in Supplementary Table S1. Tannin content showed moderate positive correlations with fruit longitudinal diameter ($r = 0.61$) and stone longitudinal diameter ($r = 0.64$), while correlations with other morphological traits were weak. Total flavonoid content was negatively correlated with all morphological traits, with the strongest negative relationship detected for stone fresh weight ($r = -0.81$) and a significant negative correlation with fruit transverse diameter ($r = -0.75$).

Supplementary Figure S1 shows scatterplots of key relationships (fruit fresh weight vs. protein, fruit fresh weight vs. Mg, and stone fresh weight vs. tannin), with data points color-coded by site to visualize potential site-level clustering effects. Regression equations and R^2 values are shown in each panel.

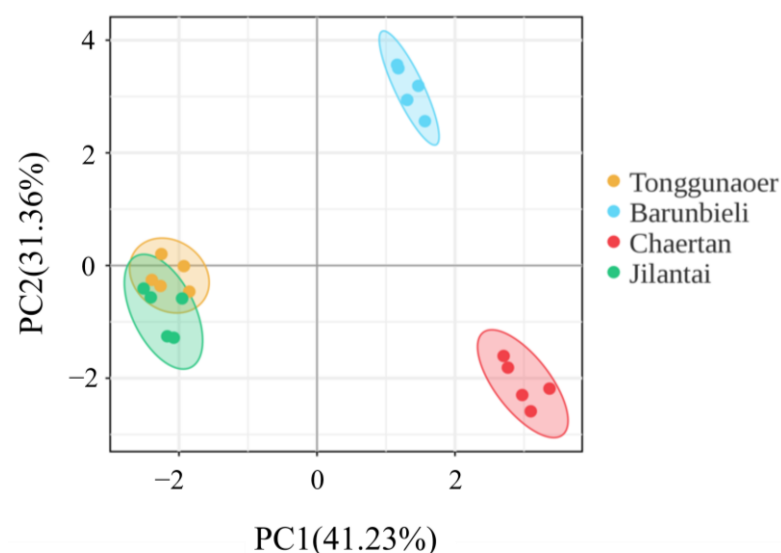
3.4. Principal Component Analysis of Nutritional Components

To clarify the overall differences in *E. angustifolia* fruit nutritional components across the four sampling sites, PCA was performed on 20 fruit samples using 13 nutritional indicators (Table 5 and Figure 3). The first two principal components accounted for 72.59% of the total variance, with PC1 and PC2 explaining 41.23% and 31.36%, respectively. According to the loading matrix (Table 5), PC1 demonstrated positive correlations with Mn (0.41), Ca (0.39), Cu (0.37), total flavonoids (0.29), and Mg (0.26), while exhibiting negative correlations with protein (-0.37), fat (-0.30), and soluble sugar (-0.14). This suggests a distinction between mineral elements and organic nutritional components. PC2 was positively correlated with Zn (0.43), Fe (0.36), fat (0.25), and protein (0.20) and negatively correlated with soluble sugar (-0.44), Mg (-0.34), and total flavonoids (-0.34), reflecting another unique pattern among nutritional indicators.

The PCA score plot demonstrates distinct separation among samples from the four sampling sites in the PC1–PC2 plane (Figure 3). Chaertan samples were predominantly distributed in the positive region of PC1 and the negative region of PC2, characterized by high levels of Mn, Ca, Cu, Mg, and total flavonoids, together with relatively high soluble sugar compared with Barunbieli. The Barunbieli samples were primarily distributed in the positive regions of PC1 and PC2, with notably high contents of Mn, Ca, Cu, Zn, Fe, and protein. Samples from Tonggunaoer and Jilantai occupied the negative region of PC1, characterized by higher fat and soluble sugar contents, but lower mineral element concentration.

Table 5. Loading matrix and variance contribution rates for the first two principal components.

Trait	PC1	PC2
Fat	−0.30	0.25
Protein	−0.37	0.20
Soluble sugar	−0.14	−0.44
Titrateable acid	0.14	−0.15
Crude fiber	0.20	−0.02
Mg	0.26	−0.34
Ca	0.39	0.18
Mn	0.41	0.11
Cu	0.37	0.21
Fe	0.20	0.36
Zn	0.15	0.43
Tannin	−0.14	0.22
Total flavonoid	0.29	−0.34
Eigenvalue	5.36	4.08
Variance (%)	41.23	31.36
Cumulative (%)	41.23	72.59

**Figure 3.** PCA score plot of *E. angustifolia* fruit samples based on nutritional components. Note: PC1 and PC2 explained 41.23% and 31.36% of the total variance, respectively. Different colors represent different sampling sites.

