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# Rye Production under Acid Soils and Drought Conditions: An Alternative for the Sustainability of High Andean Livestock Farming in Peru

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**Abstract:** The rye (*Secale cereale* L.) crop shows a high potential to contribute to the sustainability of high Andean livestock because it supports the agroclimatic conditions and acid soils in the Peruvian Andes. The production of green forage, hay, and grain from the rye crop in acid soils was studied with the use of different levels of phosphorus and potassium fertilization in four local rye ecotypes (CBI-001, CSM-001, CJS-001, and CCE-001). The green forage yield (GFY) ranged from 32.35 to 53.62 t ha$^{-1}$, dry matter from 6.05 to 8.56 t ha$^{-1}$, and hay from 7.0 to 10.36 t ha$^{-1}$; nutritional levels ranged from 9.02% to 13.56% protein and 6.50% to 7.75% ash levels, mainly with differences between ecotypes ($p < 0.05$). No differences existed between fertilization levels for the number of stems per plant, spikes per plant, and grains per ear ($p > 0.05$). Also, CBI-001 and CCE-001 were superior with 1868.4 and 1797.8 kg ha$^{-1}$ of grain, respectively ($p = 0.0072$); the use of 60 kg ha of nitrogen, 120 kg ha$^{-1}$ of $P_2O_5$, and 80 kg ha$^{-1}$ of $K_2O$ gave higher grain and residue yields. The high nutritional value and yield of the rye ecotypes studied in acid soil conditions and without irrigation can be an alternative for livestock feeding and grain production in the rainy season in the Andes as a dual-purpose crop.

**Keywords:** crop residues; animal feed; drought; *Secale cereale* L.; fertilization

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## 1. Introduction

Rye (*Secale cereale* L.) is a mainly European cereal; about 75% of the world's production is developed in Russia, Belarus, Poland, Germany, and Ukraine. It has an excellent overwintering capacity and the highest rate of tolerance to drought stress, saline soils, or soils with the presence of aluminum or so-called acids [1–3]. In addition, it is a crop with multiple uses, making it a valuable genetic resource due to its ability to produce high yields even when grown under stressful environmental conditions [4]. However, due to its genome's complexity and exogenous nature, rye remains poorly known in some South American regions [5,6]. In Peru, an average rye grain production of 61 tons was reported between 2017 and 2020 [7]; therefore, the local demand is not covered, leaving an agro-productive space of this genetic material for the highland area where climatic conditions are adverse [8] due to the importance that its production is intended for the manufacture of bread and in the growing demand for ethanol and biomethane production as a bioenergy source [9] because of its large amount of bioactive and nutritional components [10]. Also, rye straw is a multipurpose substrate for animal fodder and bedding material [11].

Cultivated rye has some fundamental agronomic traits, including crushing, grain yield, and disease resistance [5], and forage production in several cuts per sowing [12], indicating the potential as a dual-purpose crop [2,13], with a significant potential to fix atmospheric C, being a suitable option in agro-ecosystems under acidic pH soil conditions [14]. Likewise, ambient temperature is exceptionally influential on the grain yield of rye, while relative humidity is a secondary factor [15]; also, rainfall (mm) during the vegetation period influences grain yield ($R^2$ = 0.7370–0.9047), increasing from 3.0 to 6.4 kg ha$^{-1}$ per mm [16]. For forage production, rye yields from 31.7 to 47.6 t ha$^{-1}$, in dry matter biomass from 6.8 to 10.4 t ha$^{-1}$, and grain from 2.9 to 5.2 t ha$^{-1}$ under certain conditions, making it a very viable product for whole crop silage [17].

Soil fertility conditions are determinants for forage and grain yield of rye depending on the time of year, so nitrogen (N) application in spring increases the concentrations of N, phosphorus (P), and potassium (K) in forage biomass linearly. They should avoid N application in autumn to prevent environmental loss and decrease production costs [18]. In mono-culture, grain, yield stabilizes at 0.8 t ha$^{-1}$ without fertilization. However, it can be as high as 1.8–1.9 t ha$^{-1}$ when 60 N, 120 kg $P_2O_5$, and 120 kg $K_2O$ were added [16], but using NPK with micronutrients (Cu, Zn, Mn) applied separately or in combination increases grain yield from 0.98 t ha$^{-1}$ to 1.48 t ha$^{-1}$ [19]. By using 90 kg N ha$^{-1}$ and 40 kg sulfur S ha$^{-1}$, grain yields of 3.68 t ha$^{-1}$ and 3.23 t ha$^{-1}$, respectively, were achieved; it is considered that the addition of S at the rate of 40 kg ha$^{-1}$ enhances the effect of N [20]. Intensive fertilization technology can produce 6.67 to 7.0 t ha$^{-1}$ of grain with an efficiency of 55.6 to 58.3 kg grain per kg N [21] and can produce up to 10.53 t ha$^{-1}$ of grain yield and 8.44–14.66 t ha$^{-1}$ of forage biomass [22]. At the environmental level, rye, with a rate of 200 kg ha$^{-1}$ of N, minimizes the emission of $N_2O$ into the soil and water. It achieved yields of up to 13 t ha$^{-1}$ of hay and more than 1.8 t ha$^{-1}$ of protein, making it an alternative crop for arid regions [23].

