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TEORES DE ÓLEO, PROTEÍNA E PRODUTIVIDADE DE SOJA EM FUNÇÃO DA ESTRATÉGIA DO MANEJO DA IRRIGAÇÃO SUPLEMENTAR

ZANANDRA BOFF OLIVEIRA[1]; ANA LUÍZA CANTO DA SILVA[2]; ÉRICA LUIZA GRINGS MAZUIM[2]; NATÁLIA FERREIRA MENDEL DA SILVA[2]; MARCUS VINÍCIUS TRÊS[3] E GIOVANI LEONE ZABOT[3]

[1] Coordenadoria Acadêmica do Campus da UFSM em Cachoeira do Sul, Curso de Engenharia Agrícola e Programa de Pós-Graduação em Agricultura de Precisão - PPGAP, Rod. Taufik Germano, 3013, Passo D'Areia, 96503-205 Cachoeira do Sul/RS, e-mail: zanandra.oliveira@ufsm.br; ORCID (https://orcid.org/0000-0003-3422-8452).
[2] Curso de Engenharia Agrícola da UFSM Cachoeira do Sul, Rod. Taufik Germano, 3013, Passo D'Areia, 96503-205 Cachoeira do Sul/RS, e-mail: ana.canto@acad.ufsm.br; erica.mazuim@acad.ufsm.br; nataliamendeldasilva@gmail.com; ORCID (https://orcid.org/0009-0006-6308-1188, https://orcid.org/0009-0001-1275-4016; https://orcid.org/0009-0005-7564-9618)
[3] Coordenadoria Acadêmica do Campus da UFSM em Cachoeira do Sul, Curso de Engenharia Agrícola e Programa de Pós-Graduação em Engenharia Agrícola - PPGEA, Rod. Taufik Germano, 3013, Passo D'Areia, 96503-205 Cachoeira do Sul/RS, e-mail marcus.tres@ufsm.br; giovani.zabot@ufsm.br; ORCID (https://orcid.org/0000-0001-5252-0735; https://orcid.org/0000-0001-7933-6161)

1 RESUMO

A irrigação suplementar pode aumentar significativamente a produtividade das culturas e contribui para que os produtos agrícolas tenham melhor qualidade. Assim, o objetivo deste estudo é avaliar a produtividade, a eficiência do uso da água (EUA), o teor de óleo e de proteína da soja, em função de diferentes estratégias de manejo da irrigação suplementar: irrigação durante todo o ciclo (T1); irrigação a partir de R1 (T2); irrigação a partir de R3 (T3); sem irrigação – sequeiro (T4). A pesquisa foi realizada a campo, na área experimental da UFSM Cachoeira do Sul - RS no ano agrícola 2024-25 e a análise da qualidade de grãos realizada em laboratório (LAPE). O incremento de produtividade pela irrigação foi de 42% (T1), 31% (T2) e de 19 % (T3). A EUA foi maior para o T4 (13,05 kg mm^{-1}), seguida do T3 (11,81 kg mm^{-1}) e menor para o T1 e T2 (10,98 kg mm^{-1}). Os valores mais elevados de proteína foram obtidos no T3 (36,4%) e T2 (35,8%) e o menor valor no T4 (35,0%). O teor de óleo nos grãos (20%), não foi influenciado pelas diferentes estratégias de suprimento hídrico.

Palavras-chave: *Glycine max* (L.), suprimento hídrico, sustentabilidade.

OLIVEIRA, Z. B.; SILVA, A. L. C.; MAZUIM, E. L. G.; SILVA, N. F. M.; TRÊS, M. V.; ZABOT, G. L.

