

Hydrogel performance on plant growth and leachate electrical conductivity under high water availability

Ygor Mota Soca Machado¹ & Nicolas Xavier de Castro²

¹ Plant Cognition and Electrophysiology Laboratory, Federal University of Pelotas, Pelotas, Brazil

² Plant Tissue Culture Laboratory, Federal University of Pelotas, Pelotas, Brazil

Correspondence: Ygor Mota Soca Machado, Plant Cognition and Electrophysiology Laboratory, Federal University of Pelotas, Pelotas, Brazil. E-mail: machadoygor017@gmail.com

Submitted: March 21, 2026

DOI: 10.14295/bjs.v5i9.856

Accepted: June 20, 2026

URL: <https://doi.org/10.14295/bjs.v5i9.856>

Published: June 23, 2026

Abstract

Hydrogels have been proposed as a strategy to reduce the leaching of highly soluble nutrients, such as nitrogen and potassium, in agricultural systems. However, the literature lacks evaluations of hydrogel performance under conditions of high water availability, a scenario in which the effectiveness of nutrient retention may be compromised; this is a relevant gap since intense rainfall events are among the main factors associated with nutrient loss in the soil. This study evaluated the performance of hydrogels in mitigating nitrogen and potassium leaching in wheat plants (*Triticum aestivum*) subjected to irrigation simulating high rainfall (4 mm day⁻¹). The experiment was conducted in a greenhouse, in a completely randomized design, with six treatments: control without fertilization; pure hydrogel; hydrogel incorporated with base fertilization; hydrogel incorporated with total cycle fertilization; base fertilization in solid form; and total cycle fertilization in solid form. Plant height was evaluated at 7, 14, 21, and 28 days after sowing, in addition to shoot and root dry mass and leachate electrical conductivity at the end of the experiment. Fertilized treatments, regardless of the application method, promoted greater growth and biomass accumulation than the control and pure hydrogel. However, the leachate electrical conductivity was higher in treatments with hydrogel than in equivalent doses applied in solid form, indicating that the hydrogel did not reduce solute loss under these conditions. The results demonstrate that, under high water availability, hydrogel does not offer an advantage over conventional fertilization in nitrogen and potassium retention, contradicting some of the expectations generated by previous studies conducted mainly under water deficit conditions. The main contribution of this work is to highlight that the effectiveness of hydrogel as a nutrient retention tool is strongly dependent on the water regime and cannot be generalized to scenarios of excessive rainfall. This finding provides direct support for agricultural management, indicating that the adoption of hydrogels to reduce nutrient losses should be carefully considered and take into account local rainfall conditions, avoiding generic recommendations based solely on their performance under water stress.

Keywords: water retention, nutrient loss, salinization, *Triticum aestivum*.

Desempenho do hidrogel no crescimento de plantas e na condutividade elétrica do lixiviado sob alta disponibilidade de água

Resumo

O hidrogel tem sido proposto como estratégia para reduzir a lixiviação de nutrientes altamente solúveis, como nitrogênio e potássio, em sistemas agrícolas. No entanto, a literatura carece de avaliações sobre o desempenho do hidrogel sob condições de alta disponibilidade hídrica, cenário em que a eficácia da retenção de nutrientes pode ser comprometida, uma lacuna relevante, já que eventos de precipitação intensa estão entre os principais fatores associados à perda de nutrientes no solo. Este estudo avaliou o desempenho do hidrogel na mitigação da lixiviação de nitrogênio e potássio em plantas de trigo (*Triticum aestivum*) submetidas à irrigação simulando alta pluviosidade (4 mm dia⁻¹). O experimento foi conduzido em casa de vegetação, em delineamento inteiramente casualizado, com seis tratamentos: controle sem fertilização; hidrogel puro; hidrogel incorporado com adubação

de base; hidrogel incorporado com adubação total do ciclo; adubação de base na forma sólida; e adubação total do ciclo na forma sólida. Avaliou-se a altura das plantas aos 7, 14, 21 e 28 dias após a semeadura, além da massa seca de parte aérea e raiz e da condutividade elétrica do lixiviado ao final do experimento. Os tratamentos fertilizados, independentemente da forma de aplicação, promoveram maior crescimento e acúmulo de biomassa do que o controle e o hidrogel puro. Contudo, a condutividade elétrica do lixiviado foi maior nos tratamentos com hidrogel do que nas doses equivalentes aplicadas na forma sólida, indicando que o hidrogel não reduziu a perda de solutos nessas condições. Os resultados demonstram que, sob alta disponibilidade hídrica, o hidrogel não apresenta vantagem sobre a fertilização convencional na retenção de nitrogênio e potássio, contrariando parte das expectativas geradas por estudos prévios conduzidos majoritariamente em condições de déficit hídrico. A principal contribuição deste trabalho é evidenciar que a eficácia do hidrogel como ferramenta de retenção de nutrientes é fortemente dependente do regime hídrico, não podendo ser generalizada para cenários de excesso de chuva. Esse achado fornece subsídio direto para o manejo agrícola, ao indicar que a adoção do hidrogel com o objetivo de reduzir perdas de nutrientes deve ser criteriosa e considerar as condições pluviométricas locais, evitando recomendações genéricas baseadas apenas em seu desempenho sob estresse hídrico.

Palavras-chave: retenção de água, perda de nutrientes, salinização, *Triticum aestivum*

1. Introduction

Plant nutrition is one of the most important aspects of agricultural production. As sessile organisms, plants need the nutrients necessary for their growth and development to be supplied within their specific niche. A lack or excess of nutrients can harm plant health, affecting the quality and quantity of production (Trindade et al., 2024). Corn plants grown with reduced macronutrients show lower height, stem diameter, number of leaves, and shoot and root dry mass when compared to the treatment with adequate fertilization, highlighting the importance of balanced plant nutrition (Lima et al., 2020).

Inefficiency in nutrient absorption by plants can be caused by various soil conditions. According to Zhu et al. (2024), soils with high salinity levels make the environment hyperosmotic, reducing the availability of water to the roots; excess sodium also compromises potassium absorption, given the similarity in charge between the two elements. Soil acidity favors the fixation of phosphorus by aluminum and iron, forming compounds that are not absorbable by plants, in addition to reducing the availability of magnesium and potassium due to the intense leaching of exchangeable bases (Souza; Lobato, 2024).

