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AGRONOMIC, MORPHOLOGICAL AND NUTRITIONAL CHARACTERISTICS OF *Tithonia diversifolia* IN TWO ENVIRONMENTS WITH POTENTIAL FOR USE AS FORAGE

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ABSTRACT

Tithonia diversifolia is a shrub species that has gained increasing importance as an alternative species for forage due to its nutritional profile. Its agronomic and nutritional characteristics can vary depending on the environment. Therefore, the objective of this study was to evaluate the agronomic, morphological and nutritional characteristics of *Tithonia diversifolia* in two altitudinal zones of the Amazonas region, Peru. Plants were cultivated in Chachapoyas (2445 m.a.s.l.) and Cajaruro (797 m.a.s.l.), two locations with contrasting soil, climate, and altitude conditions. The bud burst, agronomic, morphological and nutritional characteristics of *T. diversifolia* were evaluated. The bud burst, dry weight, dry matter content, plant height, growth rate, carbohydrate content, and gross energy were significantly higher ($p \leq 0.05$) in *T. diversifolia* cultivated in Cajaruro. In contrast, crude protein and mineral content were higher ($p \leq 0.05$) in Chachapoyas. No significant differences ($p > 0.05$) were found for fresh weight, number of leaves/plant, number of shoots/plant, ether extract, and crude fiber. These results suggest that *T. diversifolia* expresses favorable characteristics for forage in a high-altitude environment, and shows high phenotypic plasticity, which is important for its adaptation and cultivation across diverse agroecological zones.
Additional Keywords: Altitude levels, germination, growth rate, nutrient, plant height

RESUMEN

Características agronómicas, morfológicas y nutricionales de *Tithonia diversifolia* en dos ambientes con potencial uso como forraje

Tithonia diversifolia es una especie arbustiva que ha cobrado creciente importancia como alternativa para forraje debido a su perfil nutricional. Sus características agronómicas y nutricionales pueden variar según el entorno. Por ello, el presente estudio tuvo como objetivo evaluar las características agronómicas, morfológicas y nutricionales de *T. diversifolia* en dos pisos altitudinales de la región Amazonas, Perú. Las plantas se cultivaron en Chachapoyas (2445 m.s.n.m.) y Cajaruro (797 m.s.n.m.), localidades que presentan condiciones contrastantes de suelo, clima y altitud. Se evaluaron las variables de brotación, así como, características agronómicas, morfológicas y nutricionales. Se registraron valores significativamente mayores ($p \leq 0.05$) de germinación, peso seco, contenido de materia seca, altura de planta, tasa de crecimiento, contenido de carbohidratos y energía bruta en *T. diversifolia* cultivada en Cajaruro. En cambio, el contenido de proteína cruda y minerales fue mayor ($p \leq 0.05$) en Chachapoyas. No se encontraron diferencias significativas ($p > 0.05$) en peso fresco, número de hojas por planta, número de brotes por planta, extracto etéreo ni fibra cruda. Los resultados indican que *T. diversifolia* presenta características favorables para forraje en ambientes de menor altitud, así como una alta plasticidad fenotípica, aspecto relevante para su adaptación y cultivo en diversas zonas agroecológicas.
Palabras clave adicionales: Altura de la planta, germinación, índice de crecimiento, niveles de altitud, nutrientes

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INTRODUCTION

Tithonia diversifolia, commonly known as the Mexican sunflower or buttercup, belongs to the Asteraceae family. It is a plant that has spread widely throughout tropical areas, however, it is highly adaptable to different environmental conditions, managing to adapt up to an altitude of

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2,500 meters above sea level (Botero *et al*., 2019; Cabanilla *et al*., 2021). It is also a species rich in different kinds of secondary metabolites such as lactones, sesquiterpenes, diterpenes and flavonoids (Ngenge *et al.*, 2022).

This species is used as an excellent botanical insecticide (Green *et al.*, 2017; Miranda *et al.*, 2022) such as the case of management of *Helicoverpa armigera* populations treated with an extract enriched with tagitinina C from *Tithonia diversifolia*, achieving up to 80 % mortality of *H. armigera* larvae (Da Costa *et al.*, 2020). Also for the treatment of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) achieving a reduction in the growth of the larvae (Miranda *et al.*, 2022). In addition, it is capable of improving the physicochemical characteristics of soil, after six months of establishment (Londoño *et al.*, 2019; Panadero and Montaña, 2019) and used as green manure (Eifediyi *et al.*, 2023).

