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Effect of planting density on the agronomic performance and forage potential of *Vicia sativa* L. in the high Andes of Peru

Robert A. Quiñones[1], Tomas Samaniego[2], Samuel Hurtado[1] and Richard Solórzano[3,4*]

*Correspondence:
Richard Solórzano
investigacion_labsaf@inia.gob.pe
[1]Estación Experimental Agraria Donoso, Dirección de Servicios Estratégicos Agrarios, Instituto Nacional de Innovación Agraria (INIA), Carretera Chancay-Huaral km 5,6, 15200 Huaral, Perú
[2]Estación Experimental Agraria Pasco, Dirección de Servicios Estratégicos Agrarios, Instituto Nacional de Innovación Agraria (INIA), Carretera Vilcabamba – Lutacocha, 19730 Vilcabamba, Perú
[3]Centro Experimental La Molina, Dirección de Servicios Estratégicos Agrarios, Instituto Nacional de Innovación Agraria (INIA), Av. La Molina N° 1981, 15024 Lima, Perú
[4]Facultad de Ciencias Ambientales, Universidad Científica del Sur (UCSUR), 15024 Lima, Perú

Abstract
In the high Andean regions of Ancash, Peru, limited high-protein forage during dry seasons challenges livestock feeding. A locally adapted ecotype of common vetch (*Vicia sativa* L.) grows spontaneously and shows resilience to harsh conditions. This study evaluates its agro-morphological traits, forage and seed yields, and chemical composition to assess its potential as a sustainable forage resource for improving livestock nutrition in the region. This study was conducted using a completely randomized design with four plant spacing treatments: 10 cm, 20 cm, 30 cm, and 40 cm, maintaining a fixed row spacing of 30 cm. Seeds were collected from smallholder agricultural fields during the dry season. The highest plant densities, particularly 10 and 20 cm spacing, produced greater dry biomass. The forage biomass contained nitrogen (5.08%) and potassium (2.03%), with crude protein and crude fiber at 26.27 and 22.82%, respectively. Seed analysis revealed a crude protein content of 25.45%, corresponding to an estimated energy contribution from protein of 102 kcal. Based on these findings, *Vicia sativa L*. demonstrates strong potential as a forage crop and a viable alternative for smallholder farmers in the high Andean regions of Ancash, particularly during dry seasons, serving as an economical and accessible protein source for livestock feed.

Keywords Legume, Crude protein, Forage

1 Introduction

A significant challenge in animal feed production is ensuring the availability of high-nutritional-value forage during the dry season. This issue is particularly critical for small-scale livestock farmers in the high Andean region, where it serves as a key limiting factor in enhancing the production of milk, meat, and fiber, thereby limiting the potential for sustainable economic development [1]. Crude protein, a key indicator of nutritional quality [2], plays a vital role in supporting essential physiological functions in animal nutrition [3]. Protein supplements are among the most costly and restrictive components of animal diets [4].

In the high Andean region of Peru, the predominant forage species are grasses, including forage oats (*Avena sativa*), *Dactylis glomerata*, and *Lolium multiflorum*. However, these grasses lack the higher protein content characteristic of legumes, which benefit from biological nitrogen fixation [5]. The need for alternative protein sources in animal feed has become a critical and pressing challenge [6]. The common vetch (*Vicia sativa* L.), is an annual legume species with a global distribution [7] and is widely used as a protein source in livestock feed [8]. Its protein content ranges from 7.7 to 27.8%, dependin on maturity stage [9], making it a valuable option. Furthermore, common vetch holds significant potential as a solution to forage shortages during dry seasons, particularly in highland regions [10]. Common vetch is a crop well-suited to altitudes ranging from 3,000 to 4,200 m above sea level. It achieves growth heights of 0.60 to 1.2 m even under increasingly harsh conditions, including low temperatures and frost [11]. Common vetch serves a dual purpose, being used both as forage and for seed production; however, its potential as a protein source is limited by certain toxic compounds [12]. Previous studies have shown that incorporating common vetch seeds as a partial substitute in animal feed—up to 25%—could represent a viablealternative to soybean protein [13]. In addition to being used as livestock feed, it is an effective nitrogen-fixing crop, contributing 59.3 kg ha^{-1} of N from atmospheric sources [14]. It also functions as green manure, providing an equivalent of 80 kg ha^{-1} of N through crop rotation [15], offering a sustainable alternative to the excessive use of chemical fertilizers. Studies have reported that common vetch exhibits higher crude protein productivity per unit of applied nitrogen (5.75 kg kg^{-1} N) compared to 3.01 kg kg^{-1} N in *Medicago sativa* [16].

In the face of increasing climatic pressures, a key challenge for sustainable agriculture is identifying promising wild species and management practices that enhance yield and quality [17]. The identification of common vetch populations growing naturally in the study area, and subsequently collected from local farmers, provides an opportunity to explore their potential for agricultural use. These populations may be considered as locally adapted or naturalized materials rather than strictly wild forms. However, the agronomic performance of these populations remains largely unknown, particularly regarding key traits such as growth characteristics, chemical composition, and seed quality. Understanding agronomic factors like planting density is essential when assessing the cultivation potential of such underutilized genetic resources, as these parameters strongly influence plant development, competition for resources, and ultimately yield and quality [18–21]. Determining the appropriate sowing density is therefore a critical step toward the productive domestication and efficient management of these species. Studies such as that of Grela et al. [22]., who investigated the nutritional composition and morphological and genotypic variability of 44 European accessions, highlight the importance of identifying differences among wild common vetch populations. In Latin America, significant research has been carried out, particularly in Argentina, on *Vicia villosa* Roth, including studies on the genetic diversity of local ecotypes compared with European ecotypes [23], and on seed production under different environmental conditions [21]. In Ecuador and Peru, research has focused on the association of *Vicia* species with crops such as rye (*Secale cereale* L.) [24] and quinoa (*Chenopodium quinoa* Willd.) [25, 26]. In particular, determining the optimal planting density of *Vicia sativa* L. has been addressed in a few key studies conducted in Australia [27] and Romania [28], which reported interesting results regarding seed and dry biomass production, among other parameters. Furthermore, research has examined the effects of planting density on soil fertility when *Vicia sativa* is used as green manure [29], as well as the influence of this factor in intercropping systems, such as with wheat [30]. This study hypothesized that sowing density significantly affects the agronomic performance and seed yield of *Vicia sativa* under Andean conditions, as observed in Huanchac, located in the Huari district of the Ancash region, Peru. Therefore, the objective of this study was to evaluate the effect of different sowing densities, manipulated through plant spacing, on the morphological traits, chemical composition, forage and seed yield, and protein content of a wild common vetch population.