Nitrogen and potassium, in particular, have high solubility, which can cause damage to the root system when applied in high doses (Viçosi; Pelá, 2020; Paula et al., 2020) and are easily lost to the environment through leaching (Jadoski et al., 2022; Gomes et al., 2022). When leached, these nutrients can reach lakes and rivers, stimulating the growth of cyanobacteria and aerobic decomposing bacteria in waterways, which reduces available oxygen and triggers eutrophication, with a reduction in local aquatic life and significant environmental impacts (Santos; Medeiros, 2023). This process also results in economic losses for producers, since agricultural production involves high investment in chemical fertilizers (Barbieri et al., 2023): when removed from the soil, nutrients cease to be absorbed by plants, reducing productivity and increasing production costs, which is often reflected in the final price to the consumer. Despite the relevance of these impacts, effective and low-cost methods capable of simultaneously reducing nitrogen and potassium leaching without compromising their availability to plants are still scarce, which represents an important gap to be explored.

Hydrogel is a type of water-retaining agent with the ability to absorb liquids and gradually release them into the environment, as needed by the plant (Li et al., 2025; Patra et al., 2022; Vedovello et al., 2024). Although it was initially developed for use in forestry, recent studies have also been testing its potential in annual crops (Filho et al., 2020; Albalasmeh et al., 2022). Minosso et al. (2021), when evaluating the use of polymeric hydrogel in two soybean cultivars (one tolerant to water deficit and the other not), observed a 67% increase in the productivity of the non-drought-tolerant cultivar.

Structurally, hydrogels are three-dimensional networks of cross-linked hydrophilic polymers, capable of absorbing and retaining large amounts of water and solutes dissolved in it, forming a gel structure that releases these compounds gradually as the soil dries (Saha et al., 2020). This absorption capacity can reach values far exceeding the dry weight of the polymer itself, making hydrogels particularly efficient in soils with low retention capacity, in which water and dissolved nutrients tend to be lost rapidly through percolation (Malik et al., 2022). According to Mamaghani et al. (2025) and Tariq et al. (2023), the association between agricultural practices and the use of polymeric hydrogels has the potential to overcome limitations that impair productivity, such as drought, since hydrogels have a high capacity to retain water and release it at a rate that avoids waste (Montesano, 2015). In

addition, by improving soil structure and increasing porosity, hydrogels indirectly contribute to nutrient retention in the root zone (Agbna; Zaidi, 2025).

Because they retain solutes along with water in their polymer network, hydrogels have been increasingly studied as fertilizer carriers, functioning as controlled-release systems that make nutrients available according to the soil moisture content (Guilherme et al., 2015). Due to this ability to absorb and retain liquids, hydrogels have high potential as a tool for retaining easily leachable nutrients, such as nitrogen and potassium, in addition to facilitating their absorption by plants (Ghobashy et al., 2020). This mechanism can reduce losses due to leaching and prolong the availability of these nutrients in the soil solution, potentially increasing fertilizer use efficiency (Agbna; Zaidi, 2025).

It is hypothesized that the incorporation of nitrogen and potassium into the hydrogel results in controlled release of these nutrients, reducing losses due to leaching and increasing their availability in the soil solution, which favors absorption by plants and improves the agronomic performance of the crop. The objective of this study was to evaluate the effects of hydrogel-associated fertilization on wheat growth and on the electrical conductivity of the leachate under conditions of high water availability, using leachate electrical conductivity as an indirect indicator of solute movement through the soil profile.

2. Materials and Methods

2.1 Experimental design

The experiment was conducted in a greenhouse from July 17 to August 14, 2024, using wheat plants (ORS Guardião cultivar). The experimental design was completely randomized, with six treatments and four replications. The treatments were defined as follows: T1, control treatment without hydrogel or fertilization; T2, swollen hydrogel containing only water; T3, swollen hydrogel incorporating the recommended base fertilization dose for the crop; T4, swollen hydrogel incorporating the total recommended fertilization dose for the entire crop cycle; T5, base fertilization applied in solid form; and T6, total fertilization for the entire crop cycle applied in solid form. The soil used in the experiment was collected from the 0–20 cm layer in an agricultural area located in Bagé, Rio Grande do Sul, Brazil. The soil contained 19% clay and was classified as medium texture. Based on the results of the soil analysis (Table 1), the soil acidity was corrected, and fertilization was carried out according to the recommendations for wheat cultivation.

Table 1. Components of the soil analysis report for fertilizer and liming recommendations.

Component	Value in the sample
% Clay (m/v)	19.0
water pH	5.4
SMP index	6.3
Phosphorus (mg/dm ³)	6.2
CTC (cmol/dm ³)	10.3

Source: Authors, 2026.

The fertilization recommendation was made according to the Fertilization and Liming Manual for the states of Rio Grande do Sul and Santa Catarina, with N and K quantities of 60 kg ha⁻¹ and 30 kg ha⁻¹, respectively. The fertilizers used were urea with 45% N and potassium chloride with 58% K, with the values corrected to meet the manual's recommendation. The experiment was conducted in 0.5 L pots (with a surface radius of 4.5 cm), and the recommended fertilizer and hydrogel application rates per area (kg ha⁻¹) were converted into quantities per pot, according to the area of each experimental unit. The quantities applied per pot were adjusted proportionally to maintain the same application rates equivalent to those in the field.

2.2 Hydrogel characterization

The hydrogel used in this study was the commercial product Hidrotterragel® (Tubarão Agronegócios Ltda., São José do Rio Preto, SP, Brazil; MAPA registration No. SP 005324-4.000001), composed of cross-linked sodium polyacrylate with polymer chains held together by hydrogen bonds. The hydrogel was prepared according to the manufacturer's recommended ratio of 5 g of product per liter of water; the mixture was allowed to stand for approximately 10 min until fully hydrated and the characteristic gelatinous consistency had formed, before the incorporation of the fertilizer solutions corresponding to each treatment.