The application of organic manures and/or in association with fertilizers considerably increases the yield and energy production of rye [24], and with the application of foliar fertilizers can reach up to 3.57 t ha$^{-1}$ applied at a dose of 8 L ha$^{-1}$ at the stage of formation of the first internode of the plant; in addition, grain yield correlates with the number of grains in the ear (r = 0.859, $p < 0.01$) and with the weight of a thousand grains (r = 0.914, $p < 0.01$) [25]. Associating it with maize can recover nitrogen and phosphorus levels by 51 and 47 respectively, and increase total forage production by 22 % of the rye [26,27]; on the other hand, rye associated with vetch can accumulate N in the soil and increase biomass productivity by 63% and 21% in vetch and rye mono-cultures, respectively [28]. Rye combined with soybeans results in better grain biomass yields and high carbon accumulation [29], it also promotes N conservation in the soil for the reduction of $NO_3$-N loss to water systems and erosion control [30].

In the highlands of Cajamarca, farmers grow rye as a reserve for livestock feed in times of drought and grain production as a dual-purpose crop, mainly in areas above 3000 ft. Therefore, the present research work was carried out to evaluate the productive yield of green forage and hay of four local rye ecotypes and determine the effect of phosphorus and potassium fertilization on grain yield and agronomic parameters of the crop for seed production in the highlands of Cajamarca.

## 2. Materials and Methods

### *2.1. Study Location*

The first experiment (EXP-1) was installed in the district of La Encañada, Cajamarca to evaluate the forage yield, its chemical composition, and the hay yield of rye. A randomized complete block design was used, blocking the slope of the land (15%–18%). The four ecotypes of rye and 04 blocks were considered in a total of 16 experimental units of 6 × 5 m each; this experiment ran for eight months, from December 2021 to August 2022, and in this period, 02 cuts were obtained. The second research experiment (EXP-02) was developed in the district of Namora, Cajamarca, under a block design with the factorial arrangement; the factors were: rye ecotypes and fertilization levels: T1: 60-30-20; T2: 60-60-40; T3: 60-90-60, and T4: 60-120-80 of NPK, respectively, with a total of 64 experimental units of 4.0 × 5.70 m for each one. The ecotypes used in both experiments were: ecotype I-Baños del Inca (CBI-001), ecotype II-San Miguel (CSM-001), ecotype III-José Sabogal (CJS-001), and ecotype IV-Huasmin-Celendín (CCE-001).

### *2.2. Genetic Material and Experimental Plots*

The rye ecotypes were collected in the field from farmers in four provinces in the southern part of the Cajamarca region (Figure 1); each genotype was then coded according to its place of origin. Each rye ecotype collected was evaluated for seed characteristics and taken to the national grass and forage program laboratory for germination and purity tests to determine the homogeneity of the ecotypes (Table 1). The particularity of each local ecotype is because they were obtained from the southern part of the Cajamarca region and are grown at higher altitudes in the highlands. Each genotype selected has been cultivated by the producers in the area for the last ten years. The seed was either from their reserve or their cultivars for the following season (related to the presence of rain). Therefore, it was considered that the ecotype chosen was local in each of the selected localities.