2 Materials and methods

2.1 Common vetch seed collection

Seeds of *Vicia sativa* L. were collected from the agricultural fields of small-scale farmers in the town of Huanchac, located in the Huari district of the Ancash region, between August and October 2023. Seeds that exhibited uniform size and shape, without visible damage or defects, and were free from diseases were selected based on visual assessment. Germination trials were conducted in trays, followed by sowing in the experimental field. Once the plants reached the blooming stage, samples were sent to the Herbarium of the Department of Biology, Faculty of Sciences, Universidad Nacional Agraria La Molina (Lima, Peru) for taxonomic identification. The species was identified as *Vicia sativa* L. by Arturo Granda Paucar, Research Associate at the Herbarium of the Department of Biology, Faculty of Sciences, Universidad Nacional Agraria La Molina. This identification was supported by the taxonomic determination certificate No. 001-2024-HM-UNALM.

2.2 Experimental site location

The experimental plot was established in the Ancash region, province, and district of Huari, at an elevation of 3156 meters, with geographic coordinates of 9°21’49.59” S latitude and 77°9’57.45” W longitude (Fig. 1). The soil physicochemical properties were characterized using standard analytical methods. Soil pH was determined following USEPA Method 9045D [31], yielding a neutral value (pH 7.2). Electrical conductivity was measured according to ISO 11265:1994 [32], with a value of 522.15 mS m^{-1}, indicating slight salinity. Total carbonate content ($CaCO_3$) was determined by titration following NOM-021-RECNAT-2000 [33], resulting in 0.8%. Soil orgnic matter was analyzed using the Walkley and Black method according to [33], with a low content of 0.95%. Available phsphorus was determined by the Olsen method [33], with a medium content of 9.5 mg kg^{-1}, while available potassium, also determined according to [34] showed a high value of 920.23 mg kg^{-1}.

The climatic conditions observed during the study are illustrated in Fig. 2. Rainfall varied significantly, ranging from a minimum of 7.2 mm in May to a maximum of 116 mm in January and 114 mm in March. These months were also characterized by high relative humidity levels, recorded at 74.52% in January and 75.71% in March. Throughout the study period, temperatures fluctuated between a minimum of 8 °C and a maximum of 21 °C. In total, the accumulated rainfall reached 603 mm, with an average temperature of 13.35 °C (Chavín Station 2023–2024, SENAMHI/DRD).

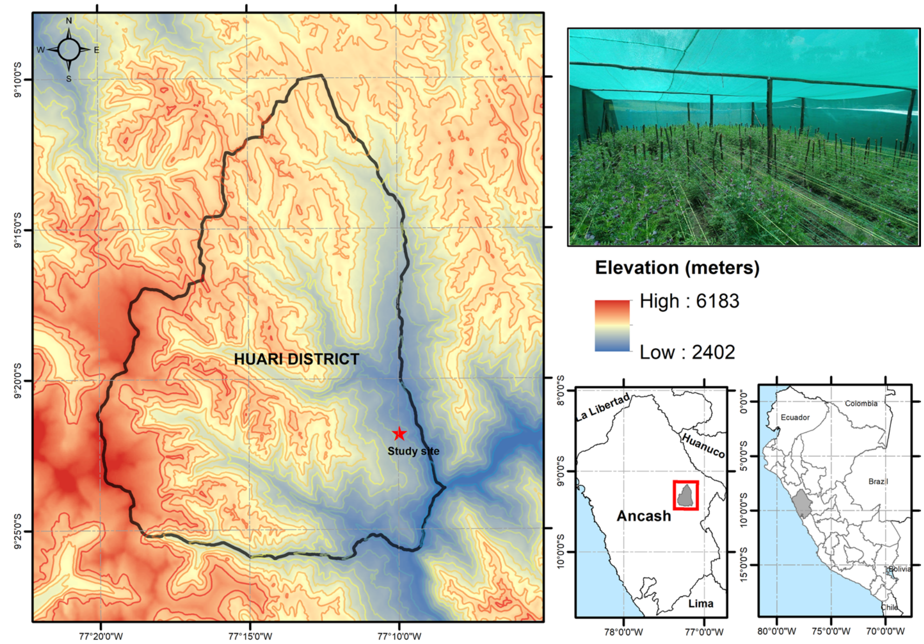

Fig. 1 The experimental plot was located in the high Andean valley of the district and province of Huari, Ancash, Peru

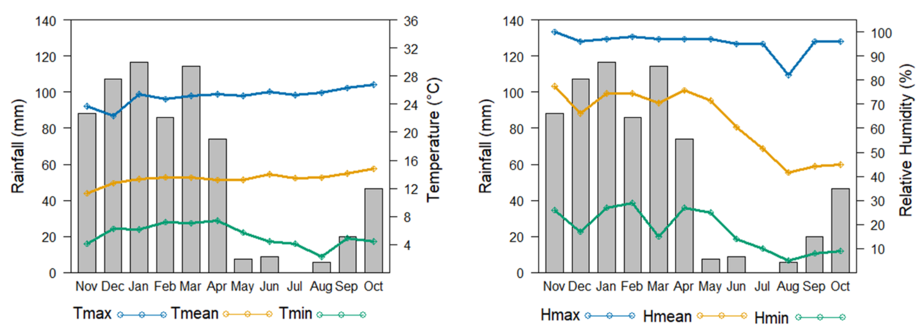

Fig. 2 Meteorological conditions during the study period (November 2022 to October 2023). Tmax: Maximum temperature; Tmean: Mean temperature; Tmin: Minimum temperature; Hmax: Maximun relative humidity; Hmean: Mean humidity; Hmin: Minimum humidity

2.3 Experimental design

The experiment was conducted using a completely randomized design with four treatments based on plant spacing, through which planting density was manipulated: 10 cm (T1), 20 cm (T2), 30 cm (T3), and 40 cm (T4), corresponding to approximately 33.3, 16.7, 11.1, and 8.3 plants m^{-2}, respectively. The experimental site was relatively homogeneous in terms of soil, relief, and climatic conditions, which justified the use of a completely randomized design. Each treatment included three replicates, with experimental units measuring 0.90 m by 6 m, consisting of three furrows spaced 30 cm apart. Throughout the study, standard agronomic practices, such as weeding, staking, and pest and disease control, were consistently applied across all treatments. The crop was grown under rainfed conditions; no fertilization was applied. Anthracnose (*Colletotrichum spp.*) was managed with a single application of a tebuconazole-based fungicide (0.1 mL per 100 mL of water), applied at the onset of the first visible disease symptoms during the vegetative growth stage. Additionally, physical barriers (a plastic shelter) were installed to reduce pest incidence and prevent interference from grazing animals, which are common in the study area.