4. Discussion

4.1. Geographic Variation in Fruit Morphological Traits and Nutritional Components

Significant geographic variation in fruit morphological traits was observed among the four sampling sites in the Alxa Region. Fruits from Chaertan were notably smaller than those from the other sites, aligning with the findings of Bey et al. [14], who identified water stress as a key factor limiting fruit size and tree productivity. Precipitation patterns in the Alxa Region are uneven, with more rainfall near the eastern foothills of Helan Mountain and considerably less in the western desert. Chaertan, located in a northern desert region with lower precipitation, likely experiences a greater water deficit during fruit development, which may have contributed to its smaller fruit size [15]. Meanwhile, the fruit may have contributed to its smaller fruit shape index, which remained relatively stable across sites, suggesting that fruit shape is predominantly governed by genomic control [16].

Geographic differences also appeared in the basic nutritional composition of *E. angustifolia* fruits. Jilantai fruits had the highest protein levels, while Chaertan had the lowest. Variations in protein content may be partially due to differences in soil nitrogen availability, as supported by the observed positive correlation between protein content and total soil nitrogen in *E. angustifolia* fruits [17]. Barunbieli fruits contained significantly less soluble sugar, potentially due to smaller diurnal temperature variations during fruit ripening at the foot of the Helan Mountains. Indeed, temperature significantly influences sugar accumulation in fruits [18]. In contrast, titratable acid levels were consistent across all sites, whereas fat content was significantly lower in Chaertan than in the other three sites, suggesting strong genetic regulation of these characteristics, consistent with previous findings on apple acidity [19].

Mineral element content varied markedly by geographic locations. Chaertan fruits had the highest Mg content, while Barunbieli had the highest Ca, Fe, and Zn contents, which may reflect differences in soil parent material at each site. However, because soil properties were not measured at the sampling sites, this interpretation remains speculative and requires confirmation in future studies. Previous research confirms that soil parent material largely determines mineral nutrient concentrations, such as Ca, Mg, and Fe [20]. Mn and Cu levels were higher at Chaertan and Barunbieli than at the other sites and were negatively correlated with fruit size. This may suggest that trace elements became diluted in larger fruits. Importantly, distribution patterns of mineral and organic nutrients were opposite, reflecting the resource allocation strategies of *E. angustifolia* under different habitat conditions [21].

We acknowledge that site-specific measurements of soil properties, local climate, and genetic data were not available for this study. Therefore, the environmental and genetic interpretations discussed above remain speculative and should be treated as hypotheses to be tested in future studies with more comprehensive environmental and molecular data.

4.2. Geographic Distribution Patterns of Fruit Bioactive Components

Tannin and total flavonoid contents exhibited contrasting geographic distributions: tannin levels were highest in Tonggunaoer, whereas total flavonoid content was highest in Chaertan. This aligned with earlier research by Karkar and Şahin [22] and Fu et al. [23], which established the coexistence and geographic variability of tannins and flavonoids across different *E. angustifolia* populations [24].

A positive correlation was observed between tannin content and stone size; Tonggunaoer, with the largest stones, also exhibited the highest tannin content. The accumulation of defensive compounds such as tannins may be stimulated by drought conditions [25]. Similar patterns have been reported for other fruit trees, where individuals with larger seeds or stones tend to accumulate higher tannin levels, as exemplified by grapevines [26].

The total flavonoid content was highest in Chaertan, which is consistent with the hypothesis that higher ultraviolet (UV) radiation may promote flavonoid accumulation. Flavonoids are known to be produced in response to UV stress in other species, which may also apply to our study sites [27]. Similar trends have been identified in other desert plants, such as sea buckthorn (*Hippophae rhamnoides*), with increased accumulation of phenolic compounds and flavonoids under violet and blue light (400–450 nm), wavelengths proximal to the UV spectrum [28]. However, because UV exposure was not measured at our sampling sites, this interpretation remains speculative and should be tested in future studies with direct UV measurements. The divergent responses of tannins and total flavonoids to environmental factors suggest distinct regulatory pathways, supporting the view that different phenolic compound classes respond differently to abiotic stress [29].

4.3. Synergy and Trade-Off Between Fruit Morphological Traits and Nutritional Components

Correlation analysis revealed important relationships between fruit morphology and nutritional components. Morphological characteristics, including individual fruit fresh weight and fruit longitudinal diameter, were positively correlated with fat and protein content, indicating that larger fruits generally accumulate larger quantities of storage compounds. This aligns with the biological profile of *E. angustifolia* as a key ecological and economic tree species in arid environments.