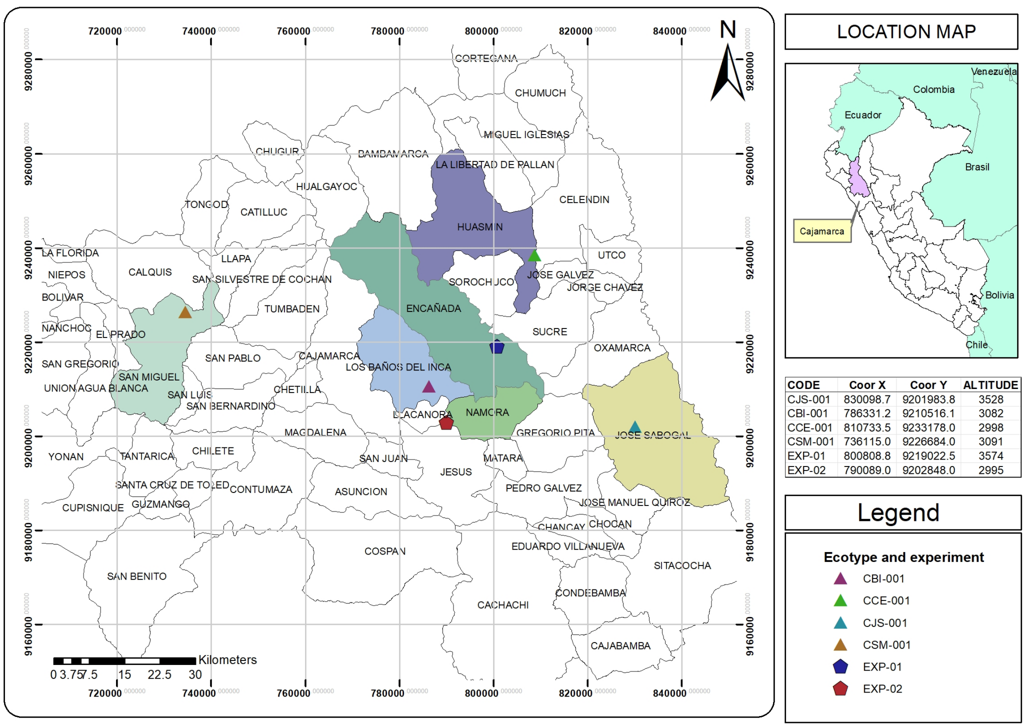


**Figure 1.** Place of origin of the ecotypes and the development of the experiments.

The plots of both experiments were sown using tractor tillage with two plow passes to homogenize the surface and desk compact the soil. The appropriate lines were drawn to carry out the correct installation of each experiment. In EXP-01, alleys of 1 m were left between treatments and 1.5 m between blocks. Moreover, in EXP-02, alleyways of 0.8 m were left between treatments and 1 m between blocks.

**Table 1.** Purity, germination, and sowing density of the four rye ecotypes.

| Ecotype | Germination (%) | Purity (%) | Sowing Density (kg ha$^{-1}$) |
|---|---|---|---|
| CBI-001 | 98.7 | 95 | 60 |
| CSM-001 | 96.3 | 96 | 60 |
| CJS-001 | 98.0 | 95 | 60 |
| CCE-001 | 98.7 | 97 | 60 |

### 2.3. Soil Characteristics and Fertilization

Analyses of pH [31], fertility, and the presence of aluminum [32] in the soil were carried out in the two experiments (Table 2). The pH and the presence of aluminum were considered for the application of calcium carbonate to alleviate crop stress by using aluminum with the adequate cation exchange capacity [33]; the quantities of nutrients used were according to the recommendations of the Laboratory of Soil, Water, and Fertilizers (LABSAF-INIA).

**Table 2.** Soil test results and fertilizer use recommendations.

| Soil Values | EXP-01 | EXP-02 |
|---|---|---|
| pH | 4.2 | 6.2 |
| Aluminum (mEq/100 g) | 0.1 | 0 |
| Organic Matter (%) | 12.71 | 1.23 |
| Phosphorus (ppm) | 47.7 | 15.63 |
| Potassium (ppm) | 190 | 290 |
| Recommended dose | | |
| Nitrogen (kg ha$^{-1}$) | 50 | 60 |
| $P_2O_5$ (kg ha$^{-1}$) | 20 | 70 |
| $K_2O$ (kg ha$^{-1}$) | 35 | 35 |
| CaO (t ha$^{-1}$) | 0.1 | 0.0 |

EXP-01: Experiment 01—fodder evaluation; EXP-02: Experiment 02—grain evaluation; pH: hydrogen potential; $P_2O_5$: diphosphorus pentaoxide; $K_2O$: potassium oxide; CaO: calcium oxide.

Urea, triple superphosphate, and potassium sulfate were used to cover the needs of nitrogen, phosphorus, and potassium, respectively. In EXP-01, the fertilizer doses were applied according to the recommendations in Table 2. For EXP-02, the amounts of nitrogen were the same for all treatments; however, the application doses of phosphorus and potassium were varied to analyze their effect on the grain production parameters. The amounts used were proportional to 50%, 100%, 150%, and 200% of the recommendation for both minerals. Due to the presence of aluminum (0.1 mEq/100 g), calcium oxide or agricultural lime has been added to EXP-01 to reduce the toxicity of this element.

### 2.4. Sampling and Parameter Evaluation

In EXP-01, data were taken on the growth and forage yield of the rye cultivar; the number of plants per square meter was determined at 25 days, and the number of tillers per square meter at 54 days was done with a quadrant of 1 m made with metal. Also, the plant height was evaluated at 81 days before cutting in centimeters, with a millimetric ruler of 1.5 m. The measurement of 10 plants was taken for each experimental unit, according to the evaluation recommendations [34]. Then, three forage samples of one square meter were obtained for each plot to obtain each treatment's green forage yield, dry matter percentage, and biomass yield.

