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Hydrogel polymer as a sustainable input for mitigating nutrient leaching and promoting plant growth in sugarcane crops

Patricia Angélica Alves Marques[1*], Fernando Campos Mendonça[1], Tadeu Alcides Marques[2], Lívia Pimentel do Prado Silva[3], Carlos Sérgio Tiritan[3], Vinícius Villa e Vila[1] and Damodhara Rao Mailapalli[4]

[1]Programa de Pós-graduação em Engenharia de Sistemas Agrícolas, Escola Superior de Agronomia "Luiz de Queiroz", Universidade de São Paulo, Avenida Pádua Dias, 11, 13418-900, Piracicaba, São Paulo, Brazil. [2]Faculdade de Tecnologia de São Paulo, Piracicaba, São Paulo, Brazil. [3]Programa de Pós-graduação em Agronomia, Universidade do Oeste Paulista, Presidente Prudente, São Paulo, Brazil. [4]Agricultural and Food Engineering Department, Indian Institute of Technology, Kharagpur, 721302, India. *Author for correspondence. E-mail: paamarques@usp.br

ABSTRACT. Nutrient leaching is a common issue in sandy soils. The use of hydrogel polymers can mitigate this problem by enhancing soil water retention. This study aims to assess the effect of hydrogel polymer application on nutrient leaching in sugarcane-cultivated soil and its impact on plant growth over a 196-day cycle. Parameters examined include soil water retention (%), nutrient leaching (N, P, K, Ca, Mg, and S) analyzed through the water collected after natural drainage, as well as various plant growth parameters such as stem height and diameter, and fresh and dry stem and leaf mass. The highest soil water retention was observed in treatments with 1.5 and 2.0 g kg^{-1} of hydrogel polymer. Regarding nutrient leaching, the treatments with 1.5 and 2.0 g kg^{-1} of hydrogel polymer exhibited the lowest values, resulting in reductions of over 85% for all accumulated nutrients leached by the end of the crop cycle. The application of hydrogel, especially at higher doses, also enhanced sugarcane growth, notably increasing fresh stem mass. These results suggest that hydrogel polymers could serve as a sustainable solution for controlling nutrient leaching in sugarcane cultivation, contributing to the sustainable development of agriculture and environmental preservation.

Keywords: polyacrylamide; sustainability; water retention; water management.

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Introduction

Sugarcane holds great global significance due to its wide range of applications. Its cultivation is expanding, particularly in tropical and subtropical regions, even in less productive areas like degraded pastures. However, one of the challenges in achieving sustainable sugarcane production is the efficient use of synthetic fertilizers (Bordonal et al., 2018).

Sugarcane is predominantly grown in sandy soils (Watanabe, Saensupo, Na-iam, Klomsa-ard, & Sriroth, 2019), which often suffer from limited water retention capacity and excessive deep percolation, leading to inefficient water and fertilizer usage (Huang & Hartemink, 2020; Li, Zhang, Novak, Yang, & Wang, 2021). Water availability in the soil is a critical factor for agricultural production, especially in regions with predominantly sandy soil textures, where water scarcity is exacerbated by climate change (Oladosu et al., 2022).

Hydrogel polymers offer a sustainable solution to address water availability issues, water stress, and prolonged drought periods in arid and semi-arid regions (Oladosu et al., 2022). These hydroretentive polymers have been investigated to combat low productivity caused by irregular water availability and poor soil structure (Jeevan, Ananthakumar, Kadalli, Thimmegowda, & Asha, 2023).

Hydrogels possess numerous beneficial properties, including colorlessness, odorlessness, non-toxicity, biodegradability, biocompatibility, high durability, and stability. They do not react with soil constituents but directly enhance water retention in the soil, thereby improving crop and water productivity under water-deficient conditions (Patra et al., 2022). Hydrogels have been explored as a potential solution to environmental issues such as nutrient leaching and soil salinization (Campo et al., 2021; Tefera et al., 2022).

Nutrient leaching from the soil occurs due to interactions between nutrients and soil colloids, leading to the formation of complexes that affect nutrient adsorption and mobility. Highly hydrated ions (Ca^{2+}, Mg^{2+}, Na^{+}, and NO_3^{-}) form outer-sphere complexes with soil solids, allowing them to move more freely with water flow. In contrast, ions like PO_4^{3-} form inner-sphere complexes with mineral components, limiting their mobility (Malavolta, 2006).

Nutrient losses, especially leaching of macronutrients, can have severe environmental consequences, including increased groundwater contamination risk (Huang & Hartemink, 2020; Shi et al., 2020; Zhao et al., 2022). Nitrogen is the most extensively studied leached nutrient, with approximately 40 to 70% of N_2 in nutrient form being susceptible to leaching (Wu & Liu, 2008). Potassium has also been extensively studied in terms of leaching (Montealegre, Vanegas, Nústez-López, & Rozo, 2022). Phosphorus is less mobile in the soil profile, studies have shown that it can be leached in smaller quantities (Zhang et al., 2023).