2.3 Hydrogel preparation

The hydrogel was used at a dose of 60 kg ha⁻¹ according to each treatment. To prepare the solutions, the required amount of water and fertilizer was added to a beaker, which remained in a mechanical stirrer for five minutes at 140 rpm until complete solubilization of the nutrients. After that, the hydrogel was incorporated into the solution for absorption and swelling.

2.4 Collection of leachate

For leachate collection, a collection system was installed for each container. A funnel was added so that its lower part extended beyond the bottom of the container and its upper part remained inside it. At the entrance of the funnel (the upper part, inside the container), a screen was added to prevent direct contact between the soil and the inner wall of the funnel, thus reducing the transport of sediments along with the leachate. A synthetic polymer screen (a material with low affinity for water) was used to prevent the leachate from being absorbed and/or filtered.

For leachate collection, polyethylene collectors coated with aluminum foil and plastic film were made to prevent heating and sunlight from affecting the collected material and potentially interfering with the results. Before use, the collectors were sterilized to remove impurities. They were positioned directly below the containers, with the lower part inserted inside the collector. The illustration of the methodology described above is shown in (Figure 1).

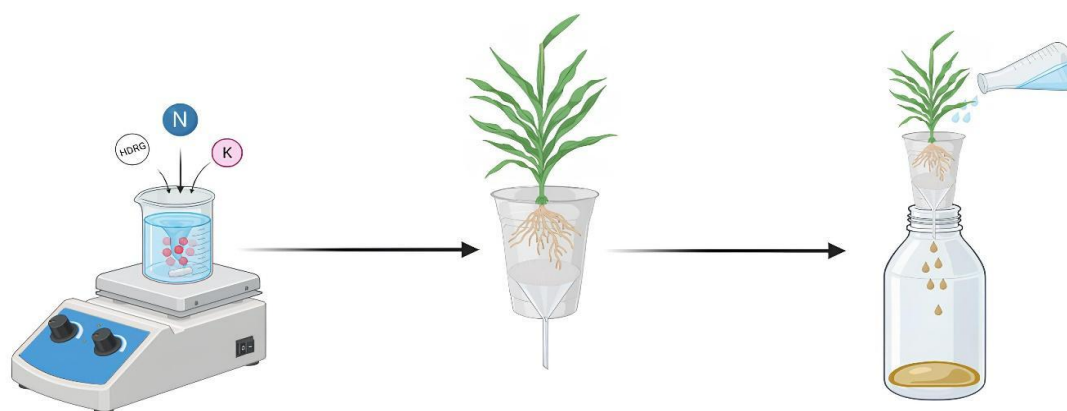


Figure 1. Methodology and configuration of the vessels for collecting leachate. Source: Authors, 2026.

2.5 Sowing

In a previous experiment, the objective was to determine the ideal distance for hydrogel deposition in relation to the seed. It was found that there was no significant difference in plant growth at different depths for the variables evaluated. Based on these results, 3 cm was adopted as the most suitable distance between the hydrogel and the seed, taking into account factors such as the high salt concentration associated with the hydrogel in the present experiment and the practical applicability of this technique.

In each pot, a two-centimeter layer of soil was added, followed by the application of hydrogel (containing nitrogen and potassium solution or just water) or solid nutrients, according to each treatment. The same mass of soil (190

g) was added to each pot and compacted in a space of five centimeters (two centimeters from the funnel to the hydrogel/fertilizer and three centimeters from the hydrogel/fertilizer to the seed). This procedure was carried out to standardize the porosity of each experimental unit as much as possible, aiming for uniform water retention. It is worth noting that the hydrogel had a low volume, which can be disregarded in relation to its effect on the final soil density. Three centimeters of soil were added, and then five seeds were sown per pot, thinning to obtain one plant per pot.

The seeds were covered with a 2 cm layer of commercial substrate to facilitate seedling emergence and suppress weed growth. Both the soil and the substrate were homogenized before use. Each pot received 50 mL of water immediately after sowing to ensure adequate moisture for seed germination. Subsequently, irrigation was carried out every four days, applying 100 mL of water per pot, corresponding to a cumulative irrigation depth of 114.61 mm over the 28-day experimental period (equivalent to 4.09 mm day^{-1}).

The volume and frequency of irrigation were established in preliminary tests to maintain soil moisture close to field capacity, while promoting controlled drainage in all experimental units. This approach ensured the generation of sufficient leachate for subsequent electrical conductivity measurements and standardization of water availability among treatments throughout the experimental period. Plant height was measured at 7, 14, 21, and 28 days after sowing (DAS). At the end of the experiment, shoot and root dry mass were determined, and the electrical conductivity of the leachate was measured.

The electrical conductivity of the leachate was used as an indirect indicator of nutrient losses. However, electrical conductivity reflects the total concentration of dissolved ions and does not allow the identification or quantification of specific nutrients. Therefore, the results should be interpreted as an estimate of total solute leaching, and not as a direct measure of individual nutrient losses.

2.6 Statistical analysis

The collected data were subjected to analysis of variance and normality testing using the *Shapiro-Wilk* method, and, in cases of significance, *Duncan's* mean comparison test was performed with a significance level of 5%. Statistical analysis was performed using the RStudio program (2025), and the graphs were created using SigmaPlot 12.0 software (2011).

3. Results

No significant differences in plant height were observed between treatments at 7 and 14 DAS (Figure 2). The average plant height ranged from approximately 7.8 to 9.0 cm plant⁻¹ at 7 DAS and from 12.5 to 14.5 cm plant⁻¹ at 14 DAS, indicating similar initial growth regardless of the fertilization strategy. Differences between treatments became evident from 21 DAS onwards. At this stage, plants that received nitrogen and potassium, incorporated into the hydrogel or applied in solid form, reached heights between 26.0 and 27.5 cm plant⁻¹, while the control and isolated hydrogel treatments showed lower values, ranging from 22.0 to 24.0 cm plant⁻¹.