Each 1 kg grass sample was taken the same day of cutting to the laboratory of the National Program of Pastures and Forages of the Experimental Station of Baños del Inca INIA, where the percentage of dry matter (DM) was analyzed according to AOAC 925.09 [35], crude protein (CP) using the Kjeldahl method AOAC, 928.08 [36], and neutral detergent fiber (NDF) using the methodology of AOAC 2002. For 04 [37,38], acid detergent fiber (ADF) using the AOAC methodology 973.18 described by [39], ethereal extract (EE) using AOAC 920.39 [40], nitrogen-free extract (NFE) using the AOAC method 923.03 [41], and ash using the AOAC method 942.05 [42,43]. Subsequently, one square meter per plot sample was obtained to conserve the leaf area as hay in the standing methodology. Under conservation with 0.2% urea [44], the yield and chemical composition were evaluated 25 days after production.

In EXP-02, morphological characters were evaluated, and primary phenological data were assessed at the recommended time. Vegetation duration and grain filling period were analyzed by monitoring crop development weekly. Plant height was measured at maturity before grain harvest from the ground to the ear, including edges similar to the recommendations [4]. At the same time, ear length, excluding borders, was examined. All measurements were performed on five plants from each of the 64 randomly selected experimental units. The number of grains per ear averaged 25 harvested and manually threshed ears. On the other hand, each plot was sampled in three square meter samples for each experimental unit to determine the total yield, grain yield, and straw yield.

### *2.5. Statistical Analysis*

Data from the two experiments were examined by tests of normality (Shapiro–Wilk test, $p < 0.05$) and homogeneity of variances (Levene, $p < 0.05$) for all parameters studied. Analysis of variance (ANOVA) ($p < 0.05$) was used except for the NDF, ELN of green forage yield, and NDF with CP of hay yield where the Kruskal–Wallis ($p < 0.05$) test was used. The Tukey test ($p < 0.05$) was used to compare the means of the treatments, the study factors, and the interaction between them. All analyses were performed with R software in RStudio (V. 2022.07.2 Build 576).

## 3. Results

### *3.1. Biomass and Hay Yield*

Table 3 shows the values of plant numbers at 25 days to assess crop performance at post-germination, the number of tillers per plant at 54 days at the phenological stage of tillering and tiller initiation [45], the plant height at cutting at 81 days, the green fodder yield, the dry matter, the biomass, and the hay yield of the four rye ecotypes.

**Table 3.** Phenological and agronomic values and forage yield of four rye ecotypes.

| Ecotype | Density [1] (Plants per $m^2$) | Tillers [#] per Plant | Plant Height (cm) | Green Forage (t $ha^{-1}$) | DM [$] (%) | Biomass (t DM $ha^{-1}$) | Hay (t $ha^{-1}$) |
|---|---|---|---|---|---|---|---|
| CBI-001 | 174 | 13 | 99.70 | 53.62 | 16.17 | 8.56 | 9.64 |
| CCE-001 | 190 | 12 | 95.33 | 48.79 | 17.55 | 8.93 | 10.36 |
| CJS-001 | 186 | 10.5 | 81.70 | 32.35 | 18.60 | 6.05 | 7.0 |
| CSM-001 | 166 | 10 | 84.90 | 34.30 | 18.83 | 6.51 | 7.54 |
| SE | 9.82 | 0.625 | 3.67 | 3.40 | 0.52 | 0.48 | 0.55 |
| *p* value | 0.7550 | 0.5439 | 0.5220 | 0.2694 | 0.8405 | 0.1495 | 0.1557 |

Notes: [1] to 25 days; [#] to 54 days; [$] dry matter; SE: standard error; (no statistical differences among treatments; ANOVA, $p < 0.05$).

### *3.2. Forage Chemical Composition*

Table 4 shows crude protein values, neutral detergent fiber, acid detergent fiber, ethereal extract, nitrogen-free extract, and ash for the four local rye ecotypes. It should be noted that the values obtained are for green forage and hay.