The biometric and yield parameters were evaluated at different stages of plant growth. At 105 days after sowing (DAS), five plants were randomly selected from each experimental unit (plot) as subsamples at 50% blooming to estimate biomass yield (both fresh and dry). Plant height (cm) was measured from the base to the apex of the plant, stem base diameter (mm) and stem diameter at the middle third were measured using a digital caliper, and the number of branches within the first 5 cm of the stem base was manually counted. At 214 DAS, grain yield and its components were assessed using ten plants per experimental unit, following an adapted methodology from ref. [10]. The evaluated parameters included pods per plant, seeds per pod, number of seeds per plant, seed weight per plant, and 100-seed weight. All seed weight measurements were determined using seeds at constant weight. The dry biomass collected at 105 DAS was utilized for the analysis of micro- and macronutrient content and for the proximate analysis of the aerial biomass. The collected samples were washed and dried in an oven for 48 h at 70 °C [35]. A representative portion of the dried leaf litter samples was ground into powder using a leaf shredder and passed through a 0.5 mm sieve. P, K, Fe, Cu, Zn, and Cd contents were quantified by inductively coupled plasma optical emission spectroscopy (ICP-OES, iCAP Series 7000, Thermo Scientific) at a certified laboratory of the National Institute for Agricultural Innovation (INIA), Lima, Peru, following standard analytical procedures. The N contents of the ground samples were determined using an autoanalyzer (LECO CN828, LECO Corporation) at the central laboratory of the National Institute for Agricultural Innovation (INIA), Lima, Peru, following ISO 13,878 [36], adapted by the laboratory for the analysis of plant tissue samples. Proximate analysis of seeds was conducted on samples collected at harvest (214 DAS). The samples were submitted to the Food Analysis Laboratory (LAA) at the Nutritional Research Institute of Peru for evaluation, following standard methods including AOAC [37] for moisture (930.04), ash (930.05), crude fats (930.09), and crude protein (2001.11), as well as AOCS (BA 6–84) for crude fiber determination. Carbohydrate content was estimated by difference as part of the proximate analysis, considering moisture, ash, protein, fat, and fiber fractions. Caloric values derived from protein, fat, and carbohydrates were obtained from the LAA, based on the conversion factors reported in the Peruvian Food Composition Table [38].

2.4 Statistical analysis

The data collected from biometric parameters and chemical analyses were subjected to statistical analysis using analysis of variance (ANOVA). Before this, the assumptions of homogeneity of variances (Bartlett test) and normality (Shapiro-Wilk test) were verified. Subsequently, a Tukey post hoc test was performed for mean comparisons at a significance level of $\alpha = 0.05$. All analyses were conducted using the open-source software RStudio, version 4.4.1.

3 Results

The results were organized into four sections, progressing logically from plant growth and morphological traits to nutritional quality and yield performance, to provide an integrated understanding of the agronomic potential of common vetch.

3.1 Biometric characteristics of forage

The analysis of plant height at blooming (105 DAS) and at harvest (214 DAS) revealed notable differences across planting densities. At blooming, the highest planting density (T1: 10 cm spacing between plants) recorded the greatest average height (75.0 ± 7.6 cm), whereas the lowest value was observed in T3 (30 cm spacing), with 50.0 ± 9.0 cm. This represents an increase of approximately 33% in plant height at the highest planting density. However, no statistical differences were found among T1, T2, and T4 heights (Fig. 4a). The model explained 65% of the total variability ($p = 0.03$, $R^2 = 0.65$), suggesting that planting density contributed moderately to plant height. The trend continued until harvest ($p = 0.01$, $R^2 = 0.71$), with T2 and T1 maintaining greater height than T3, showing a consistent difference of about 30% among treatments (Fig. 4b). Significant differences were found in the number of branches ($p = 0.01$ and $R^2 = 0.72$; Fig. 4g), with treatment T1 showing the lowest branching capacity. Similarly, the lowest stem base diameter was recorded in T1 (2.75 ± 0.49 mm) compared to the other treatments (Fig. 4c). In contrast, stem diameter values ranged from 2.05 to 2.29 mm across treatments, with no significant differences observed (Fig. 4d).

Regarding biomass production, treatment T1 achieved the highest fresh biomass yield, significantly surpassing the other treatments ($p = 0.0007$ and $R^2 = 0.86$). Specifically, T1 produced 90, 172, and 239% more than T2, T3, and T4, respectively (see Fig. 4e). In terms of dry biomass production, similar results were observed ($p = 0.0002$ and R^2 = 0.90), with treatments T1 and T2 showing higher values than T3 and T4. Dry biomass ranged from approximately 69 and 59 g m^{-2} in T1 and T2, respectively, to about 23–25 g m^{-2} in T3 and T4, representing increases of 133 to 195% (Fig. 4f).

3.2 Nutrient concentration in forage

In the evaluation of macronutrient content in the aerial parts of the plant at 50% blooming (105 DAS). The highest N levels were observed in treatment T1 (5.1 ± 0.3%) and T2 (4.8 ± 0.2%), which were greater compared to T3 (3.9 ± 0.4%) and T4 (3.7 ± 0.3%). The model explained a substantial proportion of the total variability ($R^2 = 0.84$) and revealed a statistically significant effect of planting density on N concentration ($p = 0.001$). Notably, N concentration in T1 and T2 exhibited increases of 37 and 30%, respectively, compared to T4 (Fig. 5a). No statistical differences were identified among treatments for P content, with values ranging between 0.32 and 0.45% (Fig. 5b). In contrast, for K, treatment T1 (2.0 ± 0.2%) showed significantly higher levels compared to the other treatments, particularly T2 (1.5 ± 0.2%) and T3 (1.5 ± 0.1%) ($p = 0.02$, $R^2 = 0.67$). This difference represents roughly a 30% higher K concentration in T1. An inverse trend was observed for Ca and Mg, with T1 showing the lowest concentrations (1.3 ± 0.1% for Ca and 0.35 ± 0.02% for Mg). In contrast, T3 recorded the highest levels (1.8 ± 0.1% and 0.48 ± 0.05%, respectively), representing approximately 35–40% higher Ca and Mg contents compared to T1.

Regarding the micronutrient content, no significant differences were found in the levels of Fe ($p = 0.15$ and $R^2 = 0.46$), Cu ($p = 0.13$ and $R^2 = 0.50$), and Mn ($p = 0.85$ and $R^2 = 0.08$) based on the Tukey test. The lowest concentrations of Fe were recorded in treatments T1 (892 ± 65 mg kg^{-1}) and T4 (793 ± 254 mg kg^{-1}). Similarly, the lowest values for Mn were observed in T1 (194 ± 29 mg kg^{-1}) and T4 (196 ± 84 mg kg^{-1}). Significant differences were observed for Zn content ($p = 0.04$, $R^2 = 0.64$), with T3 (73 ± 12 mg kg^{-1})

showing the highest value, approximately 39% higher than T1 (52 ± 4 mg kg^{-1}). These findings indicate that T1 demonstrated slightly higher macronutrient levels, except for Ca and Mg, while T3 showed superior micronutrient concentrations, excluding Cu, as illustrated in Fig. 5.

