

# Forage productivity of triticale (*Triticosecale wittmack* L.) and canola (*B. napus*) under different fertilization sources: Response in production, quality and water use efficiency

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## ABSTRACT

**Objective:** To evaluate triticale and canola crops in terms of agronomic traits, forage production (FP), forage quality (FQ), and irrigation water use efficiency (IWUE) under three different fertilization sources in semi-arid conditions in northern Mexico.

**Design/Methodology:** The study was conducted at the INIFAP La Laguna Experimental Field (25° 30' N, 103° 15' W). Sowing took place during the winter cycle, using triticale ( $\times$  *Triticosecale wittmack*), cv. 'Río Nazas', and canola (*B. napus*), cv. 'Hyola-401'. Three treatments were applied: (1) Chemical Fertilization (CF), consisting of 150 kg ha<sup>-1</sup> of nitrogen (N); (2) Biofertilization (BF), involving seed inoculation with microorganisms and oxidizable organic carbon; and (3) Control Treatment (CT), with an application of 60 kg ha<sup>-1</sup> of phosphorus (P). The same amount of phosphorus was applied in both CF and BF treatments. A randomized complete block design with four replicates in a 2×2 factorial arrangement was used. Harvesting was performed at the pod development stage for canola and the milk-dough stage for triticale. Variables evaluated included yield, agronomic traits, nutritional forage quality, and irrigation water use efficiency.

**Results:** The tallest canola plants (132.8 cm) were observed under the biofertilization treatment. A significant species×treatment interaction was found, with triticale showing the highest IWUE-NE (Net Energy) values under both fertilization sources (2.96 and 3.24 Mcal m<sup>-3</sup>, respectively). Canola exhibited the highest crude protein levels under both chemical and biofertilization treatments.

**Conclusions:** Triticale demonstrated superior performance in FP and net energy production. Canola showed greater potential in plant height, *in vitro* digestibility, neutral detergent fiber, and crude protein content. Biofertilization had a positive effect compared to the control treatment in terms of plant height, FP, and IWUE.