SOYBEAN OIL, PROTEIN CONTENT AND YIELD AS A FUNCTION OF SUPPLEMENTAL IRRIGATION MANAGEMENT STRATEGIES

2 ABSTRACT

Supplemental irrigation can significantly increase crop productivity and improve the quality of agricultural products. In this context, the objective of this study was to evaluate soybean yield,

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water use efficiency (WUE), and grain oil and protein contents under different supplemental irrigation management strategies: irrigation throughout the entire crop cycle (T1), irrigation starting at R1 (T2), irrigation starting at R3 (T3), and rainfed cultivation (T4). The experiment was conducted in the experimental area of the Federal University of Santa Maria, Cachoeira do Sul Campus, Rio Grande do Sul, Brazil, during the 2024/25 growing season. The grain quality analyses were performed at the Laboratory of Agroindustrial Process Engineering (LAPE). Compared with the rainfed treatment, the irrigation treatment increased the grain yield by 42%, 31%, and 19% for T1, T2, and T3, respectively. The highest WUE was observed in T4 (13.05 kg mm^{-1}), followed by T3 (11.81 kg mm^{-1}), while T1 and T2 presented the lowest values (10.98 kg mm^{-1}). The highest protein contents were obtained in T3 (36.4%) and T2 (35.8%), whereas the lowest value was observed in T4 (35.0%). The average grain oil content, 20%, was not affected by the different water supply strategies.

Keywords: *Glycine max* (L.), water supply, sustainability.

3 INTRODUCTION

Soy (*Glycine Soybean (max* M.) is one of Brazil's main summer crops and plays an important role in the economy. The production is concentrated mainly in the Central-West and South Regions, with Mato Grosso at the top of the ranking. In the state of Rio Grande do Sul, the area under soybean cultivation in the 2024/2025 crop season was estimated to be approximately 6.8 million hectares (Emater/RS- Ascar, 2025). This growth of the crop over the years is due to its high demand, both for human and animal feed and for industrial uses (CONAB, 2024).

The increased demand for food to meet the constant growth of the human population (FAO, 2009), coupled with a global context of climate change, has represented a major challenge for agricultural production (IPCC, 2014; Tamiru; Fekadu, 2019). While there is a real need to intensify agricultural production, there is also a need for increasingly sustainable technological approaches. In this context, improving plant efficiency can be a process used to sustainably increase the potential of agricultural production (Kaiser; Galvis; Armbruster, 2019; Singer *et al*., 2020). This can be accomplished using different strategies involving genetic material and the efficient management of production factors (Zanon *et al*., 2018). However, yield factors such as light and water can also be added to this set (Gupta, 2017; Lemes *et al*., 2021). Compared with cultivation under rainfed conditions, the use of irrigation can increase soybean productivity by two or even three times (Sentelhas). *et al*., 2015; Silva *et al*., 2020; Oliveira; Baranzelli; Knies, 2023), since water deficit is the main cause of reduced soybean crop productivity in Brazil (Silva *et al*., 2020).

The benefits of irrigation can be associated with improvements in soil conditions, such as aeration and temperature, which also influence nutrient absorption, especially nitrogen (N), in this study (Hungria; Campo; Mendes, 2007). Irrigation management should be carried out in a way that maximizes water use. If the irrigating farmer's objective is to maximize productivity, irrigation management implies that the necessary irrigation is carried out to fully meet the water needs of the crops. However, if the objective is to maximize water use efficiency, deficit irrigation that corresponds to maximum economic efficiency can be adopted (Pereira; Angelocci; Sentelhas, 2002). However, understanding this relationship between water supply and the quality of the grains produced is fundamental since the variation in protein and oil content is determined mainly by genetic factors but strongly influenced by the environment, especially during the grain-filling period (Pipolo). *et al*., 2015). The protein content in soybeans varies from 31.7 to 57.9%, and the oil concentration varies from 8.0 to 25.4%, indicating their commercial value (Pipolo). *et al*., 2015; Moraes *et al.*, 2006).

Therefore, the objective of this study is to evaluate the yield, productivity, water use efficiency, oil content, and protein content components in soybean grains as a function of different supplemental irrigation strategies: irrigation throughout the cycle; irrigation from R1; irrigation from R3; and no irrigation – rainfed.

4. MATERIALS AND METHODS

The experiment was installed in the 2024/25 agricultural year in the experimental area of UFSM Cachoeira do Sul (longitude -52.96, latitude -30.01 and altitude 79.2 m), whose soil is a Red Argisol. The climate, according to the Köppen classification, is subtropical (Cfa). The work was conducted in a randomized block design with four treatments and six replications, totaling 24 experimental plots. The area of each experimental plot was 6.75 m²· The treatments consisted of different supplemental irrigation strategies: irrigation throughout the cycle (T1); irrigation from R1 (T2); irrigation from R3 (T3); and no irrigation—rainfed (T4).