At 28 DAS (days after sowing), the treatment that received the total dose of fertilizer in solid form produced the tallest plants, reaching approximately 30.0 cm per plant, representing increases of 21% and 26% compared to the control and hydrogel-only treatments, respectively. The treatment that combined the total dose of fertilizer with hydrogel resulted in intermediate values (approximately 27.0 cm per plant), while no significant difference was observed between equivalent fertilization rates applied with or without hydrogel.

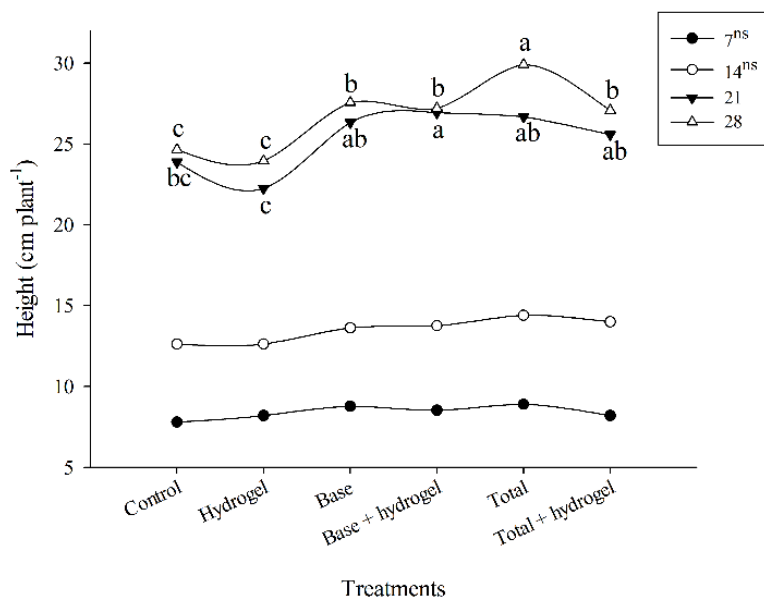


Figure 2. Height of wheat plants subjected to different levels of potassium and nitrogen fertilization, with or without hydrogel, at 7, 14, 21, and 28 days after sowing. Points with different letters differ from each other according to *Duncan's* test ($p < 0.05$). Source: Authors, 2026.

A similar trend was observed for biomass accumulation. Shoot dry matter ranged from approximately 138 to 153 mg plant^{-1} in the control and hydrogel-only treatments, while the fertilized treatments produced between 230 and 273 mg plant^{-1} (Figure 3). The highest value was observed in the treatment that received the total dose of fertilizer in solid form, corresponding to increases of approximately 79% and 98% compared to the control and hydrogel-only treatments, respectively. However, no significant differences were detected between the fertilized treatments, regardless of the fertilizer application method.

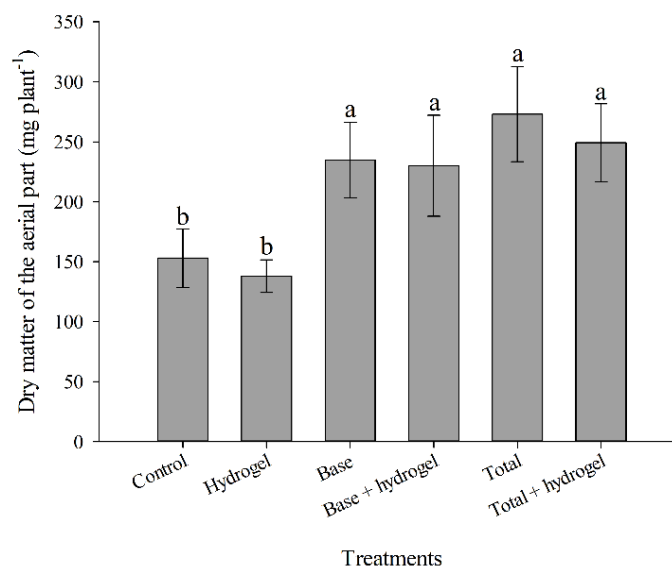


Figure 3. Dry matter of the aerial part of wheat plants subjected to different levels of potassium and nitrogen fertilization, with or without hydrogel. Columns with different letters differ from each other according to *Duncan's* test (p -value < 0.05). Source: The Authors, 2026.

Root dry matter was significantly affected by the fertilization strategy (Figure 4). The control and isolated hydrogel treatments showed the lowest values, with averages of 92 and 102 mg plant⁻¹, respectively. The application of the basal fertilizer dose, both in solid form and associated with hydrogel, resulted in intermediate values of root biomass, ranging from 127 to 134 mg plant⁻¹. The greatest accumulation of dry matter in the roots was observed in the treatment that received the total fertilizer dose in solid form (approximately 216 mg plant⁻¹), representing increases of 135% and 112% compared to the control and isolated hydrogel treatments, respectively. The treatment that combined the total fertilizer dose with hydrogel showed intermediate values (approximately 170 mg plant⁻¹) and did not differ statistically from the treatment that received the basal fertilizer dose.

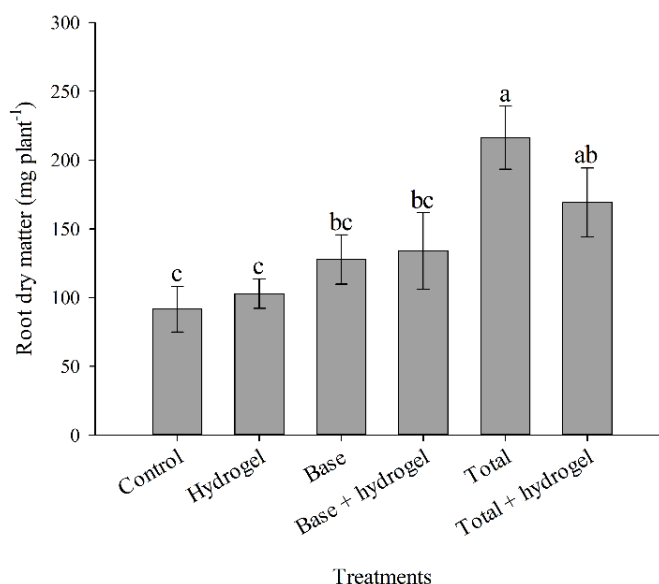


Figure 4. Dry matter of the root system of wheat plants subjected to different levels of potassium and nitrogen fertilization, with or without hydrogel. Columns with different letters differ from each other according to *Duncan's* test (p -value < 0.05). Source: Authors, 2026.