**Table 4.** Chemical composition of green forage and forage preserved as hay of the four rye ecotypes.

| Ecotype | Crude Protein (%) | NDF (%) | ADF (%) | Ether Extract (%) | Nifex (%) | Ash (%) |
|---|---|---|---|---|---|---|
| Green forage | | | | | | |
| CBI-001 | $10.15^{a}$ | $7.58^{a}$ | $48.83^{a}$ | $5.23^{c}$ | $48.20^{c}$ | $6.75^{b}$ |
| CSM-001 | $9.02^{b}$ | $64.76^{c}$ | $40.51^{b}$ | $5.80^{a}$ | $50.83^{a}$ | $6.50^{b}$ |
| CJS-001 | $9.80^{a}$ | $63.17^{d}$ | $38.51^{c}$ | $5.20^{c}$ | $49.84^{b}$ | $7.50^{a}$ |
| CCE-001 | $9.89^{a}$ | $66.21^{b}$ | $41.24^{b}$ | $5.54^{b}$ | $48.15^{c}$ | $6.75^{b}$ |
| SE | 0.09 | 0.16 | 0.21 | 0.05 | 0.17 | 0.14 |
| *p* value | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | 0.005 |
| Forage in hay | | | | | | |
| CBI-001 | $10.46^{b}$ | $68.49^{a}$ | $43.66^{a}$ | 4.00 | $42.59^{b}$ | $7.00^{b}$ |
| CSM-001 | $10.37^{b}$ | $66.97^{a}$ | $40.26^{d}$ | 4.22 | $44.96^{a}$ | $7.00^{b}$ |
| CJS-001 | $13.56^{a}$ | $64.31^{b}$ | $41.13^{c}$ | 4.03 | $43.03^{b}$ | $7.75^{a}$ |
| CCE-001 | $9.45^{c}$ | $68.09^{a}$ | $42.23^{b}$ | 3.66 | $44.91^{a}$ | $7.50^{ab}$ |
| SE | 0.12 | 0.40 | 0.16 | 0.15 | 0.24 | 0.13 |
| *p* value | <0.001 | 0.0002 | <0.001 | 0.1168 | 0.0001 | 0.0057 |

NDF: Neutral detergent fiber; ADF: Acid detergent fiber; Nifex: Nitrogen-free extract; SE: standard error. columns with different letters in each factor show differences (HSD Tukey, $p < 0.05$).

Crude protein values for green rye forage ranged from 9.02 % to 10.15 %, with CBI-001 higher than CSM-001 ($p < 0.001$). However, when kept as hay, crude protein values increased from 9.45 % for CCE-001 to 13.65 % for CJS-001.

### 3.3. Crop Parameters Grain Production

Table 5 shows the results of agronomic characteristics, such as stalk density per plant, number of flowering stalks per plant, length, ear length, number of grains per ear of the four forage rye ecotypes, and the fertilizer levels used in the study.

**Table 5.** Effect of fertilization levels and ecotypes on agronomic traits of forage rye.

| Ecotype | Number of Stems per Plant | Flowering Stems per Plant | Length of Stems (m) | Length of Spikes (cm) | Grains per Spike |
|---|---|---|---|---|---|
| CBI-001 | 4.56 | 4.06 | 1.18 | 10.80 $^{ab}$ | 45.63 |
| CSM-001 | 4.94 | 4.25 | 1.15 | 11.34 $^{a}$ | 47.19 |
| CJS-001 | 4.25 | 4.00 | 1.15 | 11.32 $^{a}$ | 47.75 |
| CCE-001 | 4.38 | 4.06 | 1.18 | 10.17 $^{b}$ | 43.44 |
| *p* value | 0.440 | 0.913 | 0.525 | 0.001 | 0.087 |
| Fertilizer levels | | | | | |
| T1 | 4.13 | 3.94 | 1.12 $^{b}$ | 11.36 | 47.75 |
| T2 | 4.56 | 3.94 | 1.14 $^{b}$ | 10.71 | 44.63 |
| T3 | 4.56 | 4.13 | 1.17 $^{ab}$ | 10.93 | 45.19 |
| T4 | 4.88 | 4.38 | 1.22 $^{a}$ | 10.63 | 46.44 |
| *p* value | 0.414 | 0.592 | 0.005 | 0.100 | 0.317 |

T1: 60N-30P-20K; T2: 60N-60P-40K; T3: 60N-90P-60K; T4: 60N-120P-80K; columns with different letters in each factor show differences (HSD Tukey, $p < 0.05$).

Table 6 shows the grain yield and straw yield of the crop of the four forage rye ecotypes, and also the effect of fertilization for these parameters. The ecotypes CBI-001, CCE-001, and CSM-001 perform best for grain or seed yield, and in general, T4 of the fertilization levels achieves the highest grain weight.