The Brasmax Trovão I2X cultivar was studied on November 21, 2024, using a tractor/seeder unit with a row spacing of 0.45 m and 14 seeds per linear meter in a no-till system over white oat crop residue. The seeds were inoculated with bacteria of the genus Citrus aegypti. *Bradyrhizobium* and *Azospirillum were* treated*, and* the base fertilization was 300kg ha^{-1} of the commercial formula 4-28-28 (NPK). Other management practices followed agronomic recommendations for the crop.

Irrigation was carried out using a surface drip irrigation system installed between the rows of crops every 0.5 m, with an emitter spacing of 0.2 m. Irrigation management was based on the soil water balance to maintain the available water capacity (AWC), with a depletion fraction of 40%, which varied according to the development of the crop root system from 10 to 35 mm. Meteorological data and reference evapotranspiration (ETo) data were obtained from an automatic station (Metos, Brazil) installed approximately 50 m from the experimental site. Crop evapotranspiration (ETc) was obtained by multiplying ETo by the crop coefficient (Kc). The simple Kc calculation takes into account the canopy cover fraction (Fc) to define the inflection and deflection points in the Kc curve (Allen *et al*., 1998). Phenological analysis of the plants was carried out twice a week, up to the phenological stages R1 and R3, to determine when to start irrigations T2 and T3.

The harvest took place on April 4, 2025, during which plants from the central area of each plot (3 m²) were uprooted and processed· After being harvested, the grains were threshed and cleaned, and their moisture content was determined and weighed. The grain mass was corrected to 13% moisture and then extrapolated to kilograms per hectare (kg ha^{-1}). From these same samples, the weight of one thousand grains (WTG) (g) was determined by counting 1000 grains, which were weighed and corrected to 13% moisture. For yield component analysis, four plants from each plot were randomly harvested for hand processing to determine the number of pods per plant and the number of grains per pod.

The water use efficiency (WUE) in kg mm^{-1} was obtained as the ratio between the average crop productivity per treatment (kg ha^{-1}) and the total water used by the crop (irrigated: rain + irrigation and rainfed: rain).

Grain quality assessments were conducted at the Agroindustrial Process Engineering Laboratory (LAPE) of the Federal University of Santa Maria, Cachoeira do Sul Campus. Oil content determination followed the procedure described by Confortin. *et al.* (2019). For this purpose, 2 g samples of soybean grains from each treatment were subjected to extraction with 200 mL of n-hexane (PA) using a Soxhlet extractor (Marconi®, model MA491/6) for 360 minutes. The samples were placed in filter paper cartridges and positioned in the extraction chamber of the equipment. The solvent was heated in a distillation flask using a heating mantle, promoting its evaporation, condensation, and continuous recirculation through the sample, enabling oil extraction. At the end of the process, the oil content was determined gravimetrically.