**Keywords:** Semi-arid, forages, biofertilizers, water.

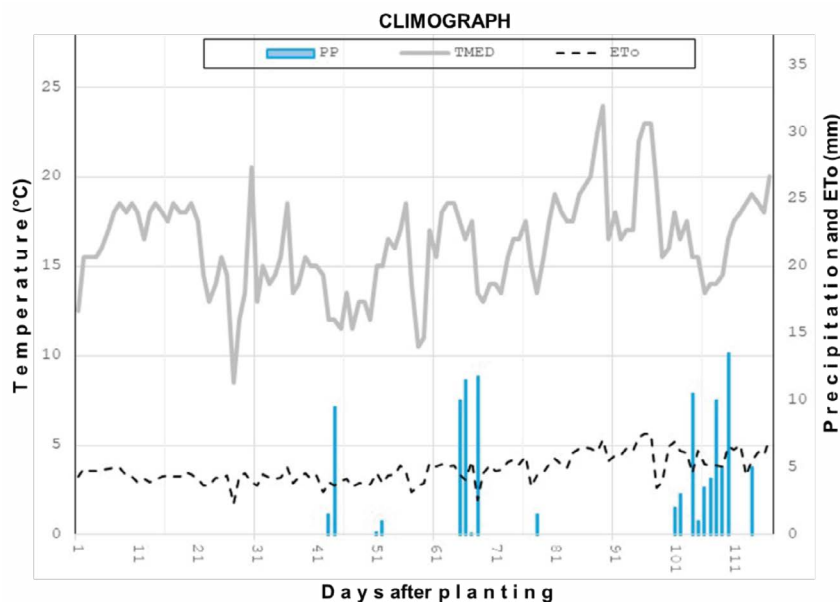
## INTRODUCTION

In forage production, water management, temperature, and plant nutrition are key factors determining quality (Lu *et al.*, 2024). Water and nutrients are absorbed by plants in solution form, and both their chemical composition and concentration exert direct effects on biomass yield and forage quality (Salvador-Castillo *et al.*, 2022; Kebede *et al.*, 2024). In this context, the use of chemical fertilizers in crop nutrition has increased steadily, resulting in production cost increases of up to 15.5%, thereby negatively impacting crop profitability (Grageda-Cabrera, 2018). Beyond the economic burden, chemical fertilization has been linked to several environmental issues, such as volatilization following hydrolysis and leaching after ammonium nitrification (Eugercios-Silva *et al.*, 2017). Given this scenario, the exploration of technologies that reduce the dependency on chemical fertilizers is essential (García-Sepúlveda *et al.*, 2019). Some studies have evaluated the potential of nitrogen-fixing crops and nutrient-assimilating microorganisms (Bernal, 2021). The development and application of biofertilizers are considered a sustainable and effective alternative to enhance soil fertility and reduce the need for synthetic fertilizers (Báez-Pérez *et al.*, 2020). Currently, a wide range of biofertilizers based on microorganisms such as bacteria and fungi are available, each fulfilling specific functions depending on the crop (Consolo *et al.*, 2014; Beltrán-Pineda *et al.*, 2022). Associations with microorganisms such as *Azospirillum brasilense*, ectomycorrhizal and endomycorrhizal fungi in the rhizosphere have been reported to enhance nutrient uptake by improving the availability of essential elements, thereby increasing nutrient use efficiency (Restrepo-Correa *et al.*, 2017). In arid and semi-arid regions of northern Mexico, where winter cropping is feasible, several studies have assessed the impact of nitrogen fertilization on forage oat production the most widely sown crop during the winter season (Caldas-López and Vega-Jara, 2020). In this regard, alternative species such as triticale ( $\times$  *Triticosecale wittmack*) and canola (*B. napus*) have been proposed for forage production (Reta *et al.*, 2010). However, limited information is available regarding the productive performance of these species under different fertilization sources, as well as their irrigation water use efficiency an essential factor for sustainable agricultural production in the region (Latsague *et al.*, 2014). Therefore, the aim of this study was to evaluate forage yield, nutritional quality, and irrigation water use efficiency of triticale cv. 'Río Nazas' and canola cv. 'Hyola-401' under two fertilization sources during the winter growing season in semi-arid conditions of northern Mexico.

## MATERIALS AND METHODS

### Experimental area

The study was conducted at the experimental site of the National Institute of Forestry, Agriculture and Livestock Research (INIFAP) - La Laguna Experimental Station, located in Matamoros, Coahuila de Zaragoza, Mexico. The site is geographically positioned at 25° 30' N and 103° 15' W, at an altitude of 1,112 meters above sea level. The climate is classified as BW(h<sup>3</sup>)hw(e), corresponding to a hot-arid type, with an average annual temperature of 22.7 °C, annual precipitation of 215 mm, and an evaporation rate of 2,600 mm (García, 2004). Climatic conditions during the crop development period are illustrated in Figure 1.



**Figure 1.** Precipitation (PP), mean temperature (TMED), and reference crop evapotranspiration (ETo) during the development cycle of the winter crops.

### Plant material and initial agronomic management

Sowing was carried out in furrows using a grain drill. The initial irrigation was applied on November 27, 2014, followed by three supplemental irrigations based on crop water requirements. The total net irrigation depth applied was 43.7 cm for canola and 57.3 cm for triticale, in clay-textured soils. The canola crop used the hybrid ‘Hyola-401’ at a seeding rate of 15.5 kg ha<sup>-1</sup>, while triticale used the variety ‘Río Nazas’ at a seeding rate of 130 kg ha<sup>-1</sup>. Irrigation was delivered through a surface irrigation system using gated pipe, in level basins (0% slope). Water application was measured for each event using the direct method (volume and time), as proposed by Sotelo-Ávila (2002) and established in NOM-001-CONAGUA-2011. Soil analysis was conducted to determine nitrogen (N) content using the Kjeldahl method, while phosphorus (P) content was measured based on NOM-021-SEMARNAT-2000 using the Olsen and Sommers (1982) method.