**Table 6.** Effect of fertilizer levels and genotype on grain and straw yield of forage rye.

| Ecotype | Total Weight Kg ha$^{-1}$ | Grain Kg ha$^{-1}$ | Straw Weight Kg ha$^{-1}$ |
|---|---|---|---|
| CBI-001 | 7325.00 $^{a}$ | 1868.4 $^{a}$ | 5456.63 $^{a}$ |
| CSM-001 | 6625.75 $^{ab}$ | 1751.1 $^{a}$ | 4874.63 $^{ab}$ |
| CJS-001 | 5787.50 $^{b}$ | 1365 $^{b}$ | 4422.50 $^{b}$ |
| CCE-001 | 6948.50 $^{a}$ | 1797.8 $^{a}$ | 5150.75 $^{ab}$ |
| *p* value | 0.0072 | 0.00119 | 0.0263 |
| Fertilizer levels | | | |
| T1 | 5875.9 $^{b}$ | 1565.9 $^{b}$ | 4310.00 $^{c}$ |
| T2 | 6231.6 $^{b}$ | 1576.1 $^{b}$ | 4655.50 $^{bc}$ |
| T3 | 6957.6 $^{ab}$ | 1720.4 $^{ab}$ | 5237.25 $^{ab}$ |
| T4 | 7621.6 $^{a}$ | 1919.9 $^{a}$ | 5701.75 $^{a}$ |
| *p* value | 0.0010 | 0.0259 | 0.0008 |

T1: 60N-30P-20K; T2: 60N-60P-40K; T3: 60N-90P-60K; T4: 60N-120P-80K; columns with different letters in each factor show differences (HSD Tukey, $p < 0.05$).

In the interaction effect between the study factors considered in EXP-02, no significant differences were found ($p < 0.05$) for all the parameters evaluated in agronomic characteristics and grain yield (Figure 2). The main effects were determined, and differences were found in both factors analyzed; this may be due to multiple environmental factors that can influence crop yield, even when they have been considered as controls in the experiments or by soil micro-elements, as referred to by Klikocka et al. [20].