T. diversifolia has proven to be a promising source of forage, due to its high nutritional content, especially rich in protein, which varies from 12.37 % to 31.1 % (Cabanilla *et al.*, 2021; Rivera *et al.*, 2021; Castaño *et al.*, 2023), and its ability to adapt to low-fertility soils (Londoño *et al.*, 2019; Canto *et al.*, 2023). This species has been incorporated into the feed of different monogastric animal species (Montero *et al.*, 2019) and has been widely used in ruminant feed, being considered a promising species for reducing gas emissions, especially methane (Firsoni *et al.*, 2022; Jamarun *et al.*, 2023; Pazla *et al.*, 2024).

The agronomic and nutritional characteristics of *Tithonia diversifolia* can vary significantly depending on environmental conditions, management and production times, and this crop can also achieve high forage mass production (Angulo *et al.*, 2024).

In Peru, there are few studies regarding the evaluation of the agronomic, morphological and nutritional characteristics of this species in different environments, especially at different altitudes; this would be of great importance for making adequate decisions in the cultivation of *Tithonia diversifolia*. Therefore, the objective of this study was to evaluate the agronomic, morphological and nutritional characteristics of *Tithonia diversifolia* in two environments, differentiated mainly by the altitude (2445 and 797 m.a.s.l) of the Amazonas region.

MATERIALS AND METHODS

Experimental plots. The experimental plots were located in two different environments: Chachapoyas (average environmental conditions of temperature with 22±3 °C, relative humidity of 85±5 % and precipitation of 58±5 mm) and Cajaruro (average environmental conditions of temperature with 28±5 °C, relative humidity of 80±5% and precipitation of 54±5 mm), belonging to the provinces of Chachapoyas and Utcubamba respectively, in the Amazonas region-Peru. (Figure 1). The study was conducted between January and April.

The experimental plot in Chachapoyas was located at 2445 m a.s.l. and Cajaruro at 797 ma.s.l.; these plots showed differences in soil, showing higher values of N, P and K in Cajaruro (Table 1). In each environment, four plots (repetitions) were prepared (4x4=16 m^2) and the cultural work for planting was carried out at points at a distance of 1.0 m between furrows and 0.75 m between plants (Cabanilla *et al*., 2021).

Planting and evaluation. Vegetative seeds (cuttings) of *Tithonia diversifolia* from the Huarangopampa Experimental Station of the National Institute of Agrarian Innovation (INIA) located in the province of Utcubamba, Amazonas-Peru were used. Cuttings of 3 to 4 nodes (2-3 cm in diameter and 30-35 cm in length) were collected, the leaves were removed (Kim *et al.*, 2021) and they were transferred to the planting environments in polystyrene boxes.

60 stakes (15/plot) were installed in each study environment (four repetitions with 15 subsamples). They were planted at a depth of 15 cm, with a 75° inclination angle (Alonso *et al.*, 2021) and at a distance of 0.75 between plants and 1.00 m between furrows (Botero *et al*., 2019). Sprinkler irrigation was carried out when necessary (absence of rainfall) and weeding was carried out constantly to avoid competition.

The assessment of bud burst was carried out on the 21st and 30th day after planting, and the percentage of sprouted cuttings was calculated according to Iriban *et al.* (2022), with four replications (the replications were the plots). The plant height was determined with a millimeter ruler from the base to the apical bud (Guatusmal *et al*., 2020); six measurements were taken, with 15-day intervals, starting on the 45th day after planting; the growth rate was calculated with this data following the methodology proposed by Rodríguez and Ojeda (2019). Both plant height and growth rate were evaluated based on 6 plants per plot (i.e., 6 subsamples), from a total of 4 plots (which represent the number of repetitions).