### Treatments and experimental design

Three fertilization treatments were applied: (1) Chemical Fertilization (CF), with 150 kg ha<sup>-1</sup> of N and 60 kg ha<sup>-1</sup> of P; (2) Biofertilization (BF), involving seed inoculation with a mixture of *Azospirillum brasilense*, ectomycorrhizal and endomycorrhizal fungi, plus oxidizable organic carbon, and 60 kg ha<sup>-1</sup> of P; and (3) Control Treatment (CT), receiving only 60 kg ha<sup>-1</sup> of P. The nutrient sources were ammonium sulfate and monoammonium phosphate (MAP). At sowing, 100% of the phosphorus and 10% of the nitrogen were applied, with the remaining nitrogen distributed between the first and second supplemental irrigations (40% and 50%, respectively). For biofertilization, inoculation was performed prior to sowing using a 10% sugar solution as an adhesive (100 g of sugar per liter of water) following the protocol of Martínez-Reyes *et al.* (2018). A randomized complete block

design with four replicates was used, arranged in a 2 (fertilization levels)×2 (crop species) factorial schemes. Each experimental unit had a surface area of 24 m<sup>2</sup>, with a usable plot area of 12 m<sup>2</sup>. Canola was harvested at the beginning of pod development, 90 days after sowing (DAS), while triticale was harvested at 128 DAS, at the milk-dough grain stage.

### **Evaluated variables**

The measured variables included plant height (PH, cm) and dry forage yield (DFY, t ha<sup>-1</sup>). Irrigation water use efficiency (IWUE, kg DM m<sup>-3</sup>) was calculated based on DFY and the total volume of water applied. Forage quality was determined through crude protein (CP), *in vitro* digestibility (IVD), neutral detergent fiber (NDF), total digestible nutrients (TDN), and net energy for lactation (NEL), using near-infrared reflectance spectroscopy (NIRS) previously calibrated as described by Núñez-Hernández *et al.* (2010). The forage quality component yield per hectare (FQCY) included CP, IVD, NDF, TDN, and NEL, calculated from DFY and the chemical composition, expressed in t or Mcal ha<sup>-1</sup>. Water use efficiency for forage quality components (IWUE-FQ) was estimated by relating the yield of nutritional components to the volume of water used, expressed in kg or Mcal m<sup>-3</sup>, to evaluate crop response according to fertilization levels, as reported by Gutiérrez-Guzmán *et al.* (2022) and Reta *et al.* (2010).

### **Statistical analysis**

Data were analyzed using the SAS<sup>®</sup> 9.4 statistical package (2008). Assumptions of variance homogeneity and normality were verified. ANOVA was conducted using the GLM procedure, and mean comparisons were performed using Tukey's test ( $\alpha=0.05$ ). In addition, Pearson's correlation analysis was conducted to assess the degree of association among variables (Herrera-Haro and García-Artiga, 2014)

## **RESULTS AND DISCUSSION**

A significant interaction effect was found between Treatment×Species ( $p<0.05$ ) for the variables dry forage yield (DFY), irrigation water use efficiency (IWUE), and *in vitro* digestibility (IVD). The highest DFY was obtained in triticale under both chemical fertilization and biofertilization treatments (Table 1). Nitrogen assimilation derived from the applied treatments enhanced nutrient translocation to demand organs, resulting in increased biomass production. Conversely, nitrogen deficiency is associated with lower yield and reduced nutritional quality of the forage. In this regard, Escalante-Estrada *et al.* (2016) reported canola yields of 7.1 t ha<sup>-1</sup> under different seeding densities, which are comparable to those obtained in the present study. Additionally, Núñez *et al.* (2007) reported triticale yields of 10.2 and 12.3 t ha<sup>-1</sup>, with IVD values of 71.5%, slightly higher than those found here. Similarly, Espinoza-Canales *et al.* (2017) reported an IVD of 67.2% in canola. These nutritional values are linked to the plant's morphophysiological traits, which vary depending on species, variety, climate, soil type, and nutrient management (Ortegón-Morales *et al.*, 2007). Plant lignification is considered the main factor affecting other nutritional components and is associated with the harvest stage (Núñez *et al.*, 2010). Regarding IWUE, the highest values were observed in the Treatment×Species

**Table 1.** Interaction effect of Treatment×Species and fertilization treatment on agronomic traits, yield performance, irrigation water use efficiency (IWUE), and nutritional quality in triticale and canola crops under two fertilization schemes in semi-arid conditions of northern Mexico.