In the proximate composition analysis of aerial biomass, crude protein content was highest in treatments T1 (26.3 ± 1.1%) and T2 (25.0 ± 1.1%), while T3 showed the lowest value (20.2 ± 1.8%). This represents an increase of approximately 30% in T1 and 24% in T2 compared to T3. The model explained 84% of the total variability (R^2 = 0.84) and indicated a highly significant effect of planting density on crude protein content (p = 0.001). Conversely, crude fiber content was lowest in T2 (20.4 ± 1.2%) and highest in T1 (22.8 ± 0.7%), showing a 12% increase in T1 compared to T2, with significant differences among treatments (p = 0.02, R^2 = 0.67). Regarding crude fat content, T1 (1.27 ± 0.03%), T3 (1.27 ± 0.02%), and T2 (1.26 ± 0.01%) exhibited higher values compared to T4 (1.16 ± 0.05%), representing an increase of approximately 9% in crude fat content in the denser planting treatments. These differences were confirmed by Tukey's test (p = 0.01, R^2 = 0.73) (Fig. 6).

3.3 Yield variables

At 214 DAS, no significant differences were detected in grain yield (p = 0.20, R^2 = 0.42), number of seeds per pod (p = 0.57, R^2 = 0.22), or seed weight per plant (p = 0.06, R^2 = 0.58) (Fig. 7). Treatment T1 showed the highest mean yield (1847 ± 453 kg ha^{-1}), despite having the lowest number of pods per plant (45 ± 28). In contrast, T4 recorded the highest number of pods per plant (105 ± 35), with a lower mean yield (1206 ± 519 kg ha^{-1}). The number of seeds per pod remained consistent across treatments, ranging from 6.8 to 7.1. Similarly, seed weight per plant exhibited no statistical differences, although greater variability was observed among treatments (Fig. 7d). Regarding the 100-seed weight, T1 (6.1 ± 0.3 g) and T2 (6.2 ± 0.2 g) exhibited the highest values, showing significant differences (p = 0.002, R^2 = 0.81) compared to T4 (5.7 ± 0.2 g). This difference represents an increase of approximately 8–9% in seed weight under higher planting densities. However, T1 recorded the lowest number of seeds per plant (260 ± 75), which differed by 121% from T4 (574 ± 83), the treatment with the highest value (p = 0.03, R^2 = 0.64). Regarding the length of the productive branch, T2 and T1 recorded the highest values, measuring 179 ± 25 cm and 150 ± 22 cm, respectively, with significant differences (p = 0.00009, R^2 = 0.44) compared to T3 (114 ± 18 cm). The productive branches in T2 were approximately 57% longer than those in T3, while those in T4 (145 ± 28 cm) were 27% longer, underscoring the marked influence of planting density on vegetative growth.

3.4 Proximate analysis of the seed

According to the Tukey test, no significant differences were observed among treatments for moisture, ash, crude fat, and crude fiber content (α = 0.05). Moisture content ranged from 11.6 to 12.7%, while ash content varied between 3.58 and 3.79%. Similarly, crude fat content was recorded between 0.89 and 1.27%, whereas crude fiber content ranged from 3.65 to 4.75% (Fig. 8).

Significant differences (p = 0.004, R^2 = 0.79) were observed among treatments in seed crude protein content, expressed on a dry biomass basis, with T1 and T2 showing the highest values (25.5 ± 1.4 and 26.0 ± 0.6%, respectively), while T3 recorded the lowest (21.8 ± 1.2%). Crude protein levels in T1 and T2 were approximately 17–19% higher than in T3. Similarly, for protein-derived caloric content, treatments T2 (104 ± 2 Kcal·100 g^{-1}) and T1 (102 ± 5 Kcal·100 g^{-1}) exhibited higher values compared to the other treatments, particularly T3 (87 ± 5 Kcal·100 g^{-1}) ($p = 0.003$, $R^2 = 0.80$). The caloric content in T1 and T2 was approximately 17–19% greater than in T3. Regarding carbohydrate content, treatments T3 and T4 recorded significantly higher values (62.2 ± 1.9 and 61.9 ± 1.2%, respectively) compared with T1 and T2, which ranged between 57.6 and 57.8% ($p = 0.002$, $R^2 = 0.81$) The carbohydrate content in T3 and T4 was approximately 7–8% higher than in the higher-density treatments. A similar trend was observed for carbohydrate-derived caloric content, where T3 and T4 recorded 249 ± 8 Kcal·100 g^{-1} and 248 ± 5 Kcal·100 g^{-1}, respectively, whereas T1 and T2 obtained values ranging from 230 to 231 Kcal·100 g^{-1} ($p = 0.003$, $R^2 = 0.80$). Regarding caloric content from fats, treatment T4 (10.0 ± 1.0 Kcal·100 g^{-1}) showed the highest value, which was significantly greater than that of T2 (7.0 ± 1.0 Kcal·100 g^{-1}) ($p = 0.01$, $R^2 = 0.70$). Certain variables, such as moisture content, crude protein content, and protein-derived caloric value, demonstrated superior performance in treatments T1 and T2, whereas treatments T3 and T4 yielded the highest values for other parameters (Fig. 8).

4 Discussion

The results demonstrate that planting density markedly influences the morphological development of common vetch, which subsequently influences its nutritional composition, proximate parameters, and seed yield. However, some evaluated parameters, such as stem base diameter, number of branches, Fe, Mn, and grain yield, did not show statistically significant differences despite apparent differences in mean values. Such variability may be associated with the use of a wild ecotype, where traits are not fully homogenized. Wild and domesticated forms occupy distinct phenotypic spaces, with greater variation typically observed in non-domesticated populations [39].

Variations in plant spacing altered key growth traits such as height, branching, and biomass accumulation—factors that directly modulate the plant's capacity to intercept light, assimilate nutrients, and allocate energy to reproductive structures. Consequently, morphological adjustments driven by density played a central role in explaining the observed differences in both forage quality and seed productivity. Specifically, a spacing of 10 cm between plants resulted in increased plant height at both blooming and harvest, along with higher yields of fresh and dry biomass.

The seeding density of common vetch has been widely studied, with varying results depending on production objectives. Several authors have reported that high seeding densities enhance dry biomass production [30, 40]. Seymour et al. [27]. identified an optimal density of 40 plants m^{-2} for maximizing seed production, while lower densities favored dry biomass accumulation. Similarly, Tigka et al. [29]. evaluated the suitability of *Vicia sativa* L. as green manure and concluded that densities around 280 plants m^{-2} were optimal for improving soil fertility.