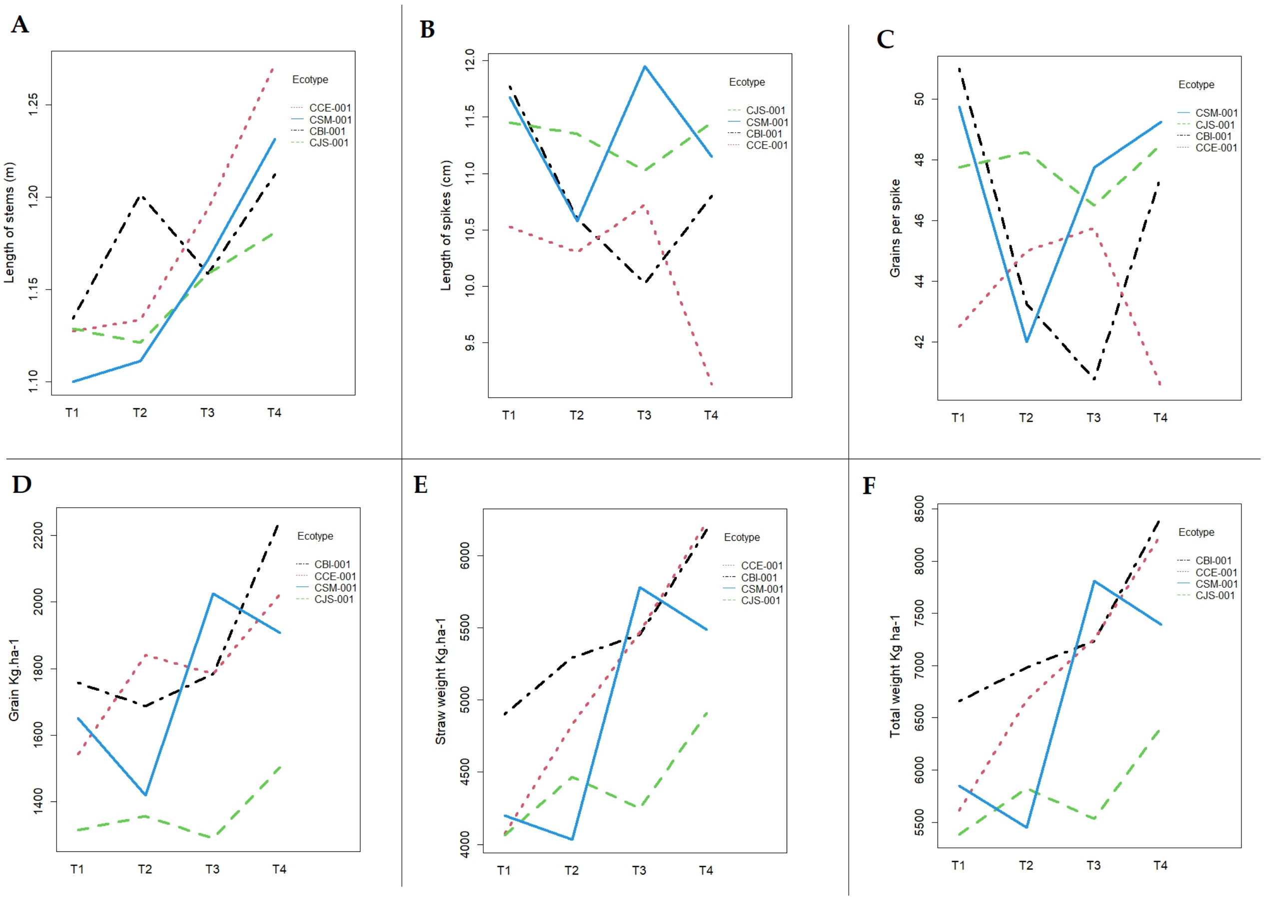


**Figure 2.** Interaction effect for rye ecotypes and four fertilizer levels. (**A**) length of stems (m); (**B**) spike length (cm); (**C**) number of grains per spike; (**D**) grain yield (kg ha$^{-1}$); (**E**) straw or residual weight (kg ha$^{-1}$); (**F**) total weight of grain plus straw (kg ha$^{-1}$). T1: 60N-30P-20K; T2: 60N-60P-40K; T3: 60N-90P-60K; T4: 60N-120P-80K.

## 4. Discussion

The green forage yield of rye evaluated with EXP-01 ranged from 6.51 t ha$^{-1}$ for CSM-001 to 8.93 t ha$^{-1}$ for CCE-001, which is similar to that reported by Ates et al. [13], Galán et al. [22], Han et al. [17], and Ku et al. [46]. Likewise, the density of emerging plants at 25 days among the four genotypes had no significant differences ($p$ = 0.8301) (Table 3), with lower values than the report of Blecharczyk et al. [34]. The plant height ranged from 81 cm for CJS-001 to 99.70 cm for CBI-001. It was determined that forage yield retained as hay had no difference among the ecotypes. This yield could be because the agronomic performance of crops under dual-purpose management is mainly affected by the prevailing climatic conditions, especially by the growth stage of produce at harvest [13], because in the area where EXP-01 was conducted, rainfall is permanent [8] at the time of forage harvest. Also, it does not impair the productivity of the genotypes studied, thus giving similar yields. Hay yield can also be affected by the time of cutting. In the present study, it was developed at 81 days and was conserved with a lower proportion of urea, thus giving a yield with the same trend; the cultivars that had better results were CCE-001 and CBI-001 with 10.36 and 9.64 t ha$^{-1}$ respectively. It is known that advanced maturity influences hay yield and its quality [47].

Table 4 shows that the protein levels for green forage were 10.15% for CBI-001, similar to CJS-001 and CCE-001 ($p < 0.001$), demonstrating that higher protein values were obtained for hay conservation up to 13.56% for the CJS-001, presenting it as an ecotype with suitable characteristics for conservation as hay. This may be because the conservation conditions were carried out using a minimum level of urea to enrich the forage and reduce the loss of forage nutrients [44]. Likewise, differences were found ($p < 0.01$) between the four ecotypes for neutral detergent fiber (NDF), acid detergent fiber (ADF), ethereal extract (EE), nitrogen-free extract (NiFEX), and ash for green forage. In contrast, for forage preserved in the hay, no differences were found for ethereal extract ($p = 0.1168$), with values even lower than those found for green forage. This may be due to the dehydration process the green forage was subjected to. On the contrary, ash levels increase with the haymaking process, between 7.00% to 7.75%, higher than the 5.8% reported by Wang et al. [48]. The crude protein levels, ADF and NDF, are similar to those written by Zhao et al. [47] under green forage and hay conditions. Due to the nutrients that rye forage has, and with the agro-climatic conditions of the high Andean zone of the northern highlands of Peru and, in particular, of Cajamarca, with acid soil conditions [2,3], in some cases poor in nutrients (Table 2), the possibility of installing and promoting the cultivation of rye is open, considering that it has forage and grain potential as a dual purpose crop in stressful environmental conditions [4]. Likewise, the ecotypes evaluated are from the high Andean zone; therefore, the genetic resource can be used to continue the process of genetic improvement, the evaluation of DNA and genes for tolerance to stress events, and the resistance of the cultivar [5], as well as for the biotechnological development of the cultivar [4] in the highlands at more than 3000 m, where the economic and social conditions are complicated.