Conversely, morphological traits were negatively correlated with mineral elements (Mn, Cu, Mg, and Ca), highlighting a growth–mineral trade-off. Although this trade-off has been documented in other fruit trees, including jujube [30] and apple [31], it is newly documented in *E. angustifolia* with the current study. Two primary mechanisms may explain this relationship: the dilution effect, in which larger fruits divert more photosynthates toward organic matter synthesis, leading to reduced relative concentrations of mineral elements [32]; and competitive inhibition, wherein the transport of organic nutrients competes with mineral element absorption and translocation. In the current study, fruit size was significantly negatively correlated with several mineral elements, suggesting that the dilution effect may play a predominant role. This preliminary finding may have important implications for *E. angustifolia* breeding programs, as breeders must either maintain an equilibrium between fruit size and mineral nutrition or mitigate this trade-off through cultivation strategies, such as foliar application of micronutrients [33].

4.4. Comprehensive Evaluation of Fruits' Nutritional Components

PCA further demonstrated pronounced geographic differences in the nutritional components of *E. angustifolia* fruits. PC1 distinguished between mineral and organic nutrients, while PC2 separated trace elements from soluble sugars. Similar PCA applications have helped assess differences in fruit quality in other species, including citrus [34], peaches [35], and pears [36]. Specifically, Chaertan fruits had high mineral-element contents, Barunbieli had high trace-element contents, and Tonggunaoer and Jilantai exhibited high organic-nutrient contents.

Overall, the fruit quality of *E. angustifolia* appears to be influenced by the combined effects of genetic and environmental factors. Organic nutrients, such as fat and protein, may be predominantly under genetic control, with minor geographic variation. In contrast, mineral elements and secondary metabolites are more strongly impacted by environmental changes, resulting in greater geographic differentiation [37]. This trend has been reported in other fruit trees, with macronutrients tending to remain stable due to genetic regulation, whereas secondary metabolites are more influenced by environmental conditions [38]. These findings highlight the importance of conserving a range of *E. angustifolia* geographic populations to maintain genetic diversity. They also suggest that different groups can be strategically leveraged based on their unique attribute profiles [33].

This study has certain limitations. First, only five trees per site were analyzed, which may not reflect the full range of natural variation within *E. angustifolia* populations. Second, the lack of soil physicochemical and climatic data precludes a direct assessment of the relationships between environmental factors and fruit quality. Third, fruit samples were collected in a single year, limiting the analysis of interannual variability. Future research should include larger sample sizes, multiple sampling years, and concurrent measurements of soil and climatic variables to establish quantitative models that link fruit quality to environmental conditions. Furthermore, integrating molecular marker approaches could clarify the genetic basis of quality traits in *E. angustifolia*, supporting the targeted cultivation and industrial utilization. Beyond its nutritional value, *E. angustifolia* is also recognized in traditional medicine for its astringent, anti-inflammatory, and wound-healing properties, which may be associated with bioactive compounds such as alkaloids, pol-

yphenols, and essential oils. Future metabolomic investigations, including mass spectrometry-based profiling of fruits, leaves, and bark, would help to systematically characterize the phytochemical composition and pharmacological potential of this species, complementing the nutritional focus of the present study.

5. Conclusions

Marked geographic variations were observed in the fruit morphology and nutritional composition of *E. angustifolia* in the Alxa Region, whereas the fruit shape index and fat content remained relatively stable. An observed tradeoff existed between organic nutrients and mineral elements (particularly Mg, Ca, Mn, and Cu) in individuals with larger fruit. While these findings are based on a single-year sampling with a modest number of biological replicates per site for nutritional traits, they provide preliminary insights into the geographic variation in nutritional composition in *E. angustifolia* in the Alxa Region. Taken together, these observations offer a basis for germplasm conservation and functional food production.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/app16147111/s1>. Figure S1: Scatterplots of key relationships between morphological traits and nutritional components (fruit fresh weight vs. protein, fruit fresh weight vs. Mg, stone fresh weight vs. tannin); Table S1: Per-tree values of 13 nutritional indicators used in the correlation and PCA analyses.

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Abbreviations

The following abbreviations are used in this manuscript:

AAS	Atomic absorption spectrometry
ANOVA	Analysis of variance
HSD	Honest significant difference
ICP-OES	Inductively coupled plasma optical emission spectrometry
LOD	Limits of detection
LOQ	Limits of quantification
PCA	Principal component analysis
RSDs	Relative standard deviations
SD	Standard deviation

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