The electrical conductivity (EC) of the leachate increased with the fertilizer application rate and was consistently higher when nutrients were incorporated into the hydrogel (Figure 5). The control and pure hydrogel treatments showed the lowest EC values, with averages of approximately 220 and 200 mS cm⁻¹, respectively. Under the basal fertilizer dose, EC increased from 300 mS cm⁻¹ in the solid fertilizer treatment to 340 mS cm⁻¹ when nutrients were associated with the hydrogel, representing an increase of approximately 14%. A similar pattern was observed for the total fertilizer dose, where EC increased from 400 to 465 mS cm⁻¹ when hydrogel was used, corresponding to an increase of 16%.

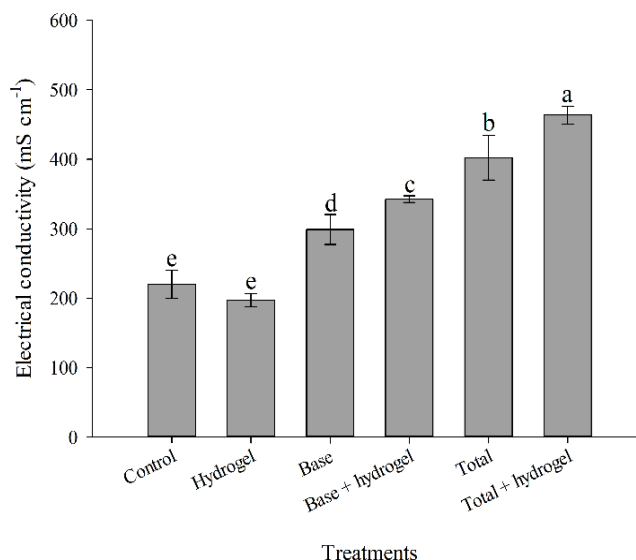


Figure 5. Electrical conductivity of leachate from wheat plants subjected to different levels of potassium and nitrogen fertilization, with or without hydrogel. Columns with different letters differ from each other according to *Duncan's test* (p -value < 0.05). Source: Authors, 2026.

4. Discussion

The absence of differences in plant height during the initial stages of development (7 and 14 days after sowing) suggests that the initial growth of wheat was not limited by the external availability of nutrients. During this phase, seed reserves likely contributed substantially to seedling establishment, reducing dependence on soil nutrient supply. From day 21 onwards, however, the fertilized treatments showed consistently superior performance to the control and to the treatments with isolated hydrogel, indicating a progressive transition from dependence on internal reserves to dependence on soil nutrient availability during vegetative growth.

The greater amount of shoot dry matter observed in the treatments that received nitrogen and potassium reinforces the central role of mineral nutrition in biomass accumulation, particularly nitrogen, which is directly associated with chlorophyll synthesis, photosynthetic capacity, and carbon assimilation (Martin et al., 2021). Similar responses have been reported in other crops, where adequate nitrogen and potassium supply promoted increases in plant height and biomass production (Fernandes et al., 2020; Soares et al., 2020). In the present study, no significant differences were detected between the fertilization methods, indicating that the incorporation of nutrients into the hydrogel promoted plant growth to a similar extent as conventional solid fertilization under the evaluated conditions.

The comparable performance between hydrogel fertilization and conventional fertilization contrasts with studies conducted under water-limited conditions, in which hydrogels improved plant growth by increasing water availability and prolonging the residence time of nutrients in the rhizosphere (Albalasmeh et al., 2022; Minosso et al., 2021). This discrepancy highlights the strong dependence of hydrogel performance on environmental conditions, particularly water availability and percolation dynamics.

Recent advances in controlled-release fertilizers have reinforced the potential of hydrogels as carriers capable of synchronizing nutrient release with plant demand, thereby increasing nutrient use efficiency (NUE) and reducing environmental losses. Stimuli-responsive and biodegradable hydrogel systems have demonstrated the ability to regulate nutrient diffusion according to environmental conditions, promoting a more gradual nutrient supply and reducing nutrient losses through leaching. Several studies have reported improvements in nitrogen use efficiency and reductions in fertilizer waste when nutrients were incorporated into hydrogel matrices rather than applied in conventional soluble forms (Kirtil, 2026; Mansouri et al., 2023; Wang et al., 2022). However, these benefits are generally more pronounced under conditions where water movement through the soil profile is moderate, and nutrient release remains synchronized with plant uptake. In the present study, the high frequency of drainage events may have reduced the ability of the hydrogel to retain nutrients within the root zone, limiting the expected

advantages associated with controlled-release systems.

Studies involving nutrient-loaded hydrogels have demonstrated substantial reductions in nutrient losses compared with conventional fertilizers. Biodegradable hydrogels used as nutrient carriers have been shown to reduce nitrate leaching while simultaneously improving nutrient availability and crop performance. Recent reviews compiling field and greenhouse studies reported reductions of up to 80% in nitrate losses when hydrogels functioned as slow-release nutrient reservoirs, particularly under drought or moderate irrigation conditions (Kirtil, 2026). Similarly, hydrogel-based composites developed for nitrate retention maintained higher nitrate concentrations in the soil while minimizing nitrate displacement to deeper soil layers (Gao et al., 2025). These findings contrast with the results obtained in the present study, where higher electrical conductivity values were observed in hydrogel treatments. Such differences may be associated with the irrigation regime adopted, which promoted frequent drainage and may have accelerated the transport of dissolved ions through the soil profile.

The relationship between hydrogels and nutrient use efficiency (NUE) has also been extensively investigated in recent years. Enhanced NUE is considered one of the main agronomic advantages of hydrogel-based fertilization systems because nutrient availability can be prolonged over time, increasing the likelihood of nutrient uptake before losses occur. Nutrient-loaded hydrogels have been reported to improve nitrogen uptake, root development, and fertilizer recovery efficiency in several crops, particularly under water-limited conditions (Wang et al., 2022; Sarhan et al., 2024). In contrast, the absence of superior plant growth in hydrogel treatments observed in the present study suggests that increased nutrient retention was not achieved under conditions of high water availability. This reinforces the hypothesis that the agronomic benefits of hydrogel application are strongly dependent on the interaction between nutrient release kinetics and soil water dynamics.