Species × Treatment		Height (cm)	DFY (t ha <sup>-1</sup> )	IWUE (kg m <sup>-3</sup> )	IVD	NDF	CP	TDN	NEL (Mcal kg <sup>-1</sup> )
					%				
Triticale	CF	120.9	11.70ab	2.04a	68.07c	54.35	12.41	50.51	1.12
	BF	129.35	12.65a	2.20a	68.98c	54.99	11.18	51.27	1.13
	CT	123.55	10.45b	1.82ab	66.68c	54.06	11.95	50.06	1.11
Canola	CF	117.4	6.20c	1.42b	84.54a	29.15	14.25	27.30	0.55
	BF	132.8	7.85c	1.80ab	80.59b	33.42	14.47	31.09	0.64
	CT	121.1	7.80c	1.79ab	83.47ab	30.91	12.51	28.92	0.59
Fertilization Treatment									
CF		119.15b	8.95b	1.73b	ns	ns	ns	ns	ns
BF		131.08a	10.25a	2.0a					
CT		122.33b	9.13ab	1.80ab					

Different letters (a, b, c) within the same column indicate statistically significant differences (Tukey,  $\alpha=0.05$ ). Abbreviations: CF=Chemical Fertilization, BF=Biofertilization, CT=Control Treatment, IWUE=Irrigation Water Use Efficiency, IVD=*In Vitro* Digestibility, NDF=Neutral Detergent Fiber, CP=Crude Protein, TDN=Total Digestible Nutrients, NEL=Net Energy for Lactation, DFY=Dry Forage Yield, ns=not significant.

interaction, where triticale outperformed canola under both fertilization treatments. DFY is a determining factor for IWUE, as its magnitude directly influences this parameter. Canola exhibited lower DFY compared to triticale, which translated into reduced IWUE. Montemayor-Trejo *et al.* (2015) reported similar IWUE values of 1.75 kg m<sup>-3</sup> for triticale, while Reta-Sánchez *et al.* (2010) obtained 1.6 kg m<sup>-3</sup> in a cropping system that included canola, maize, and soybean. Significant main effects ( $p<0.05$ ) were also observed based on treatment, with biofertilization (BF) yielding the highest values for plant height, DFY, and IWUE. Dos Santos *et al.* (2020) reported lower canola plant heights (106 cm) under the same variety during the winter cycle in the Southern Hemisphere (humid subtropical climate with hot summers and no defined dry season), which contrasts with the arid climate of the La Laguna region (hot, dry, with summer rains). In that study, minimum temperatures close to 0 °C were recorded, which partially restricted growth as they approached the lower threshold for canola development. Additionally, alternating periods of excess humidity (85-106 DAS) and moisture deficit (120-140 DAS) limited root development and water uptake area, thereby constraining cellular development and overall plant growth conditions that explain the height differences observed between both studies. Likewise, in a nearby region in Tamaulipas, Mexico, Ortégón-Morales *et al.* (2007) reported canola heights of 103 cm for the same variety. These differences are mainly attributable to agronomic management and climatic conditions across regions, including variations in sowing dates (earlier in northeastern Mexico), which allowed for a longer growing period under cooler conditions favorable for this winter crop. In contrast, spring sowing exposes the crop to temperatures approaching the upper threshold for winter crop development. The northeastern study also relied on residual soil moisture and applied only two supplemental irrigations, suggesting

lower water stress compared to the current study. Both studies applied similar rates of P and K (60-00), but differed in nitrogen application (100 kg ha<sup>-1</sup>), which collectively contributed to the observed differences in plant height. Regarding dry forage yield (DFY), the BF treatment again resulted in the highest values. Similar results (10.1 t ha<sup>-1</sup>) were reported by Núñez *et al.* (2007). In a study conducted in the La Laguna region, Montemayor-Trejo *et al.* (2015) reported IWUE values of 1.75 kg m<sup>-3</sup> for triticale, although with lower nitrogen fertilization (52 kg N ha<sup>-1</sup>) applied via central pivot sprinkler irrigation. Sowing occurred in October, differing in timing and agronomic management compared to the present study conditions that explain the variation in IWUE between the two studies.