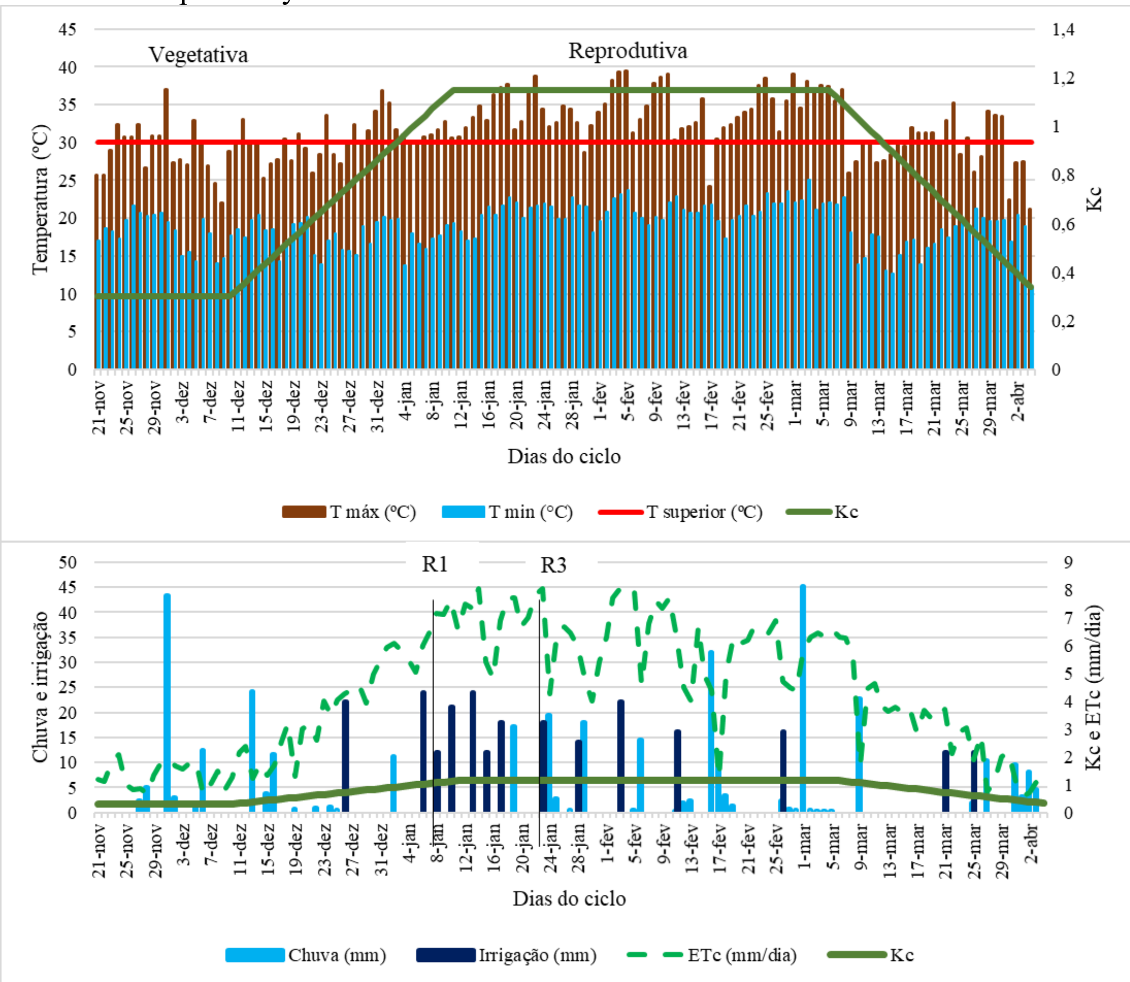
Total nitrogen quantification was performed according to the methodology proposed by Tedesco *et al.* (1995). The samples were subjected to acid digestion using a solution of H_2SO_4 (0.025 mol L^{-1}) and H_2O_2 (30% v/v), followed by distillation using the Kjeldahl method in a micro-Kjeldahl steam distillation apparatus (TECNAL®, model TE-0363). The crude protein content was estimated from the nitrogen content using a conversion factor of 6.25, which is recommended for soybean grains.

The response variables—thousand-grain weight (TGW), number of pods per plant, number of grains per pod, productivity, WUE, oil content, and protein content were subjected to statistical analysis. Analysis of variance (F test) was performed, followed by comparison of means using Tukey's test and Sisvar software, with a significance level of 5%.

5. RESULTS AND DISCUSSION

During the soybean development cycle, the temperature range varied between 10.7 and 39.5 °C (Figure 1). On several occasions, the maximum air temperature exceeded the ideal values for the crop, which are between 20 and 30 °C (Farias *et al*., 2007). During the reproductive period, for several days, the maximum temperature approached 40 °C, which can negatively affect the growth rate, impair flowering, and reduce pod retention capacity, effects that are aggravated under water deficit conditions (Yamasaki *et al*., 2002).

Figure 1. Meteorological variables and water balance parameters observed during the soybean development cycle.



Source: Authors.