Extreme rainfall events are among the major factors responsible for nutrient losses in agricultural soils, particularly for highly soluble nutrients such as nitrate and potassium. Under these conditions, rapid water percolation can exceed the retention capacity of soil amendments and controlled-release systems, increasing nutrient displacement beyond the root zone (Kirtil, 2026; Zhu et al., 2024). Although hydrogels are frequently proposed as a strategy to mitigate nutrient losses through improved water and nutrient retention, their effectiveness under intense drainage remains insufficiently understood and appears to be highly dependent on environmental conditions and irrigation management (Mamaghani et al., 2025; Agbna; Zaidi, 2025).

The results obtained in the present study suggest that, under conditions designed to promote continuous drainage, hydrogel incorporation was not sufficient to reduce the overall movement of dissolved ions. Similar limitations have been reported in studies indicating that the efficiency of hydrogel-based nutrient delivery systems decreases when water flux through the soil exceeds the nutrient retention capacity of the polymer matrix (Gao et al., 2025; Kirtil, 2026). Therefore, the effectiveness of hydrogels as nutrient retention agents should not be generalized across contrasting hydrological scenarios, and irrigation management should be considered a critical factor influencing their agronomic performance.

Root dry matter increased with the level of fertilization, especially at the total fertilizer dose. This result indicates that greater nutrient availability favored root development and overall plant growth. Although high concentrations of nitrogen and potassium can alter soil osmotic conditions (Filho et al., 2020; Paula et al., 2020), the present experiment did not include measurements of osmotic potential or soil solution salinity. Therefore, any relationship between root growth and osmotic adjustment remains speculative and should be interpreted with caution.

The electrical conductivity of the leachate increased with the fertilizer application rate and was consistently higher in treatments where nutrients were incorporated into the hydrogel. Since electrical conductivity reflects the total concentration of dissolved ions, these results indicate a higher concentration of solutes in the leachate, but do not allow for the identification or quantification of specific nutrients. Consequently, electrical conductivity should be interpreted as an indirect indicator of the overall movement of solutes, and not as a direct measure of nitrogen or potassium losses.

The higher electrical conductivity observed in the hydrogel treatments suggests that the incorporation of nutrients into the polymer did not reduce the concentration of dissolved ions in the leachate under the irrigation regime adopted in this study. A possible explanation is that the prior solubilization of nutrients may have increased the availability of ions in the soil solution, facilitating their movement during drainage events. However, this hypothesis cannot be confirmed without direct quantification of nitrogen and potassium concentrations in the leachate.

It is important to consider that the experimental design included an irrigation regime specifically designed to promote controlled drainage and ensure leachate collection. The cumulative irrigation depth of 114.61 mm over 28 days likely intensified water percolation through the soil profile, creating conditions different from those

commonly observed in field management. Therefore, the responses observed in this study should be interpreted within the context of high water availability and frequent drainage events.

The superior performance observed with the total fertilizer dose indicates that, under experimental conditions, the greater availability of nutrients promoted plant growth without causing detectable reductions in biomass accumulation or plant height. A plausible explanation is that frequent drainage events reduced the accumulation of soluble salts in the root zone, thus mitigating the potential adverse effects associated with concentrated fertilizer application. However, since soil salinity and nutrient concentrations in the soil solution were not measured, this interpretation should be considered a hypothesis, not a proven mechanism.

Overall, the results demonstrate that the incorporation of hydrogel did not improve wheat growth compared to conventional fertilization and was not associated with lower leachate electrical conductivity under the experimental conditions. These results suggest that the effectiveness of hydrogels as nutrient retention agents is strongly influenced by irrigation management and environmental conditions. Further studies, combining direct measurements of nutrient concentrations in leachate with different irrigation regimes, are needed to elucidate the mechanisms governing nutrient dynamics in hydrogel-based fertilization systems.

5. Conclusions

Nitrogen and potassium fertilization promoted greater plant growth and biomass accumulation during the initial development of wheat, regardless of the application method. Under the irrigation regime adopted in this study, the incorporation of nutrients into the hydrogel resulted in plant performance similar to that obtained with conventional solid fertilization. Furthermore, hydrogel application was not associated with lower leachate electrical conductivity, suggesting limited effectiveness in reducing overall solute movement under conditions of high water availability and frequent drainage events.

The results indicate that the effectiveness of hydrogel as a nutrient retention strategy is strongly dependent on water dynamics and may be reduced under conditions that favor leaching. However, because the experiment was conducted only during the first 28 days of crop development, the findings should be interpreted as representative of the early growth stage of wheat and should not be directly extrapolated to grain yield or full-season crop performance. Future studies should include longer evaluation periods, direct quantification of nutrient concentrations in the leachate, and different irrigation regimes to better understand the role of hydrogels in nutrient management throughout the crop cycle.

6. Authors' Contributions

Ygor Mota Soca Machado: conception of the original idea, experimental design, data collection and analysis, manuscript writing and revision. *Nicolas Xavier de Castro*: data collection, manuscript writing and revision.

7. Conflicts of Interest

No conflicts of interest.

8. Ethics Approval

Not applicable.

9. References

- Agbna, G. H. D., & Zaidi, S. J. (2025). Hydrogel performance in boosting plant resilience to water stress—A review. *Gels*, 11(4), 276. <https://doi.org/10.3390/gels11040276>
- Albalasmeh, A. A., Osama, M., Mamoun, A. G., Abdulaziz, G. A., Mohammad, A. A., & Ahmad, M. A. (2022). Effect of hydrogel on corn growth, water use efficiency, and soil properties in a semi-arid region. *Journal of the Saudi Society of Agricultural Sciences*, 21(8), 518-524. <https://doi.org/10.1016/j.jssas.2022.03.001>
- Barbieri, E., Pereira, G. M., Feitosa Filho, L. A., & Hahn, K. G. (2023). Custo de produção agrícola: comparativo de rentabilidade das culturas de trigo, soja e milho nas safras de 20/21 e 22/23, em uma unidade produtiva situada em Ampére no sudoeste do Paraná. *RECIMA21 - Revista Científica Multidisciplinar*, 4(1), e414375. <https://doi.org/10.47820/recima21.v4i1.4375>.