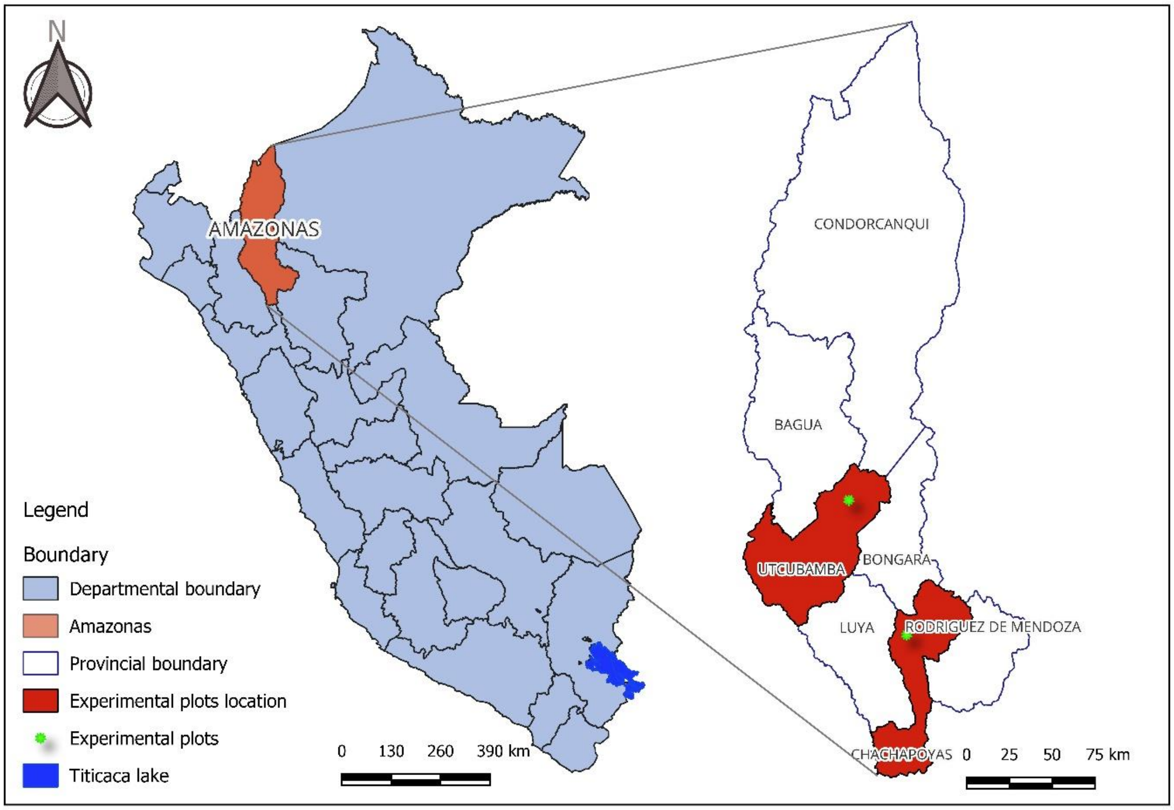

Figure 1. Experimental plot's location of the study.

Table 1. Soil characteristics of the experimental plots

Environment	pH	N (%)	P (ppm)	K (ppm)	Texture
Cajaruro	8.56	0.30	10.81	325.75	Clay
Chachapoyas	8.53	0.08	2.54	99.76	Clay-sandy

N, nitrogen; P, phosphorus; K, potassium.

The number of shoots/plant was determined on days 21 and 30 from planting on 6 plants (subsamples) from a total of 4 plots (replications), and at the end of the study (day 120) the number of leaves/plant was evaluated on 3 plants (subsamples) from the same 4 plots (replications) (Rodríguez and Ojeda, 2019). In addition, the plants were harvested (including leaves and secondary stems) to determine the production of fresh matter (Navas and Montaña 2019), these were transferred to the Animal Nutrition and Food Bromatology Laboratory (LABNUT from spanish Laboratorio de Nutrición Animal y Bromatologia de Alimentos) of the Toribio Rodríguez de Mendoza National University in Amazonas for nutritional analysis.