Statistically significant differences (p<0.05) were observed in the Treatment×Species interaction for dry matter production (DMP) and forage quality variables (Table 2). Specifically, chemical fertilization (CF) in canola resulted in the highest values for forage quality component of *in vitro* digestibility (FQC-IVD), while triticale exhibited the highest values for net energy for lactation (FQC-NEL) under both fertilization treatments. In this context, Núñez *et al.* (2007) reported higher FQC-IVD values in triticale (7.3 t ha<sup>-1</sup>), slightly above those obtained in canola within the same study region. These differences may be attributed to crop management and climatic conditions throughout the development cycle.

Statistically significant differences (p<0.05) were observed in the Treatment×Species interaction for irrigation water use efficiency in forage quality production (IWUE-FQC) (Table 3). Canola exhibited the highest value (p<0.05) for IWUE-IVD, whereas triticale recorded the greatest values for IWUE-NEL under both fertilization treatments. As a main effect of fertilization, the highest IWUE-NEL was observed in the biofertilization (BF) treatment (p<0.05). This result can be attributed to nitrogen availability, which enhances

**Table 2.** Effect of the Treatment×Species interaction and fertilization treatment on the production of forage quality components: IVD, NDF, CP, TDN, and NEL, under semi-arid conditions in northern Mexico.

Species × Treatment		FQC				
		FQC-IVD (t ha <sup>-1</sup> )	FQC-NDF (t ha <sup>-1</sup> )	FQC-CP (t ha <sup>-1</sup> )	NDT (t ha <sup>-1</sup> )	FQC-NEL (Mcal ha <sup>-1</sup> )
Triticale	CF	5.51 <sup>c</sup>	4.40	1.01	4.09	13049 <sup>ab</sup>
	BF	5.59 <sup>c</sup>	4.45	0.91	4.15	14284 <sup>a</sup>
	CT	5.40 <sup>c</sup>	4.38	0.97	4.05	11507 <sup>c</sup>
Canola	CF	6.85 <sup>a</sup>	2.36	1.15	2.21	3384 <sup>c</sup>
	BF	6.53 <sup>b</sup>	2.71	1.17	2.52	5086 <sup>c</sup>
	CT	6.76 <sup>ab</sup>	2.50	1.01	2.34	4598 <sup>c</sup>
Fertilization Treatment						
CF		ns	ns	ns	ns	8216 <sup>b</sup>
BF						9676 <sup>a</sup>
CT						8052 <sup>b</sup>

Different letters (a, b, c) within the same column indicate statistically significant differences (Tukey, α=0.05). Abbreviations: Trat=Fertilization Treatment, Esp=Species; BF=Biofertilization, CF=Chemical Fertilization, CT=Control Treatment, FQC=Forage Quality Component Production; IVD=*In Vitro* Digestibility (t ha<sup>-1</sup>), CP=Crude Protein, TDN=Total Digestible Nutrients, NEL=Net Energy for Lactation, ns=not significant.

**Table 3.** Effect of the Treatment×Species interaction and fertilization treatment on irrigation water use efficiency (IWUE) for forage quality component production in triticale and canola crops under two fertilization schemes in semi-arid conditions of northern Mexico.

Species × Treatment		IWUE-FQC				
		IWUE-IVD (kg m <sup>-3</sup> )	IWUE-NDF (kg m <sup>-3</sup> )	IWUE-CP (kg m <sup>-3</sup> )	IWUE-TDN (kg m <sup>-3</sup> )	IWUE-NEL (Mcal m <sup>-3</sup> )
Triticale	CF	0.96 <sup>c</sup>	0.77	0.17	0.71	2.96 <sup>ab</sup>
	BF	0.97 <sup>c</sup>	0.77	0.16	0.72	3.24 <sup>a</sup>
	CT	0.94 <sup>c</sup>	0.76	0.17	0.71	2.61 <sup>b</sup>
Canola	CF	1.57 <sup>a</sup>	0.54	0.26	0.51	0.76 <sup>c</sup>
	BF	1.49 <sup>b</sup>	0.62	0.27	0.58	1.14 <sup>c</sup>
	CT	1.55 <sup>ab</sup>	0.57	0.23	0.54	1.03 <sup>c</sup>
Fertilization Treatment						
CF						1.86 <sup>b</sup>
BF	ns	ns	ns	ns		2.19 <sup>a</sup>
CT						1.82 <sup>b</sup>