However, Karagić et al. [28]. reported that establishing *Vicia sativa* L. in widely spaced rows (50 plants m^{-2}) led to better morphological development, promoting a higher number of branches and pods, as well as an increase in the weight of 1000 seeds. Although this metric differs from that used in the present study, both reflect seed mass and show comparable responses to planting density. Similarly, in the present study, lower sowing

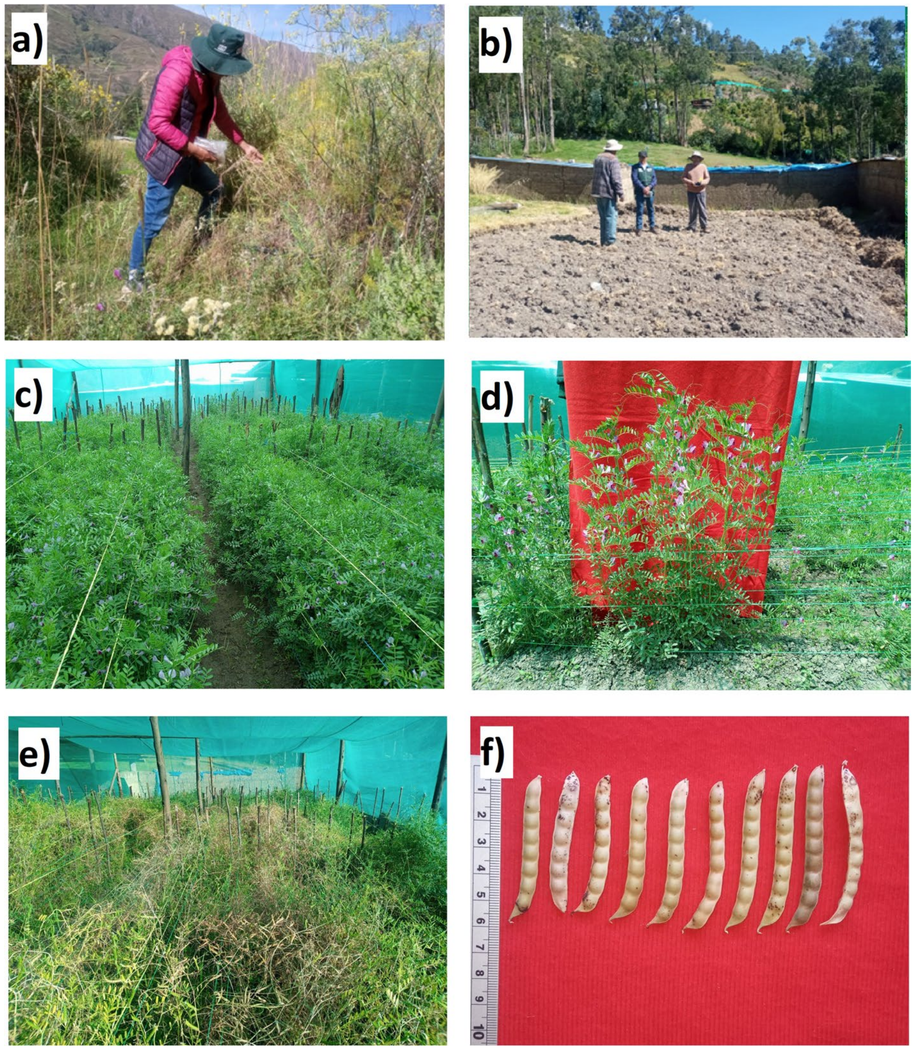

Fig. 3 **a** Seed collection; **b** preparation of experimental plots; **c** vegetative growth of common vetch; **d** measurement of biometric variables; **e** experimental plot prepared for harvest; **f** assessment of harvest parameters

densities promoted a higher number of branches per plant. However, in contrast, higher sowing densities resulted in greater biomass production. In this context, more plants per unit area led to partial shading, promoting elongated shoots and expanded leaf area [41]. Different species exhibit adaptive mechanisms to deal with high planting densities by modifying branch number, length, and arrangement (branch plasticity) to maintain high yields despite variations in density [22, 42].

The fresh biomass yield ranged from 1200 to 4130 kg ha^{-1}, while the dry biomass yield varied between 235 and 695 kg ha^{-1}, as evaluated at 105 DAS. Several studies have reported a wide range of biomass production for common vetch. For instance, Sánchez et al. [43]. documented values ranging from 493 to 20,562 kg ha^{-1} for fresh biomass, while dry biomass ranged from 14 to 3796 kg ha^{-1} at 47 and 103 DAS, respectively, under a fertilization regime of 60–60 for N and P. Similarly, Li et al. [44]. reported fresh biomass yields between 210 and 1531 kg ha^{-1} when evaluating different cutting models. In the present study, no fertilization was applied, which may explain the lower biomass values compared to fertilized systems. Environmental conditions, soil nutrient availability, and crop genetics strongly influence these variations [10, 21, 45], particularly under high