The biochemical composition was evaluated 120 days after planting. One composite sample was collected from each of the three plots. In each plot, leaves and secondary stems were taken from an average of five plants, mixed thoroughly, and a 1.5 kg sample was obtained. The material was transported to the LABNUT laboratory and manually chopped with knives. Subsequently, a portion was dried in an oven at 105 °C for 24 hours to determine the dry matter content, while another portion intended for chemical analysis was dried at 60 °C for 48 hours. A rotary mill (Tecnal, TE-651/2, Brazil) was used to grind the samples and subsequently determine the content of crude protein using the Method 928.08 (Kjeldahl method-titrimetric determination), ash whit method gravimetric, ether extract with method gravimetric - ether extraction and nitrogen-free extract was determinate by difference (AOAC, 2012), crude fiber was performed with Method 7-Ankom described by Marichal *et al*. (2011) and gross energy was determined using a bomb calorimeter (Model Parr 6200).

Data analysis. A completely randomized design (CRD) was used in this study, with two treatments corresponding to altitudinal zones or environments (Chachapoyas and Cajaruro districts). In each zone, four plots (replications) were established, and 15 vegetative seeds (cuttings) of *Tithonia diversifolia* were planted in each plot (subsamples or experimental units).

Prior to the analysis, the assumptions of normality and homoscedasticity were verified using the Shapiro-Wilk and Levene's tests, respectively.

For the analysis of the variables studied, a one-way analysis of variance was considered, with the different environments as the only factor. In all cases, a significance level of 0.05 was used; when the analysis of variance showed significant differences, the comparison of means was carried out using the Tukey method. For these analyses, the statistical program R 4.4.0.was used. In addition, correlations were obtained using the Pearson method between productive and morphological variables, and between nutritional characteristics.

RESULTS AND DISCUSSION

Agronomic characteristics. The number of bud-bursting cuttings and the percentage of bud burst were higher in Cajaruro ($p \leq 0.05$); germination was 100 and 70 % for Cajaruro and Chachapoyas respectively, for day 30 of evaluation (Table 2).

Table 2. Number and percentage of bud burst *Tithonia diversifolia* at 21 and 30 days in the Chachapoyas and Cajaruro districts

Variables evaluated	Days after planting	Environments		Significance level
		Chachapoyas	Cajaruro	
Number of bud-bursting cuttings	21	6.75[1]±0.50b	12.00±0.82a	*
	30	10.50±0.58b	15.00±0.00a	*
Percentage of bud burst	21	45.00±3.33b	80.00±5.44a	*
	30	70.00±3.85b	100.00±0.00a	*

[1]/ Values represent the mean ± standard deviation (n=4). Different letters in the same row indicate statistically significant differences according to Tukey's test ($p \leq 0.05$), for each environment. *: significant at $p \leq 0.05$

Dry weight and percentage of dry matter were higher in Cajaruro ($p \leq 0.05$), but no differences were found between environments for fresh weight, number of leaves/plant and number of shoots/plant ($p > 0.05$) (Table 3). Cajaruro plants had 894.50 g·plant^{-1}, on average representing about three times the dry weight of Chachapoyas plants; likewise, the percentage of dry matter was 24.88 % in Cajaruro, representing almost double that of Chachapoyas plants.

The results show greater bud burst in *Tithonia diversifolia* cultivated in Cajaruro (797 m a.s.l.), which is located at a lower altitude compared to Chachapoyas (2445 m a.s.l.); these results agree with those reported by Iriban *et al.* (2021), who reported higher values at lower altitudes. The bud burst results of this study were similar to the results found by López *et al.* (2019) under nursery conditions managed with different types of fertilizers. These differences in bud burst may be attributed to the higher temperatures and more favorable edaphoclimatic conditions in Cajaruro, which are known to stimulate faster metabolic activity during seed germination and early growth.

In contrast, the cooler temperatures and possible soil limitations at higher altitudes like Chachapoyas could delay or reduce seedling vigor and establishment.

Table 3. Productive and morphological characteristics of *Tithonia diversifolia* grown in the Chachapoyas and Cajaruro districts

Characteristics	Days after planting	Environments		Significance level
		Chachapoyas	Cajaruro	
Fresh weight (g/plant)	120	2145.83[1]±488.04	3525.42±1101.50	
Dry weight (g/plant)	120	275.67±60.08b	894.50±347.67a	*
Dry matter percentage (%)	120	12.86±0.54b	24.88±1.82a	*
Leaves/plant	120	355.67±47.06	416.79±107.02	
Shoots/plant	21	2.96±0.16	2.79±0.67	
	30	3.00±0.19	2.88±0.64	

[1]/ Values represent the mean ± standard deviation (n = 4). Different letters in the same row indicate statistically significant differences according to Tukey's test ($p \leq 0.05$), for each environment. *: significant at $p \leq 0.05$.