Different letters (a, b, c) within the same column indicate statistically significant differences (Tukey,  $\alpha=0.05$ ). Abbreviations: Trat=Fertilization Treatment, Esp=Species; BF=Biofertilization, CF=Chemical Fertilization, CT=Control Treatment; IWUE=Irrigation Water Use Efficiency for IVD (*In Vitro* Digestibility), CP (Crude Protein), TDN (Total Digestible Nutrients), and NEL (Net Energy for Lactation); ns=not significant.

biomass yield and productivity key factors associated with the energy content of forage. These findings are consistent with previous studies by Ballesteros-Rodríguez *et al.* (2015) and López-Jara *et al.* (2022), who reported higher NEL values in triticale compared to canola, emphasizing the influence of variety and nutrient management on IWUE and forage nutritional quality.

When comparing means by species, statistically significant differences ( $p<0.05$ ) were identified in all analyzed IWUE and DMP variables (Table 4). The results for productive performance showed significant differences ( $p<0.05$ ) in DFY, IWUE, NDF, TDN, and NEL, with triticale exhibiting superior values, whereas IVD was significantly higher ( $\alpha=0.05$ ) in canola. In this regard, Reta *et al.* (2010) reported IWUE-CP values of 0.21 kg m<sup>-3</sup> in a cropping system that included canola, maize, and soybean, which were higher compared to triticale and slightly lower than those observed in canola in the present study. Moreover, regarding IWUE-NEL, annual cropping systems including canola showed lower water productivity compared to triticale. It is important to note that spring or summer crops typically exhibit greater evapotranspiration than winter crops, which significantly impacts IWUE. Additionally, in terms of forage quality component production (FQC), canola outperformed triticale in the production of *in vitro* digestible matter per unit area. These findings are consistent with those reported by Núñez-Hernández *et al.* (2010) and Espinoza-Canales *et al.* (2017). Furthermore, canola recorded the highest values ( $p<0.05$ ) for IWUE-IVD, FQC-IVD, IWUE-NDF, FQC-NDF, and IWUE-CP, indicating greater productivity per m<sup>3</sup> of applied irrigation water. In contrast, triticale showed higher performance in IWUE-TDN, FQC-TDN, IWUE-NEL, FQC-NEL, and FQC-NDF.

**Table 4.** Irrigation water use efficiency, forage quality component production, and agronomic and nutritional traits in triticale and canola crops under two fertilization schemes in semi-arid conditions of northern Mexico.

Species	IWUE-FQC							
	IWUE-IVD ( $\text{kg m}^{-3}$ )	IWUE-NDF ( $\text{kg m}^{-3}$ )	IWUE-CP ( $\text{kg m}^{-3}$ )	IWUE-TDN ( $\text{kg m}^{-3}$ )	IWUE-NEL ( $\text{Mcal m}^{-3}$ )			
Triticale	0.96 <sup>b</sup>	0.58 <sup>b</sup>	0.17 <sup>b</sup>	0.71 <sup>a</sup>	2.94 <sup>a</sup>			
Canola	1.54 <sup>a</sup>	0.77 <sup>a</sup>	0.25 <sup>a</sup>	0.54 <sup>b</sup>	0.98 <sup>b</sup>			
FQC								
	FQC-IVD ( $\text{t ha}^{-1}$ )	FQC-NDF ( $\text{t ha}^{-1}$ )	FQC-CP ( $\text{t ha}^{-1}$ )	FQC-TDN ( $\text{t ha}^{-1}$ )	FQC-NEL ( $\text{Mcal ha}^{-1}$ )			
Triticale	5.50 <sup>b</sup>	4.41 <sup>a</sup>	0.96	4.10 <sup>a</sup>	12947 <sup>a</sup>			
Canola	6.71 <sup>a</sup>	2.52 <sup>b</sup>	1.11	2.36 <sup>b</sup>	4350 <sup>b</sup>			
Agronomic Traits, Yield, IWUE, and Forage Quality								
	Height (cm)	DFY ( $\text{t ha}^{-1}$ )	IWUE ( $\text{kg m}^{-3}$ )	IVD (%)	NDF (%)	CP (%)	TDN (%)	NEL ( $\text{Mcal kg}^{-1}$ )
Triticale	123.77	11.60 <sup>a</sup>	2.02 <sup>a</sup>	67.91 <sup>b</sup>	54.46 <sup>a</sup>	11.84	50.61 <sup>a</sup>	1.12 <sup>a</sup>
Canola	124.60	7.28 <sup>b</sup>	1.67 <sup>b</sup>	82.86 <sup>a</sup>	31.16 <sup>b</sup>	13.74	29.10 <sup>b</sup>	0.59 <sup>b</sup>