Efforts should focus on improving strategies for nutrient retention, enhancing crop fertilizer use efficiency, and improving soil moisture (Shi et al., 2020; Zhao et al., 2022). The application of hydrogels in soils can reduce nutrient leaching, increase water absorbency/retention capacity, and subsequently boost agricultural production (Liu, Wang, Chen, & Cheng, 2022). While studies on Ca, Mg, and S leaching are less common than other macronutrients in the literature, some evidence suggests that these nutrients can also move within the soil profile, particularly in response to soil correction practices such as agricultural gypsum application (Castro-Pias, Tiecher, Cherubin, Silva, & Bayer, 2020).

This study aims to investigate the impact of hydrogel polymer application on nutrient leaching in sugarcane-cultivated sandy soil.

Material and methods

The experiment was conducted within a protected environment at the University of Western São Paulo, São Paulo State, Brazil, located at 51°26'00" W 22°07'30" S, with an altitude of 430 meters. The local climate, classified as mesothermal (*Aw*) according to Köppen, experiences hot summers and dry winters. The soil used for this study falls under the category of Red-Yellow Eutrophic Argisol, as per the Brazilian Soil Classification, equivalent to an Ultisol in the US Soil Taxonomy (Santos et al., 2018). The protected environment measured 20 meters in length, eight meters in width, with a 150 μm thick plastic cover and a ceiling height of six meters, enclosed by an anti-aphid nylon mesh. The chemical and physical properties of the soil are outlined in Table 1. The water storage capacity in the soil, accounting for the effective root system depth of 50 cm for sugarcane, was 75 mm, using θ_{cc} = 21.9% and θ_{pmp} = 6.9%, as determined from the soil water retention curve adjusted (Van Genuchten, 1980).

Table 1. Physical and chemical properties of the soil studied.

P	K	Ca	Mg	S	Al	H+Al	Mn	Fe	Cu	Zn	B
mg dm^{-3}	mmol$_c$ dm^{-3}						mg dm^{-3}				
36.0	1.8	11.0	3.0	1.3	0.0	19.0	16.1	23.2	1.3	0.6	0.1
pH	OC	CEC		Sand	Silt	Argil	Textural class		Soil density	Total porosity	
$CaCl_2$	g dm^{-3}	mmol$_c$ dm^{-3}			g kg^{-1}				g cm^{-3}	%	
5.5	7.0	34.0		795.7	64.3	140.0	sandy		1.7	37.1	

OC: Organic carbon; CEC: cation exchange capacity; P: resin extraction; B: hot water extraction and Mn, Fe, Cu, and Zn: DTPA extraction.

The experiment employed a completely randomized design, consisting of five treatments based on hydrogel doses (0.0, 0.5, 1.0, 1.5, and 2.0 g kg^{-1}), expressed as grams of hydrogel per kilogram of soil, with five repetitions. The hydrogel used was Hydroplan-EB™, registered with the Ministry of Agriculture and Supply under the registration number SP 09203/00001-2. The sugarcane variety utilized was RB 86-7515TM, a commonly cultivated variety in western São Paulo State due to its high productivity, rapid growth, and tolerance to soils with low to medium productivity. The crop was grown in 20-liter pots measuring 25 cm in width and 50 cm in height. Hydrogel doses were individually applied to the pots after measuring the soil. Each pot featured an independent drainage system for collecting and assessing drained water volume and leached nutrients. Pots were suspended on a 1-meter-high platform, equipped with a funnel at the bottom and a graduated cylinder for content collection.

Seedlings were planted in the pots after a 70-day production period. The soil underwent chemical fertilization using a commercial formulation of 08-28-16 (N/P/K), adjusted based on the chemical analysis of the soil and following crop recommendations (Cantarella, Mattos Junior, Boaretto, Quaggio, & Van Raij, 2022).

The fraction of water retained in the soil (WRS) was determined by applying a known volume of water and collecting naturally drained water volume 24 hours after each application, repeated every 14 days using funnels placed at the bottom of the pots. The soil solution extracted was used for subsequent determinations. The percentage of WRS was calculated using Equation 1.

$$WRS\ (\%) = \frac{(Va - Vc)}{Va} \cdot 100 \qquad 1$$

where: WRS - water retained in the soil (%); Va - volume applied to the soil (mL); Vc - naturally, drained volume gathered 24 hours after soil water application (mL).

Daily irrigation was performed in each pot, with individualized irrigation tailored to replace 110% of crop evapotranspiration (ETc). This ensured that a volume of water was drained for further analysis. The accuracy of the applied volume was ensured by weighing lysimeters, using an analytical balance with a precision of 0.1 g.

Nutrient leaching (N, P, K, Ca, Mg, and S) was assessed by analyzing the water collected after natural drainage. The samples underwent extractions following the method outlined by Malavolta (1992).

Stem height and diameter measurements were taken during the growth process. Stem height was measured from the soil surface to the first leaf emission using a graduated tape (1.00 mm). Stem diameter measurements were recorded every 14 days in the middle third of the stem, using a digital caliper with a precision of 0.01 mm. At the conclusion of the experiment, various destructive parameters were evaluated, including total fresh mass of stem + leaves (TMF), stem fresh mass (SFM), leaf fresh mass (LFM), stem dry mass (SDM), and leaf dry mass (LDM). Mass measurements were obtained using an analytical balance with a precision of 0.01 g. Before determining dry mass, the materials were dried in an oven with forced air ventilation at 65°C until a constant mass was achieved (Benincasa, 2003).