The dry matter percentages were similar to those of Alonso *et al*. (2012), who reported values of 19.5 and 23.8% and lower than those reported by Angulo *et al*. (2024) at 75 days of age. The number of leaves/plant was lower than that reported by Jiménez *et al*. (2024) who achieved 436.5 leaves/plant at 90 days' post homogenization cut. However, the number of shoots/plant was also lower than the results shown by Andrade *et al*. (2024), who reported 2.10 to 3.56 shoots/plant at 15 and 30 days of evaluation respectively; likewise, Jiménez *et al*. (2024) reports values of 5.37 and 5.25 at 30 and 45 days after the homogenization cut, these differences may be due to the fact that the evaluations of this experiment were in the process of adaptation of the plant (21 and 30 after installing the plots) while the evaluations carried out by the authors were already with old plantations of more than one year of installation (Navas and Montaña 2019; Canto *et al*., 2023; Jiménez *et al.*, 2024).

Additionally, management factors such as prior homogenization cuts, fertilization regimes, and plant age at the time of evaluation significantly influence vegetative development. In our case, the absence of homogenization and the early evaluation period likely limited shoot and leaf production.

Plant height was higher ($p \leq 0.05$) in *Tithonia diversifolia* grown in Cajaruro compared to plants grown in Chachapoyas at all stages of evaluation (Figure 2a). Plants in Cajaruro (235.83 cm) were about 2.6 times the size of plants from Chachapoyas (89.86 cm) at 120 days of evaluation.

Growth rate was higher in Cajaruro plants ($p \leq 0.05$) at all evaluation stages (Figure 2b). Cajaruro plants grew approximately 2.0 $cm \cdot day^{-1}$ on day 120 of the evaluation, showing nearly 2.6 times the growth rate of Chachapoyas plants (0.75 $cm \cdot day^{-1}$).

Plant height and growth rate were lower in the Chachapoyas environment, but in the Cajaruro environment they were higher than the results of Cabanilla *et al*. (2021) who achieved a plant height of 171 cm at 75 days post homogenization cut, also Jiménez *et al*. (2024) achieved a plant height at 45 days of 149.5 cm. However, Jiménez *et al*. (2024) achieved superior results with 4 meters of height at 90 days, in the same way Andrade *et al*. (2024) reports values of 289.5 cm of silver height at 70 days post homogenization cut, these studies mostly carried out soil fertilization and a homogenization cut, in addition to the different environments and the type of soil, in addition these differences can be attributed to the type of management and the season in which they were evaluated (Flores *et al*., 2019; Navas and Montaña 2019; Uu *et al*., 2022).

In our study, the greater plant height and growth rate observed in Cajaruro are likely due to a combination of favorable temperature, altitude, and potentially higher solar radiation, which can enhance photosynthetic activity and biomass accumulation. On the contrary, environmental stressors in Chachapoyas, such as lower temperatures and potentially lower nutrient availability, may have restricted growth. Additionally, the absence of fertilization and cutting management in our study further explains the modest growth responses compared to other research with more intensive agronomic practices.