Different letters (a, b) within the same column indicate statistically significant differences (Tukey,  $\alpha=0.05$ ). IWUE=Irrigation Water Use Efficiency for IVD (*In Vitro* Digestibility), CP (Crude Protein), TDN (Total Digestible Nutrients), and NEL (Net Energy for Lactation,  $\text{Mcal m}^{-3}$ ); DFY=Dry Forage Yield; NDF=Neutral Detergent Fiber; ns=not significant.

The correlation analysis among yield, agronomic traits, nutritional variables, and water productivity in forage from canola and triticale under different fertilization sources is presented in Table 5. Of the total evaluated data, 37.3% showed significant correlations 24.0% were positive and 13.3% negative. Approximately 5% of the correlations were significant at  $p>0.05$ , while 32.3% were highly significant ( $p>0.0001$ ), with 22.3% displaying a negative trend and 10% a positive trend. Plant height did not show any significant correlation with the response variables, indicating that, under the study conditions, taller plants did not translate into higher forage yield or improved forage quality. In contrast, total fresh biomass (TFB) and dry forage yield (DFY) were correlated with 83.3% (21 variables) of the measured parameters. These variables were not correlated only with plant height, crude protein (CP), and DMP-CP (dry matter production of crude protein). For TFB, 85% of the correlations were highly significant ( $p>0.0001$ ) and negatively associated, while 15% showed a positive trend. In the case of DFY, 80.9% of the correlations were positive and 19.1% negative. The irrigation water use efficiency for neutral detergent fiber production (IWUE-NDF) was negatively correlated with TFB ( $r=-0.82$ ), and positively correlated with dry matter (DM), DFY, root length (RL), IWUE, and biomass per irrigation depth (BID), with  $r=0.87$ ,  $0.86$ ,  $0.92$ ,  $0.67$ , and  $0.86$ , respectively (see Table 5). IWUE was positively associated with yield and RL, confirming findings by Gutiérrez-Guzmán *et al.* (2022), who reported that increasing irrigation depth led to greater biomass production and higher net energy for lactation (NEL) per unit area. IWUE showed a negative correlation with IVD ( $r=-0.62$ ), as well as with FQC-IVD and IWUE-IVD. On the other hand, IWUE was positively correlated with DM, DFY, and RL ( $r=0.62$ ,  $0.90$ , and  $0.60$ , respectively), and also with NDF, TDN, NEL, FQC-NDF, FQC-TDN, FQC-NEL, and FQC-NELA

**Table 5.** Correlation coefficients among yield, agronomic traits, chemical composition, and irrigation water use efficiency (IWUE) in forage from canola and triticale under different fertilization sources.