- Chaboussou, F. (2006). Plantas doentes pelo uso de agrotóxicos. São Paulo: Expressão Popular.
- Costa, M. M. M. N. (2024). Salinidade do solo/Acidez do Solo. Campina Grande: Embrapa Algodão. (Circular Técnica, 145). Available in: <https://www.infoteca.cnptia.embrapa.br/infoteca/bitstream/doc/1176428/1/COSTA-MAGNA-CIR-TEC-145.pdf>. Acesso em: 19 jun. 2026.
- Fernandes, C. N. D., Fernandes, C. N. V., Viana, T. V. A., Sobreira, A. E. A., Alves, J. L. S., & Azevedo, B. M. (2020). Fertirrigação nitrogenada e potássica na cultura do milho verde. *Revista Brasileira de Agricultura Irrigada*, 13(6), 3724-3730. <https://doi.org/10.7127/rbai.v13n6001141>
- Filho, H. A. M., Silva, C. A., & Bastos, A. V. S. (2020). Níveis de irrigação associados a doses de hidrogel na cultura do pimentão. *Revista Brasileira de Agricultura Irrigada*, 14(2), 3906-3918. <https://doi.org/10.7127/rbai.v14n101096>
- Franco, M. F. S., & Delgado, E. U. A. (2022). Relação entre adubação e qualidade dos produtos agrícolas. *Research, Society and Development*, 11(4), e36311427562. <https://doi.org/10.33448/rsd-v11i4.27562>
- Gao, X., Guo, Z., Yang, Z., Meng, Q., Fu, H., Zhang, J., & Yan, M. (2025). Sustained nitrate release from hydrogel encapsulated layered double hydroxides-biochar composite: Experiments and theoretical elucidation. *Industrial Crops and Products*, 238. <https://doi.org/10.1016/j.indcrop.2025.122332>
- Ghobashy, M. M., Amin, M. A., Mustafa, A. E., El-Diehy, M. A., El-Damhougy, B. K., & Nady, N. (2024). Synthesis and application of a multifunctional poly (vinyl pyrrolidone)-based superabsorbent hydrogel for controlled fertilizer release and enhanced water retention in drought-stressed *Pisum sativum* plants. *Scientific Reports*, 14(1), 27734. <https://doi.org/10.1038/s41598-024-76255-7>
- Gomes, M. P., Rezende, C. H. S., Souza, J. A., & Rocha, G. C. (2022). Lixiviação de potássio em um latossolo cultivado com café. *Irriga*, 27(3), 597-606. <https://doi.org/10.15809/irriga.2022v27n3p597-606>
- Guilherme, M. R., Aouada, F. A., & Fajardo, A. R. (2015). Superabsorbent hydrogels based on polysaccharides for application in agriculture as soil conditioner and nutrient carrier: A review. *European Polymer Journal*, 72, 365-385. <https://doi.org/10.1016/j.eurpolymj.2015.04.017>
- Jadoski, S. O., Andrade, A. R. S., Jadoski, C. J., Bueno, J. C. M., & Teixeira, L. A. R. (2022). Lixiviação de nitrato em cultivo de alface em sistema de cultivo protegido. *Revista Foco*, 15(5), 1-16. <https://doi.org/10.54751/revistafoco.v15n5-015>
- Kaneko, F. H., Rinzo, R. T., Oliveira, B. L., Prado, J. A., Assis, G. P. B., Piletti, L. M. M., & Silva, I. P. F. (2021). Doses e fontes de fósforo na cultura da soja. *Cultura Agrônômica*, 29(4), 400-411. <https://doi.org/10.32929/2446-8355.2020v29n4p400-411>
- Kirtil, E. (2026). Recent advances in biodegradable hydrogels for sustainable agriculture: From water retention to nutrient delivery. *European Journal of Agronomy*, 177, 128098. <https://doi.org/10.1016/j.eja.2026.128098>
- Koch, M., Naumann, M., Pawelzik, E., Gransee, A., & Thiel, H. (2019). The importance of nutrient management for potato production part I: Plant nutrition and yield. *Potato Research*, 63, 97-119. <https://doi.org/10.1007/s11540-019-09431-2>
- Li, J., Li, L., Zhang, Y., Zhang, Q., Wang, Y., & Yu, X. (2025). Bio-based hydrogel particles with enhanced water retention properties for alleviating drought stress of saline soil. *Journal of Cleaner Production*, 518. <https://doi.org/10.1016/j.jclepro.2025.145960>
- Lima, J. C., Nascimento, M. N., Jesus, R. S., Silva, A. L., Santos, A. R., & Oliveira, U. C. (2020). Crescimento inicial e diagnose nutricional de plantas de milho cultivadas com omissão de macronutrientes em argissolo. *Nativa*, 8(4), 567-571. <https://doi.org/10.31413/nativa.v8i4.9033>
- Mamaghani, K. R., Alikarami, M., & Saremi, H. (2025). Polymeric hydrogels in agriculture: Environmental performance, sustainability challenges, and future perspectives. *ACS Agricultural Science & Technology*, 5(12), 2341-2360. <https://doi.org/10.1021/acsagcitech.5c00808>
- Malik, S., Chaudhary, K., & Malik, A. (2023). Superabsorbent polymers as a soil amendment for increasing agriculture production with reducing water losses under water stress condition. *Polymers*, 15(1), 161. <https://doi.org/10.3390/polym15010161>
- Martin, T. N., Corrêa, A. R., Ferreira, M. M., Arismendi, G. A., & Lanzarin, M. M. (2021). Nitrogênio em cobertura, tratamento de semente e aplicação foliar no trigo. *Enciclopédia Biosfera*, 18(36), 253-265. https://doi.org/10.18677/EnciBio_2021B18