The cumulative rainfall during the cycle totaled only 356.6 mm, an insufficient amount to meet the crop's water demand, since the accumulated crop evapotranspiration (ETc) was 577.6 mm. At the beginning of the development cycle, rainfall was well distributed, supplying the crop's water needs until December 25th, practically throughout the entire vegetative phase. However, in January, a period of high average evapotranspiration (6.4 mm day^{-1}), rainfall was poorly distributed and insufficient to meet the water demand of the soybeans, indicating a water deficit. The most significant water scarcity occurred during the flowering period (R1–R2), when there was no rainfall event between January 2nd and January 19th (Figure 1). Thus, the accumulated irrigation was 243, 197, and 110 mm for treatments T1, T2, and T3, respectively. Water deficit is the main factor affecting soybean productivity loss (Silva *et al.*, 2020) because of flower and pod abortion, as well as reduced grain size and weight (Kuss, 2006).

In addition to the direct effects of water deficit on soybean growth and productivity, water availability and thermal conditions significantly influence biological nitrogen fixation. Temperatures above 30 °C can compromise the survival and activity of bacteria of the genus *Bradyrhizobium*, which are responsible for the symbiotic fixation of N_2, reducing the availability of this nutrient to plants and, consequently, protein synthesis (Hungria; Vargas, 2000).

Additionally, the simultaneous occurrence of high temperatures and water restriction can alter carbon metabolism, promoting modifications in the biochemical pathways involved in the formation of reserve compounds, such as proteins and lipids, which affect the chemical composition of the grains (Pípolo, 2002).

Supplemental irrigation increased the number of pods per plant by 50%, 26%, and 10% for treatments T1, T2, and T3, respectively (Table 1). Andrade Júnior *et al.* (2002), analyzed irrigation levels for cowpea in Piauí and reported that the production component with the greatest positive variability in response to increased grain productivity was the number of pods per plant. Oliveira, Baranzelli, and Knies (2023) reported, on average, an increase in the number of pods per plant of 29.8% with supplemental irrigation in soybean cultivation in Cachoeira do Sul – RS. The grain yield (GY) was greater in treatments T2 and T3, possibly because of the greater amount of photoassimilates allocated to the grains as a result of the lower number of pods in these treatments than in T1. Navarro Junior and Costa (2002) reported that reducing the number of pods per plant without reducing the leaf area caused a small increase in grain weight. The grains per pod component are directly linked to the genetics of the cultivar (Mundstock; Thomas, 2005). Thus, it was not influenced by the treatments, with an average value under the study conditions of 2.33 grains per ^{pod}.

Table 1. Soybean yield components as a function of different supplemental irrigation management strategies.

Treatment	Plant pods $^{-1}$		Pod grains $^{-1}$		PMG (g)	
T1	75.5	the	2.38	the	170.3	ab
T2	63.4	ab	2.34	the	183.7	the
T3	55.5	b	2.27	the	190.7	the
T4	50.4	b	2.35	the	165.7	b
CV	38.1		11.1		35.6	
DMS	19.4		0.21		24.8	

where numbers followed by the same letters in the rows do not differ statistically from each other ($p \leq 0.05$); T1: irrigation throughout the cycle; T2: irrigation from R1; T3: irrigation from R3; T4: rainfed; CV: coefficient of variation; and LSD: least significant difference.
Source: Authors.

Supplemental irrigation increased soybean productivity by 42%, 31%, and 19% in T1, T2, and T3, respectively. The maximum productivity obtained of $^{6,548.3}$ kg ha^{-1} demonstrates that supplemental irrigation is an essential tool for achieving high soybean productivity. In a study under the same edaphoclimatic conditions, Oliveira, Baranzelli, and Knies (2023) reported slightly higher productivity ceilings of 6,882.5 kg ha^{-1} in the 2020-21 agricultural year, when the rainfall totaled 426 mm. Pigatto, Oliveira, and Knies (2023), evaluating the productivity of 22 soybean cultivars during a La Niña year in the same study region, reported productivities ranging from 3,507.1 to 5,043.1 kg ha^{-1} with the use of supplemental irrigation when rainfall was only 151 mm in the 2022–23 agricultural year. Thus, the increase in soybean productivity with greater water availability is noticeable. However, the water use efficiency (WUE) is greater in the rainfed treatment (T4), followed by the irrigation strategy with supplementation from R3 (T3).