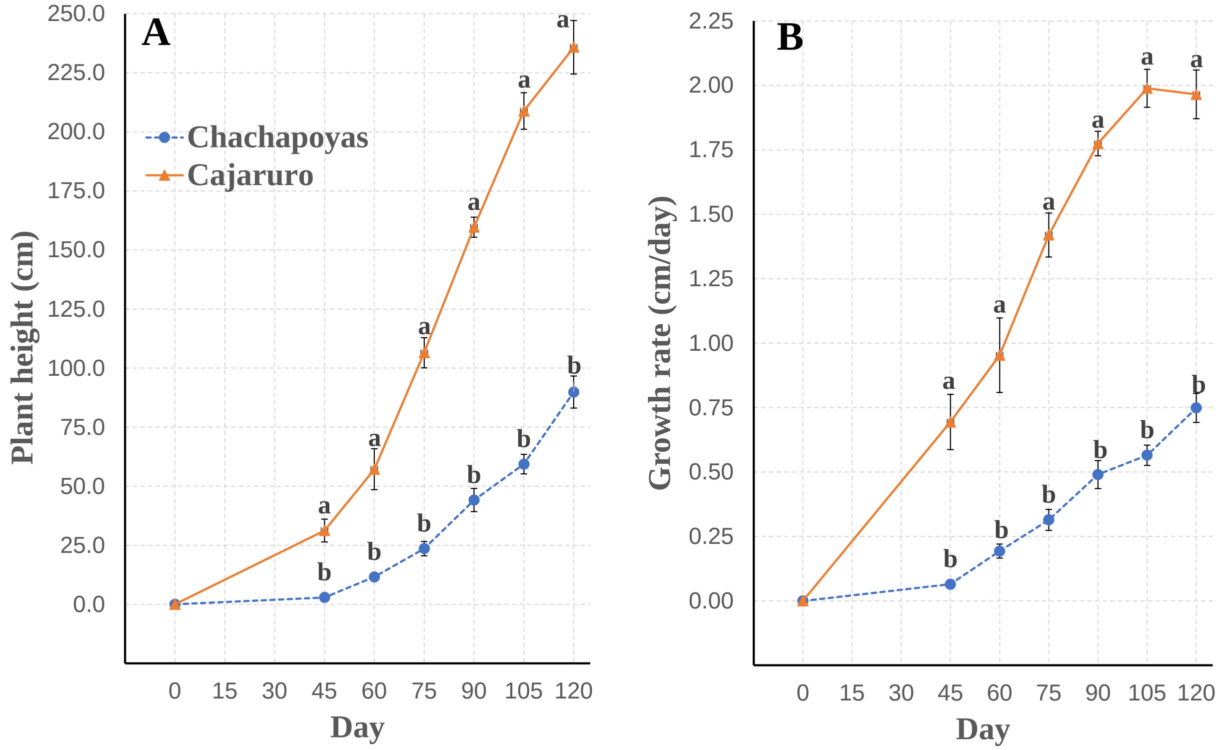

Figure 2. Evolution of *Tithonia diversifolia* plants during 120 days in different environments: A) Plant height; B) Growth rate. Values indicate the mean ± standard deviation (n=4). Different letters on each evaluation day indicate statistically significant differences according to Tukey's test ($p \leq 0.05$) for each environment.

These findings underscore the importance of local environmental and management factors in determining agronomic performance and suggest that site-specific recommendations are necessary for optimizing *T. diversifolia* productivity.

Nutritional value. Protein, mineral, carbohydrate, and crude energy contents were significantly influenced ($p \leq 0.05$) by the environments (Table 4); plants from Cajaruro had higher carbohydrate and crude energy contents, but lower protein and mineral contents compared to plants grown in Chachapoyas. In contrast, ether extract and crude fiber contents were similar across environments ($p > 0.05$). These differences may be related to the environmental and soil conditions of each site: Cajaruro has higher average temperatures (28±5 °C) and higher soil nutrient availability (N: 0.30 ppm, P: 10.81 ppm, K: 25.75 ppm), which could promote greater carbohydrate accumulation. In contrast, Chachapoyas, with cooler temperatures (22±3 °C) and lower nutrient levels (N: 0.08 ppm, P: 2.54 ppm, K: 99.76 ppm), may favor protein and mineral accumulation due to reduced dilution effects and possibly slower growth rates under milder conditions.

Regarding gross energy, significant differences were observed ($p \leq 0.05$), with higher values in Cajaruro (4256.28 kcal·kg^{-1}) and lower in Chachapoyas (3977.43 kcal·kg^{-1}), probably due to the greater accumulation of carbohydrates in Cajaruro plants, favored by higher temperatures and greater availability of nutrients in the soil.

Table 4. Nutritional characteristics of *Tithonia diversifolia* in different environments after 120 days of planting, in the Chachapoyas and Cajaruro districts

Characeristics	Environments		Significance
	Chachapoyas	Cajaruro	
Crude protein (%)	22.20[1]±2.06a	17.51±0.17b	*
Ether extrac (%)	2.88±0.06	3.17±0.40	
Crude fiber (%)	20.41±0.94	18.76±0.89	
Ash (%)	15.37±0.12a	13.17±0.23b	*
Nitrogen-free extract (%)	29.42±2.79b	40.57±1.59a	*
Gross energy (kcal·kg^{-1})	3977.43±62.23b	4265.28±57.45a	*

[1]/ Values indicate the mean ± standard deviation (n=3). Different letters in the same row indicate statistically significant differences according to Tukey's test (p≤0.05) for each environment. *: Significant at p≤0.05.