- Minosso, R. R., Sostisso, G. L., & Dranski, J. A. L. (2021). Componentes de rendimento e produtividade da soja cultivada com hidrogel. *Revista Científica Rural*, 23(1), 69-82. <https://doi.org/10.30945/rcr-v23il.3139>
- Montesano, F. F., Parente, A., Santamaria, P., Sannino, A., & Serio, F. (2015). Biodegradable superabsorbent hydrogel increases water retention properties of growing media and plant growth. *Agriculture and Agricultural Science Procedia*, 4, 451-458. <https://doi.org/10.1016/j.aaspro.2015.03.052>
- Patra, S. K., Poddar, R., Brestic, M., Acharjee, P. U., Bhattacharya, P., Sengupta, S., Pal, P., Bam, N., Biswas, B., Barek, V., Ondrisik, P., & Skalicky, M. (2022). Prospects of hydrogels in agriculture for enhancing crop and water productivity under water deficit condition. *International Journal of Polymer Science*. <https://doi.org/10.1155/2022/4914836>
- Paula, R. H. R., Anjos, D. N., Freitas, P. H. G., & Ribeiro, J. S. (2020). Efeito da salinidade do cloreto de potássio na emergência e no crescimento inicial de plântulas de soja. *Pesquis Agro*, 3(1), 110-117. <https://doi.org/10.33912/pagro.v3il.664>
- Pereira Filho, J. V., Mendonça, A. M., Sousa, G. G., Viana, T. V. A., Ribeiro, R. M. R., & Canjá, J. F. (2020). Crescimento inicial da cultura da fava irrigada sob estresse salino e hídrico. *Revista Brasileira de Agricultura Irrigada*, 14(3), 4036-4046. <https://doi.org/10.7127/RBAI.V14N101139>
- Pérez, C. D. P., Pozza, E. A., Pozza, A. A. A., Elmer, W. H., Pereira, A. B., Guimarães, D. S. G., Monteiro, A. C. A., & Rezende, M. L. V. (2020). Boron, zinc and manganese suppress rust on coffee plants grown in a nutrient solution. *European Journal of Plant Pathology*, 156(3), 727-738. <https://doi.org/10.1007/s10658-019-01922-9>
- Queiroz, B., Ságio, S. A., & Teixeira, J. R. T. (2020). Doses de fósforo no desenvolvimento da cultura da soja na região central do Tocantins. *Agri-Environmental Sciences*, 6, 1-7. <https://doi.org/10.36725/agries.v6i0.1995>
- R Core Team. (2023). R: A language and environment for statistical computing. Vienna: R Foundation for Statistical Computing. Available at: <https://www.R-project.org/>. Accessed on: September 3, 2025.
- Rossi, A. C. M., Kusano, D. M., Lopes, F. S., & Silva, M. A. C. (2020). Distribuição vertical de fósforo no solo proveniente do superfosfato triplo. *Research, Society and Development*, 9(10), e6049108894. <https://doi.org/10.33448/rsd-v9i10.8894>
- Saha, A., Sekharan, S., & Manna, U. (2020). Superabsorbent Hydrogel (SAH) as a Soil Amendment for Drought Management: A Review. *Soil and Tillage Research*, 204, 104736. <https://doi.org/10.1016/j.still.2020.104736>
- Santos, E. O., & Medeiros, P. R. P. (2023). A ação antrópica e o processo de eutrofização no Rio Paraíba do Meio. *Sociedade & Natureza*, 35(1), 1-13. <https://doi.org/10.14393/SN-v35-2023-66441>
- Soares, P. P. S., Mesquita, N. L. S., Almeida, J. R., Coutrim, R. L., Cairo, P. A. R., & Silva, L. D. (2020). Crescimento, qualidade de raízes e atividade da redutase do nitrato em plantas de rabanete submetidas a doses de potássio e fontes de nitrogênio. *Scientia Plena*, 16(6). <https://doi.org/10.14808/sci.plena.2020.060205>
- Systat Software Inc. (2010). SigmaPlot for Windows version 12.0 [software]. San Jose: Systat Software Inc. Available at: <https://grafiti.com>. Accessed on: January 15, 2026.
- Tariq, Z., Iqbal, D. N., Rizwan, M., Ahmad, M., Faheem, M., & Ahmed, M. (2023). Significance of biopolymer-based hydrogels and their applications in agriculture: a review in perspective of synthesis and their degree of swelling for water holding. *RSC Advances*, 13(35), 24731-24754. <https://doi.org/10.1039/D3RA03472K>
- Trindade, P. S. C., Sena, W. L., Sales, T. M., Silva, A. L. P., & Lélis, A. T. (2024). Desenvolvimento de mudas de Theobroma cacao L. sob omissão de macro e micronutrientes. *Observatorio de la Economía Latinoamericana*, 22(1), 1276-1295. <https://doi.org/10.55905/oelv22n1-068>
- Viçosi, K. A., & Pelá, A. (2020). Doses de nitrogênio em cobertura e inoculação com *Rhizobium tropici* na cultura do feijão-vagem. *Cultura Agronômica*, 29(3), 326-336. <https://doi.org/10.32929/2446-8355.2020v29n3p326-336>
- Vedovello, P., Sanches, L. V., Teodoro, G. S., Majaron, V. F., Bortoletto-Santos, R., Ribeiro, C., & Putti, F. F. (2024). An overview of polymeric hydrogel applications for sustainable agriculture. *Agriculture*, 16(4), 840. <https://doi.org/10.3390/agriculture14060840>
- Zhu, H., Zheng, B., Zhong, W., Xu, J., Nie, W., Sun, Y., & Guan, Z. (2024). Infiltration and leaching characteristics of soils with different salinity under fertilizer irrigation. *Agronomy*, 14(3), 553. <https://doi.org/10.3390/agronomy14030553>

Funding

Not applicable.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Copyrights

Copyright for this article is retained by the author(s), with first publication rights granted to the journal.

This is an open-access article distributed under the terms and conditions of the Creative Commons Attribution license (<http://creativecommons.org/licenses/by/4.0/>).