Variables	PH	TFB	DM	DFY	RL	IWUE	BID	IVD	NDF	CP	TDN	NEL	NELA	FQC-IVD	FQC-NDF	FQC-CP	FQC-TDN	FQC-NEL	FQC-NELA	IWUE-IVD	IWUE-NDF	IWUE-CP	IWUE-TDN	UEA-ENL	UEA-NLA	
PH	1																									
TFB	0.01	1																								
DM	0.07	-0.94***	1																							
DFY	0.28	-0.73***	0.88***	1																						
RL	0.07	-0.94***	0.98	0.88***	1																					
IWUE	0.4	-0.38	0.62***	0.9***	0.6***	1																				
BID	0.22	-0.68***	0.72***	0.78***	0.76***	0.67***	1																			
IVD	-0.11	0.88***	-0.94***	-0.87***	-0.97	-0.62***	-0.81***	1																		
NDF	0.1	-0.9***	0.94***	0.88***	0.98	0.64***	0.83***	-0.98	1																	
CP	-0.31	0.3	-0.18	-0.14	-0.24	0.02	-0.11	0.16	-0.17	1																
TDN	0.1	-0.9***	0.94***	0.88***	0.98	0.64***	0.82***	-0.98	1	-0.17	1															
NEL	0.09	-0.9***	0.94***	0.88***	0.98	0.64***	0.83***	-0.98	1	-0.17	1	1														
NELA	0.09	-0.9***	0.94***	0.88***	0.98	0.64***	0.83***	-0.98	1	-0.17	1	1	1													
FQC-IVD	-0.11	0.88***	-0.94***	-0.87***	-0.97	-0.62***	-0.81***	1	-0.98	0.16	-0.98	-0.98	-0.98	1												
FQC-NDF	0.1	-0.9***	0.94***	0.88***	0.98	0.64***	0.83***	-0.98	1	-0.17	1	1	1	-0.98	1											
FQC-CP	-0.31	0.3	-0.18	-0.14	-0.24	0.02	-0.11	0.16	-0.17	1	-0.17	-0.17	-0.17	0.16	-0.17	1										
FQC-TDN	0.1	-0.9***	0.94***	0.88***	0.98	0.64***	0.82***	-0.98	1	-0.17	1	1	1	-0.98	1	-0.17	1									
FQC-NEL	0.09	-0.9***	0.94***	0.88***	0.98	0.64***	0.83***	-0.98	1	-0.17	1	1	1	-0.98	1	-0.17	1	1								
FQC-NELA	0.09	-0.9***	0.94***	0.88***	0.98	0.64***	0.83***	-0.98	1	-0.17	1	1	1	-0.98	1	-0.17	1	1	1							
IWUE-IVD	-0.09	0.92***	-0.97	-0.89***	-0.99	-0.62***	-0.79***	0.99	-0.99	0.2	-0.99	-0.99	-0.99	0.99	-0.99	0.2	-0.99	-0.99	-0.99	1						
IWUE-NDF	0.14	-0.82***	0.87***	0.86***	0.92***	0.67***	0.86***	-0.96	0.98	-0.09	0.98	0.98	-0.96	0.98	-0.09	0.98	0.98	0.98	0.98	1***	1					
IWUE-CP	-0.27	0.6***	-0.51*	-0.41*	-0.53***	-0.16	-0.36	0.47*	-0.49*	0.93***	-0.49*	-0.48*	0.47*	-0.49*	0.93*	-0.49***	-0.48*	0.52*	-0.39*	0.52*	-0.39	1				
IWUE-TDN	0.13	-0.82***	0.87***	0.86***	0.92***	0.67***	0.86***	-0.95	0.98	-0.09	0.98	0.98	-0.95	0.98	-0.09	0.98	0.98	0.98	0.98	-0.93***	1	-0.39	1			
IWUE-NEL	0.13	-0.84***	0.88***	0.87***	0.93***	0.67***	0.86***	-0.96	0.98	-0.1	0.98	0.99	-0.96	0.98	-0.1	0.98	0.99	0.99	0.99	-0.95	1	-0.4*	1	1		
IWUE-NELA	0.13	-0.84***	0.88***	0.87***	0.93***	0.67***	0.86***	-0.96	0.98	-0.1	0.99	0.99	-0.96	0.98	-0.1	0.99	0.99	0.99	0.99	-0.95	1	-0.4*	1	1	1	

( $r=0.64$ ). Additionally, there was a positive correlation with IWUE-NDF, IWUE-TDN, IWUE-NEL, IWUE-NELA, and BID, with  $r=0.67$ . Crude protein showed no significant correlation with yield or forage quality variables, consistent with results reported by Núñez-Hernández *et al.* (2010).

## CONCLUSIONS

Based on the above findings, triticale under chemical fertilization and biofertilization demonstrates greater potential for dry forage yield, irrigation water use efficiency in dry forage production, and net energy for lactation.

Conversely, canola shows potential in irrigation water use efficiency for dry forage production, with higher values in neutral detergent fiber, *in vitro* digestibility, and crude protein content.

The application of *Azospirillum brasilense*, ectomycorrhizal and endomycorrhizal fungi, along with oxidizable organic carbon (biofertilization), resulted in significant improvements compared to the control treatment in terms of forage quality and irrigation water use efficiency.

Seed inoculation with these microorganisms had a positive effect on nutrient assimilation by the plant, leading to increased biomass production, as demonstrated by the results of this study.

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