The results of crude protein content of *T. diversifolia* in this study were lower than those of Rivera *et al.* (2021) who reported values of 35.2 and 30.8 % for the rainy season and dry season respectively at 40 days of age; likewise Argüello *et al*. (2020) and Angulo *et al*. (2024) reports higher values with 25.4 % and 25.2 % of crude protein (CP) at 75 days of evaluation and 60 days respectively; however, Cabanilla *et al*. (2021), and Uu *et al*. (2022), they reported values ranging from 12.0 to 28.1 % CP depending on their cutting season, height and cutting age. However, other authors report lower values than those reported in this study, which vary from 3.6 % to 20 % of CP depending on the cutting age, type of fertilization, genetics and parts of the plant (Navas and Montaña 2019; Arias *et al*., 2023; Castaño *et al*., 2023; Jiménez *et al*., 2024). These differences may be attributed to multiple factors, including phenological stage at harvest, environmental stress conditions, nutrient availability, and ecotypic variations, all of which influence nitrogen metabolism and protein biosynthesis.

The ethereal extract content was similar to the Chachapoyas environment and lower in Cajaruro than reported by Ekeocha and Fakolade (2012) and Angulo *et al*. (2024) and lower than reported by Firsoni *et al*. (2022), Borrás *et al*. (2024), and Jiménez *et al*. (2024) who reported values higher than 4 %. Crude fiber values were higher than reported by Ekeocha and Fakolade, 2012 who reported an average of 21.80 %. The ash value was lower than the results obtained by Cabanilla *et al*. (2021) using the cuttings planting method and similar to those reported by Ekeocha and Fakolade (2012) lower in the evaluation of stems and flowers of *T. diversifolia*. The nitrogen-free extract was lower than that found by Ekeocha and Fakolade (2012) who reported values of 44.38 %. The gross energy was higher than that reported by Mahecha and Rosales (2005) and Aye (2016) who reported values of 3912 and 3940 kcal·kg^{-1} respectively. These variations can be explained by agroecological differences among study sites, harvest timing, soil fertility, and analytical methodologies used in each study, as well as intrinsic plant characteristics such as genotype and biomass partitioning. The results differ due to different factors such as plant parts, cutting age, rainy or dry cutting season (Guatusmal *et al*., 2020; Cabanilla *et al*., 2021; Borrás *et al*., 2024).

Highly significant positive correlations (p≤0.001) were established between plant height and dry matter, dry matter percentage, and growth rate (Figure 3); dry matter percentage also showed a strong correlation with dry matter (g). That is, larger plants exhibit higher values for their productive and agronomic characteristics. This reflects a coordinated physiological response in which vigorous vegetative growth is associated with increased biomass accumulation and resource use efficiency, particularly under favorable environmental conditions (Jones *et al*., 2017).

Regarding nutritional characteristics, positive relationships were observed between crude protein and minerals and crude fiber; in contrast, negative relationships were observed between crude protein content and ether extract, carbohydrates, and gross energy (Figure 3). Regarding nutritional characteristics, positive relationships were observed between crude protein and minerals and crude fiber; in contrast, negative relationships were observed between crude protein content and ether extract, carbohydrates, and gross energy

(Figure 3). These relationships likely reflect physiological trade-offs in nutrient allocation, where tissues richer in protein and fiber correspond to structural complexity, whereas higher carbohydrate and energy concentrations are associated with storage compounds (Sanaullah *et al*., 2014).

Positive correlations were observed between gross energy and carbohydrate content, but negative correlations were observed with mineral content. This pattern supports the principle that energy density in forages is driven primarily by carbohydrate concentration, while increased mineral content dilutes the caloric density, aligning with established biochemical mechanisms in forage science (Argüello *et al*., 2020).