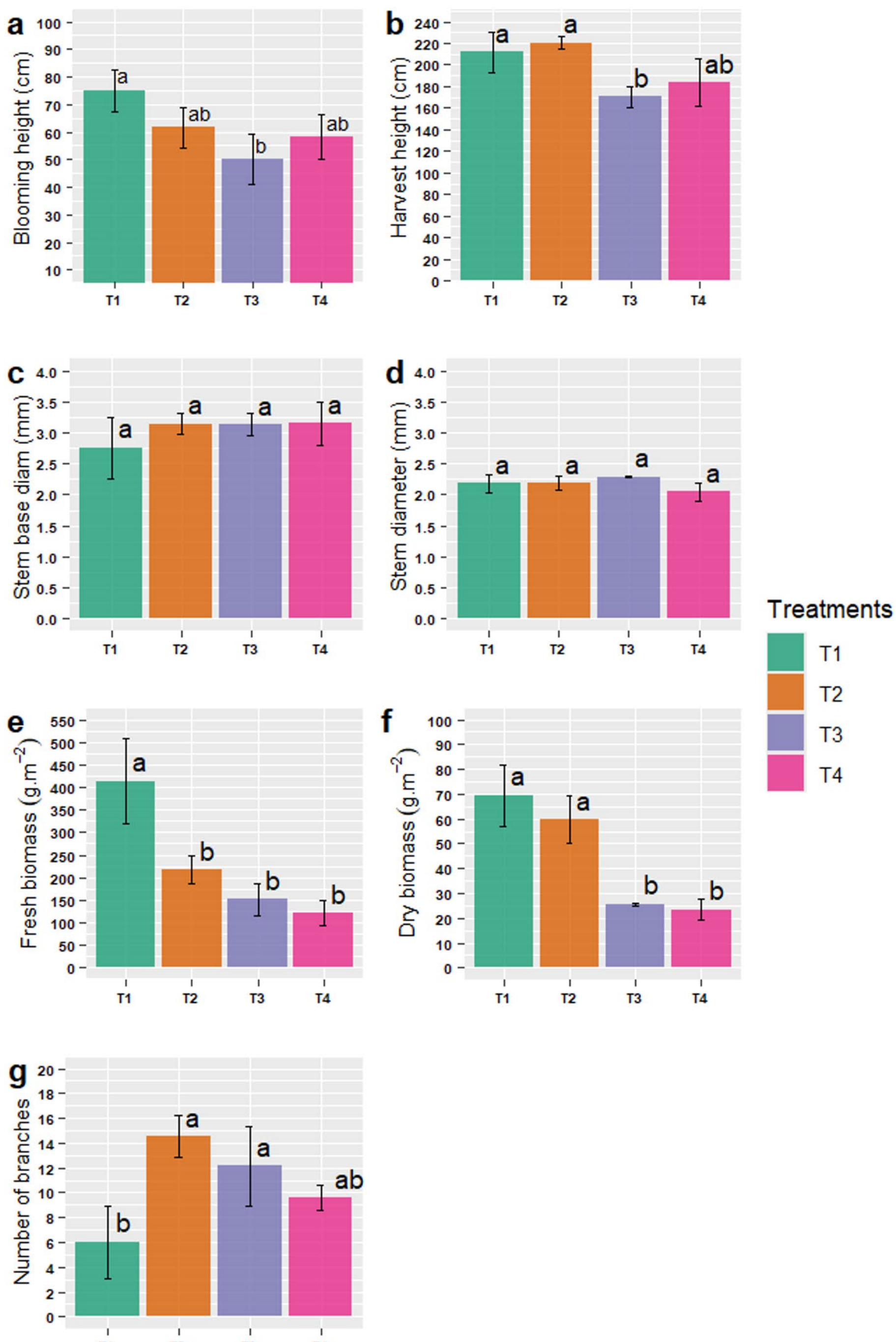

Fig. 4 Agromorphological characteristics of forage across treatments T1, T2, T3, and T4, correspond to planting spacings of 10, 20, 30, and 40 cm between plants in the *Vicia sativa* L. crop. (**a**) Bloming height, (**b**) Harvest height, (**c**) Stem base diameter, (**d**) stem diameter, (**e**) Fresh biomass, (**f**) Dry biomass, and (**g**) Number of branches. Different letters above the bars indicate statistical differences according to the Tukey test (α = 0.05), and the vertical line segments on each bar represent the standard deviation

Andean production systems, where low temperatures, limited soil fertility, and rainfed conditions can constrain crop growth and biomass accumulation [46, 47].

Changes in plant architecture also influenced nutrient accumulation in the forage. Lower density was associated with higher concentrations of Ca, Mg, and Zn, whereas a decline in N and K levels was observed. These trends differ from Baligar et al. [48].,

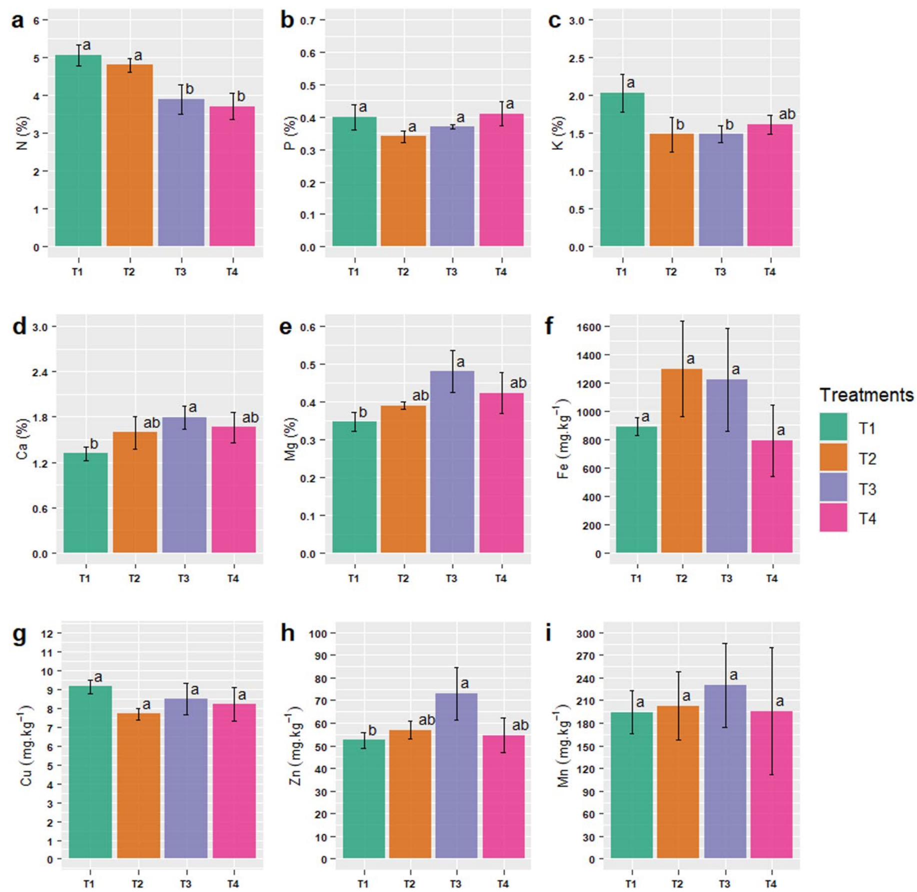

Fig. 5 The concentrations of macro- and micronutrients in the aerial parts of *Vicia sativa* L. at 105 DAS correspond to the blooming stage. T1, T2, T3, and T4 represent various planting spacing treatments. (**a**) N, (**b**) P, (**c**) K, (**d**) Ca, (**e**) Mg, (**f**) Fe, (**g**) Cu, (**h**) Zn, and (**i**) Mn. Different letters above the bars indicate statistical differences according to the Tukey test (α = 0.05), and the vertical line segments on each bar represent the standard deviation

who reported that reduced light availability negatively affects nutrient concentrations and protein content in legumes. In the present study, these differences may be explained by reduced interplant competition at lower densities, which can enhance root development and nutrient uptake, particularly for less mobile elements such as Ca and Mg. Conversely, the higher N and K concentrations observed at greater planting densities may reflect the increased physiological demand associated with enhanced biomass production under these conditions [49, 50]. The results obtained in this study align with nutrient concentration ranges reported in previous research on other Vicia species and forage legumes [51–53]. However, Fe and Mn concentrations were notably high, comparable to certain vetch cultivars [54], and approached toxicity thresholds for most crops [55]. These elevated levels may be associated with the inherent mineral composition of the soil and environmental conditions typical of high Andean systems, where soils may present relatively high concentrations of micronutrients such as Fe and Mn, which in the region can reach values (DTPA) of up to 340 and 170 mg kg^{-1}, respectively, even under near-neutral pH conditions [46]. From a nutritional perspective, although iron is an essential element for animal metabolism, excessive concentrations in forage may interfere with the absorption of other minerals or affect feed intake depending on consumption levels [56].