Similar results were reported by Almeida (2021), who reported an increase in soybean productivity with increased water availability, with yields between 2,700 and 5,400 kg ha^{-1} for water replenishment ranging from 40 to 120% of the demand of the crop. Conversely, the authors reported higher WUE values under conditions of lower water availability. This behavior is related to the physiological and biochemical mechanisms triggered by plants in response to water deficit (Xiong *et al*., 2022). Among these adaptations, the increase in stomatal resistance stands out (Ohsumi). *et al*., 2007), greater development and deepening of the root system (Miyazaki; Arita, 2020) and improved water use efficiency (Blum, 2009). Such responses were also observed in the present study, in which the treatments subjected to lower water availability presented higher WUE values (Table 2).

Table 2. Productivity and water use efficiency of soybeans as a function of different supplemental irrigation management strategies.

Treatment	Productivity (kg ha $^{-1}$)		USA (kg mm $^{-1}$)	
T1	6,548.3	the	10.98	b
T2	6,070.3	ab	10.99	b
T3	5,474.0	ab	11.81	ab
T4	4,615.2	b	13.05	the
CV	35.6		35.4	
DMS	1,701.5		1.96	

where numbers followed by the same letters in the rows do not differ statistically from each other ($p \leq 0.05$); T1: irrigation throughout the cycle; T2: irrigation from R1; T3: irrigation from R3; T4: rainfed; CV: coefficient of variation; and LSD: least significant difference.
Source: Authors.

The protein content in soybean grains varied slightly between treatments, ranging from 35.0 to 36.4%. However, these differences were statistically significant (Table 3), with the highest protein concentration obtained in T3 and T2 and the lowest in T4.

Table 3. Protein and oil contents of soybean grains as a function of different supplemental irrigation management strategies.

Treatment	Protein (%)		Oil (%)	
T1	35.4	bc	20.0	the
T2	35.8	ab	20.3	the
T3	36.4	the	20.2	the
T4	35.0	w	19.5	the
CV	0.9		3.1	
DMS	0.8		1.6	

where numbers followed by the same letters in the rows do not differ statistically from each other ($p \leq 0.05$); T1: irrigation throughout the cycle; T2: irrigation from R1; T3: irrigation from R3; T4: rainfed; CV: coefficient of variation; and LSD: least significant difference.
Source: Authors.

Water stress, combined with the effects of high temperatures during the reproductive period (Figure 1), may explain the lower protein concentration in the grains in T4 (Pípolo, 2002; Rangel *et al*., 2004). Pípolo (2002) reported a change in protein content at high temperatures because of the lower availability of N to the grains. One hypothesis for the lower protein concentration in T1 was the greater pressure from fungal diseases on the plants in this treatment. Fungal diseases cause premature defoliation, reducing the area available for photosynthesis, a process essential for the production of carbohydrates and, consequently, proteins. The average oil content of 20% did not differ significantly between treatments, although it was slightly lower in T4 (Table 3), which is in agreement with the findings of Pípolo. *et al.* . (2015) reported that the variation in total protein and oil content in soybean grains is primarily determined by genetic factors, that is, by the cultivar chosen.

6 CONCLUSIONS

The maximum soybean productivity (6,548.3 kg ha^{-1}) was obtained with full irrigation throughout the entire development cycle, whenever necessary. Deficit irrigation strategies resulted in productivity reductions to 6,070.3 kg ha^{-1} when initiated from R1 and to 5,474.0 kg ha^{-1} when initiated from R3.

Compared with rainfed soybeans, the productivity increases provided by irrigation were 42% for irrigation throughout the cycle, 31% when started at R1, and 19% when started at R3.

Water use efficiency was higher under rainfed conditions (13.05 kg mm^{-1}), although it was associated with lower productivity, followed by the irrigation strategy starting at R3 (11.81 kg mm^{-1}). Very similar values were observed for irrigation initiated at R1 and for irrigation throughout the entire cycle, with 10.98 kg mm^{-1}.

The highest protein content in soybean grains was observed with irrigation initiated at R3 (36.4%) and R1 (35.8%), whereas the lowest value was recorded in rainfed soybeans (35.0%). The oil content in the grains (20%) was not influenced by the different water supply strategies.

When water availability for irrigation is insufficient to supply the entire crop cycle, it is recommended to concentrate irrigation during the reproductive phase, since this strategy increases water use efficiency, increases productivity, and improves the quality of the final product.

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