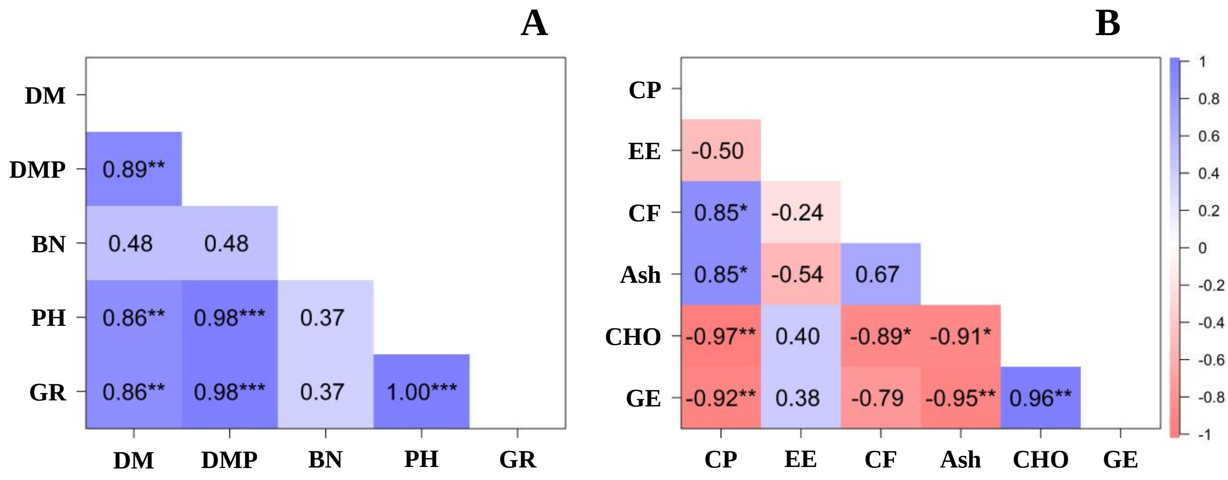

Figure 3. Correlation matrix A) between agronomic-morphologic characteristics, and B) between nutritive value characteristics of *Tithonia diversifolia* plants. Corr, Pearson correlations. Significant: * $p \le 0.05$, ** $p \le 0.01$, *** $p \le 0.001$. DM, dry matter; DMP, dry matter percentage; BN, number of blades; PH, plant height; GR, growth rate; CP, crude protein; EE, ether extract; CF, crude fiber; CHO, carbohydrates; GE, gross energy.

This research provides practical insights for the strategic cultivation and use of *T. diversifolia* in contrasting agroecological zones. The findings demonstrate that environmental conditions significantly affect agronomic performance and nutritional composition, highlighting the potential to optimize biomass yield and nutritional quality through site-specific management. In warmer, nutrient-rich environments like Cajaruro, higher dry matter production and energy content can be harnessed for improved biomass supply, while cooler, less fertile areas like Chachapoyas may favor protein and mineral accumulation, beneficial for forage. These results can guide decisions on site selection, cutting management, and integration into sustainable forage systems. Further studies are encouraged to assess seasonal effects, long-term productivity, and animal performance in feeding trials. It is proposed to incorporate *T. diversifolia* into diversified forage strategies tailored to local agroclimatic conditions to enhance livestock productivity and resource use efficiency.

CONCLUSION

The agronomic, morphological, and nutritional characteristics of *Tithonia diversifolia* varied greatly between the two study environments. It showed better results for most of the studied traits in Cajaruro. In this environment, the species exhibited superior performance in terms of bud burst, plant height, dry matter production, and growth rate, which are key indicators of biomass productivity. In contrast, plants grown in Chachapoyas showed higher crude protein and mineral contents, making them valuable for improving the nutritional quality of livestock diets.

These results are vitally important for decision-making regarding the installation of this species, as it demonstrates a wide range of adaptability and can be cultivated as a forage alternative across diverse agroecological zones.

Additionally, strong positive correlations were found between plant height, dry matter, and growth rate, confirming the agronomic potential of the species under favorable conditions. Negative correlations between protein and energy-related traits highlight important trade-offs that should be considered in forage management.

Therefore, this study supports the strategic use of *T. diversifolia* as a multifunctional forage crop, adaptable to both high- and low-altitude conditions, depending on the desired agronomic or nutritional outcomes.

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