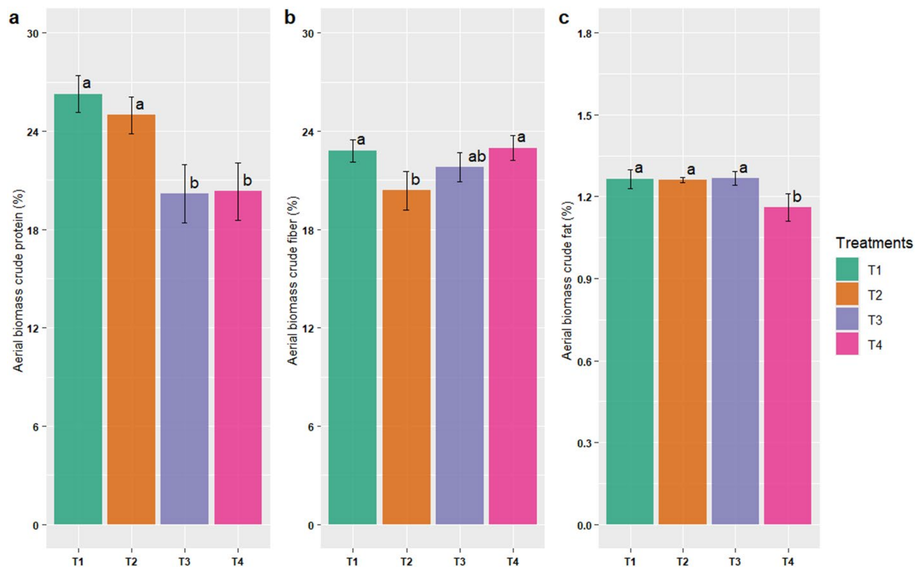

Fig. 6 Nutritional composition in the aerial biomass of *Vicia sativa* L. at 105 DAS, corresponding to different spacing treatments (T1, T2, T3, T4). (**a**) Aerial biomass crude protein, (**b**) Aerial biomass crude fiber, and (**c**) Aerial biomass crude fat. Different letters above the bars indicate statistical differences according to the Tukey test (α = 0.05), and the vertical line segments on each bar represent the standard deviation

Planting density also influenced the proximate composition of the forage. Higher sowing densities were associated with increased crude protein and crude fat content, consistent with the observed variation in N content (Fig. 5a), as nitrogen is a fundamental component of proteins [57]. This response may be explained by changes in plant competition and plant structure, where higher densities can enhance light interception and promote vegetative growth, leading to greater nitrogen assimilation and protein accumulation in plant tissues [58]. Protein levels in common vetch can fluctuate depending on the phenological stage [59], contributing to the broad variation in reported protein concentrations. For instance [44], documented protein content ranging from 15.07 to 20.86% in common veth, while Rahmati et al. [51]. reported an even wider range of 9.3 to 21.5%. These findings hghlight the potential of common vetch as a valuable component of livestock feed, offering a direct and accessible protein source compared to alternative supplements such as bone and fish meal [60].

Finally, these morphological and compositional responses translated into notable differences in seed yield and quality. Gwladys et al. [61]. suggest that planting density significantly impacts agronomic parameters, particularly yield. In the present study, higher densities resulted in greater yield per unit area, alongside an increase in seed weight (Fig. 7e). However, lower densities led to plants producing more seeds and higher seed weight per plant (Fig. 7d and f), although the increased plant population in denser plantings compensated for these characteristics. These findings are consistent with those reported by Kebede [10] for common vetch, where 100-seed weight ranged from 4.9 to 5.4 g, with a seed yield of 0.8 tons per hectare. Salehi et al. [62]. further noted that common vetch can reach up to 2 m in length while maintaining yields above 250 kg ha^{-1}, demonstrating its adaptability to high planting densities. Additionally, selecting genotypes with reduced branching capacity or implementing closer spacing could further optimize yield [63], as evidenced by Zhou et al. [8]., who reported seed yields of 402 kg ha^{-1}. These results highlight the importance of optimizing planting density as a practical strategy to

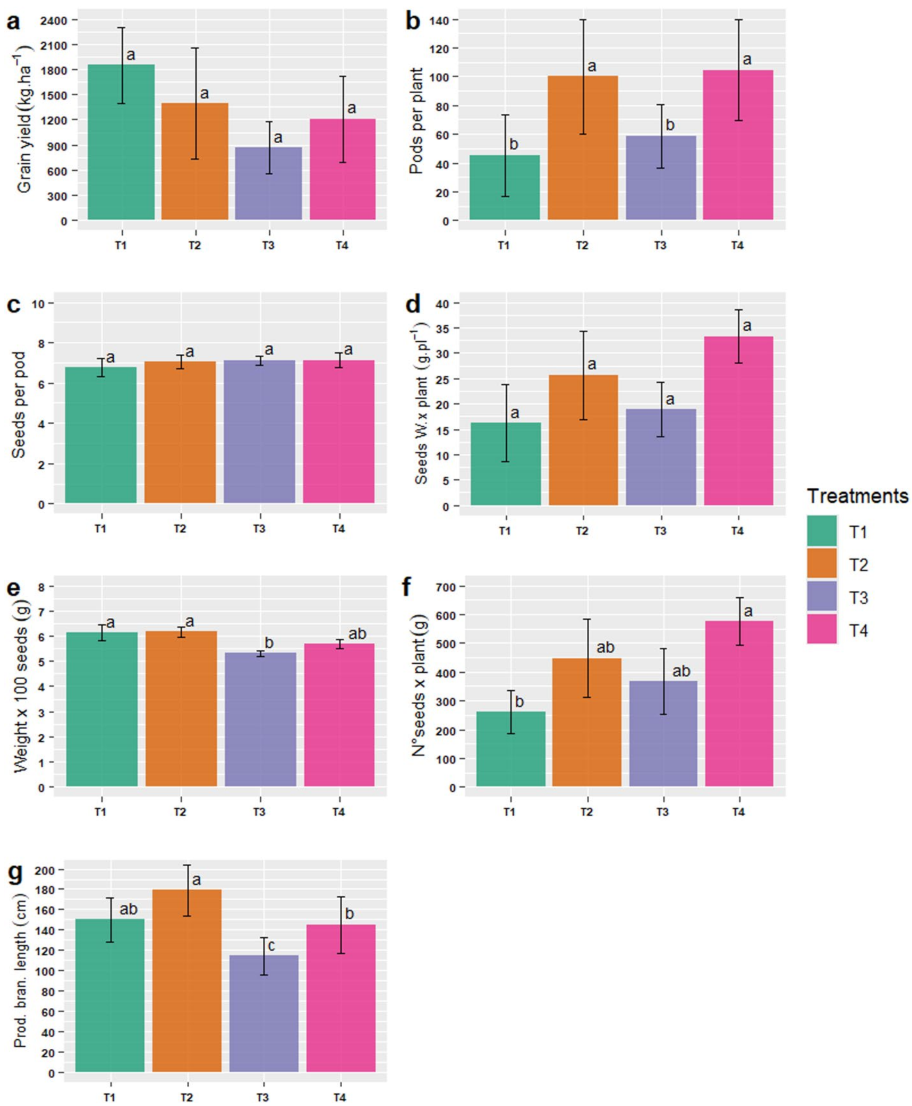

Fig. 7 Yield variables of *Vicia sativa* L. cultivation at physiological maturity (214 DAS), corresponding to planting spacing treatments T1, T2, T3, and T4. (**a**) Grain yield, (**b**) Pods per plant, (**c**) Seeds por pod, (**d**) Seeds weight per plant, (**e**) Weight per 100 seeds, (**f**) Number of seeds per plant, and (**g**) Productive branch length. Different letters above the bars indicate statistical differences according to the Tukey test ($\alpha = 0.05$), and the vertical line segments on each bar represent the standard deviation

maximize seed yield in high Andean production systems, particularly for local ecotypes for which agronomic management practices are not yet well defined.