In EXP-02, the effect of fertilization and the four rye ecotypes on grain yield parameters, straw, and agronomic characteristics, such as stalk length, number of stalks per plant, spike length, and number of grains per spike, were evaluated. Differences were determined for ear length ($p = 0.001$) among the ecotypes (superior in CSM-001 and CJS-001 with 11.34 cm and 11.32 cm, respectively). On the other hand, the fertilization level factor with phosphorus and potassium as the main effect affected the length of the stems ($p = 0.005$) because these nutrients favor the development of the plant, as it is observed that T4 and T3 have higher values (Table 5). Although fertilization affects grain yield, especially when the doses of phosphorus are 120 kg ha$^{-1}$ and potassium 80 kg ha$^{-1}$, according to Young [49], P fertilization does not influence the concentration of nutrients in cereal rye. This would indicate that to achieve a higher production of grain, straw should be applied and up to 90 kg ha$^{-1}$ of phosphorus and 60 kg ha$^{-1}$ of potassium for soils with conditions similar to those shown in EXP-02 of Table 2. Table 6 shows that straw yield was evaluated because it is an essential by-product for cattle and sheep feeding during the dry season in this area; therefore, according to EXP-02, a higher straw biomass yield is achieved with a higher fertilizer application. It is also considered that rye with fertilization is more tolerant to wet years than dry years; this could be due to the excess moisture conditions that could be the result of oxygen deficiency in the root zone of the crop [16], especially for the uptake of macronutrients, except for P content, taking into account that the interaction with N reduces the mass ratios of $K^+$:$Ca^{2+}$ and $K^+$:$Mg^{2+}$, influencing the Ca:P ratio [20].

No interaction effect was found between fertilization levels and the four ecotypes studied in Figure 2A; for stem length, it is found that greater size was achieved with T4, and the ecotypes that had better performance and were affected by the level of $P_2O_5$ and $K_2O$ were CCE-001 and CSM-001. This showed that the size of the stems develops when the dose of fertilizer increases. A similar tendency is observed in the yield of grain and straw in Figure 2E and Figure 2D, respectively, with the ecotypes CCE-001 and CBI being the ecotypes that developed the best productive performance for grain and straw. There is no marked tendency for the fertilization level for spike length and the number of grains per spike, as shown in Figure 2B,C. Considering that the plant absorption efficiency was higher at higher phosphorus and potassium rates, responding to higher production, this indicates the use of the plant because the amount of nitrogen was stable and not generating an interaction due to being a monoculture [26]. It has also been reported that the acceptable use of N in crops contributes to sustainable food production without degrading the environment [29], and the same is true for phosphorus and potassium since there can be a synergistic interaction between the nutrients for rye productivity. Therefore, it is explained that primary fertilization increases the grain's nutrient content compared to the plot without fertilization [19]. Finally, it can be mentioned that in both experiments, good results have been achieved as the four ecotypes have their own productive particularities for forage yield, including their nutritional composition and grain yield, demonstrating their high potential, considering that the soil conditions where the experiments were developed are those prevailing in the northern highlands region. For the above mentioned, it can be said that dual-purpose rye can represent a suitable alternative for biomass production in a variety of agro-ecological conditions, including areas where the cultivation of other cereal crops would not be competitive [2].

Green forage, hay, and rye crop residues can be used to feed crossbred and improved cows (European breeds) in the high Andean area. In principle, the requirement of lactating cows is high in dry matter, about 3% of their live weight [50], but these cows experience deficient feeding because the requirements of protein and dry matter are not met with the pastures that occur in the area, mainly ryegrass [51]. This is taking into account that the use of rye grain in ruminants does not exceed 15% due to the starch content [52], and that the forage can be used for fiber filling and as hay in times of drought.

## 5. Conclusions

It was determined that the rye ecotype CBI-001 achieved the best green forage yield with 53.62 t $ha^{-1}$; however, CCE-001 achieved higher biomass content in dry matter and hay, meaning it is an outstanding ecotype for forage production. Differences were found between ecotypes for crude protein content, NDF, FDA, ether extract, nitrogen-free extract, and ash, both for green forage and for forage preserved as hay. Protein levels increased in hayed forage up to 13.56 % for CJS-001 because it was the ecotype with the lowest plant height at the time of cutting at 80 days. It was found that there were no main effects or interaction effects when different levels of phosphorus and potassium application were evaluated for the number of stems per plant, flowering stems per plant, and grains per ear. Likewise, it was determined that if there is a main effect for the ecotypes in grain and straw yield, those being superior to the CBI-001 and CCE-001 ($p$ = 0.0072), the effect of fertilization gave better results when using 60 kg $ha^{-1}$ of nitrogen, 120 kg $ha^{-1}$ of $P_2O_5$, and 80 kg $ha^{-1}$ of $K_2O$; these being very similar to the dose of 60 kg $ha^{-1}$ of nitrogen, 90 kg $ha^{-1}$ of $P_2O_5$, and 60 kg $ha^{-1}$ of $K_2O$. Finally, the ecotypes studied, especially the outstanding ones, can be installed and multiplied for use as dual-purpose crops and animal feed, which is the limitation of inputs in the country's northern highlands.

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