Higher densities also resulted in seeds with increased moisture content, likely due to greater seed weight (Fig. 7e), which may contribute to slower moisture loss. Regarding crude protein content and its associated caloric value, the findings closely align with nitrogen content (Fig. 5a) and the proximate analysis of aerial biomass (Fig. 6a), suggesting efficient nutrient translocation to the seeds. This process is mainly driven by the remobilization of nitrogen and other nutrients from vegetative tissues to developing seeds through phloem transport during the grain filling stage [64, 65]. Under these conditions, a reduction in photoassimilate availability for seed filling may lead to lower accumulation of storage compounds such as lipids and carbohydrates. However, fat and carbohydrate levels declined under high sowing densities, likely due to increased

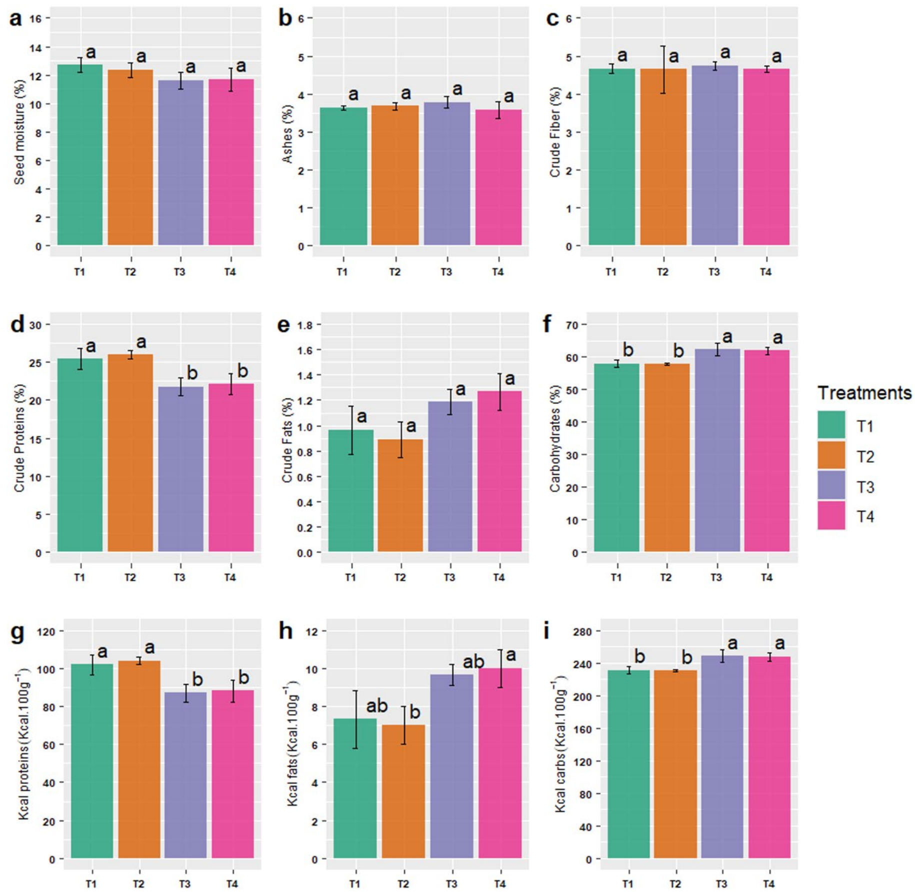

Fig. 8 Proximate composition analysis of *Vicia sativa* L. seeds across treatments, where T1, T2, T3, and T4 represent planting spacing treatments of 10, 20, 30, and 40 cm between plants, respectively. (**a**) Seed moisture, (**b**) Ashes, (**c**) Crude fiber, (**d**) Crude proteins, (**e**) Crude fats, (**f**) Carbohydrates, (**g**) Kcal proteins, (**h**) Kcal fats, and (**i**) Kcal carbohydrates. Different letters above the bars indicate statistical differences according to the Tukey test (α = 0.05), and the vertical line segments on each bar represent the standard deviation

interplant competition, which can limit photosynthetic efficiency and alter carbon allocation to reproductive organs [66, 67]. Overall, the observed trends are consistent with those reported in previous studies on vetch seeds [22, 68, 69]. These results highlight vetch seeds as a valuable feed option for livestock due to their high protein and mineral content, superior digestibility, and substantial energy value, making them particularly suitable for ruminant nutrition [70].

5 Conclusions

This study provides valuable insights into biomass yield for forage purposes, seed yield, and its components, as well as the proximate composition of common vetch forage and seeds. Specifically, it examines a particular ecotype adapted as a weed in agricultural fields of the high Andean regions of Ancash. The findings indicate that plant spacing significantly influences both forage and seed yield, with higher planting densities—particularly at 10 cm between plants and 30 cm between rows (approximately 333000 plants ha^{-1})—resulting in the highest fresh and dry biomass yields and favorable protein content. Therefore, this planting density may be considered as a suitable planting density to optimize productivity under high Andean conditions. This suggests a preliminary alternative to address the growing demand for high-protein forage. Additionally, the proximate analysis of the seeds revealed that this semi-wild ecotype is characterized by a high protein and caloric content, positioning it as a potential protein supplement for livestock feed. However, further studies are required, particularly concerning its toxicity levels, as limited reports exist on this aspect of the species.

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Author contributions
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Data availability
The data that support the findings of this study are available from the corresponding author upon request.

Declarations

Ethics approval and consent to participate
Permission to collect plant material was obtained from the farmers, and no specific governmental permits or licenses were required because the species occurs naturally in agricultural fields and is not classified as threatened or protected. The study complied with relevant local, national, and international guidelines for plant research; the species is not listed in the IUCN Red List and is not regulated under CITES. Informed consent was obtained from the individuals whose identifying images appear in Fig. 3 for publication of these materials.

Competing interests
The authors declare no competing interests.

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