All data underwent analysis of variance using ANOVA. Significant differences ($p < 0.05$) between the analyzed quantitative factors were further subjected to regression analysis to establish potential functional relationships between dependent and independent variables, specifically hydrogel doses and sugarcane development stages. Data analysis was conducted using the statistical software SISVAR (Ferreira, 2019).

Results

Throughout the evaluation period, from 14 days after transplanting (DAT) to 196 DAT, a total of 90 liters of water were applied to each pot, equivalent to 992 mm. These values were calculated to replace 110% of the evapotranspiration during the period, allowing for surplus drainage. The results of soil water retention, as shown in Figure 1 and Table 2, indicate a significant increase in water retention with the application of hydrogel. As the hydrogel doses increased, there was a corresponding increase in water retention.

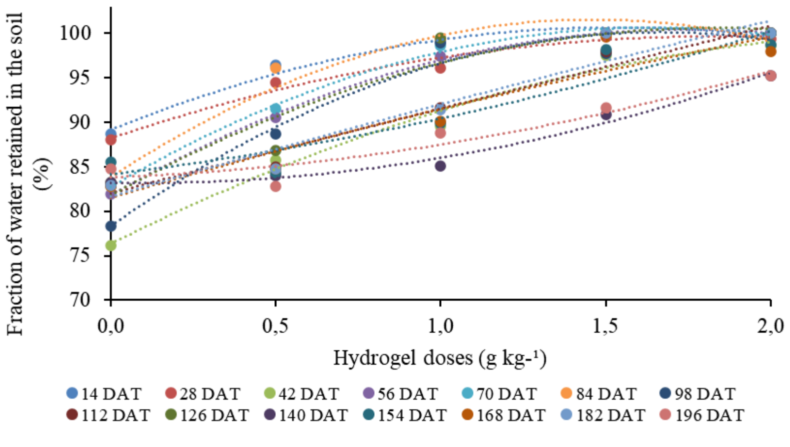

Figure 1. Fraction of water retained in the soil (%) for different hydrogel doses during the sugarcane crop cycle. DAT: Days after transplanting.

The cumulative water retention over the entire period exhibited a quadratic trend, with a coefficient of determination close to or greater than 0.90. Without hydrogel application, water retention in the soil remained below 90% on all 14 evaluated days, reaching its lowest point at 42 DAT (76.17%). However, with the highest doses of hydrogel (1.5 g and 2.0 g kg^{-1} soil), water retention consistently exceeded 90%, often approaching 100%. These two doses increased water retention by 17.38 and 17.71%, respectively, compared to the treatment without Hydroplan-EB.

Table 2. Regression models explaining soil water retention as a function of hydrogel doses over 14 days during the sugarcane cycle.

Days after transplanting (DAT)	Regression model	R^2
14	$y = -4.91x^2 + 15.05x + 89.15$	0.98*
28	$y = -0.36x^2 + 12.41x + 88.23$	0.97*
42	$y = -3.61x^2 + 18.579x + 76.35$	0.98*
56	$y = -6.11x^2 + 21.34x + 81.78$	0.99*
70	$y = -6.63x^2 + 21.81x + 82.73$	0.99*
84	$y = -8.30x^2 + 24.26x + 83.84$	0.96*
98	$y = -7.86x^2 + 26.20x + 78.34$	0.97*
112	$y = -0.12x^2 + 9.65x + 82.02$	0.97*
126	$y = -5.55x^2 + 20.45x + 81.79$	0.91*
140	$y = 3.42x^2 - 0.62x + 83.21$	0.98*
154	$y = 1.78x^2 + 4.50x + 84.15$	0.87*
168	$y = -0.94x^2 + 10.91x + 81.53$	0.89*
182	$y = -0.48x^2 + 10.86x + 81.66$	0.93*
196	$y = 2.32x^2 + 1.34x + 83.84$	0.92*

Y: Fraction of water retained in the soil (%); X: Hydrogel doses (g kg^{-1}); R^2: Determination coefficient; *: significance difference with 5% of significance.

Figure 2 illustrates the nutrient leaching behavior of N, P, K, Ca, Mg, and S over the course of the crop cycle. It is evident that all nutrients exhibited a similar trend, with increasing nutrient leaching as the crop cycle progressed. Regardless of the hydrogel dose applied, it was effective in reducing nutrient leaching compared to the control treatment without hydrogel.

Nitrogen displayed the highest leaching (Figure 2A), with an accumulated leaching of 18.04 g kg^{-1} in the absence of hydrogel. The lowest hydrogel dose already reduced this to 11.73 g kg^{-1}, while the highest dose reduced to 1.55 g kg^{-1}, with no significant difference between the doses of 1.5 and 2.0 g kg^{-1}.

For phosphorus leaching (Figure 2B), without hydrogel application, 1.61 g kg^{-1} leached by 196 DAT, whereas doses of 1.5 and 2.0 g kg^{-1} resulted in leaching of 0.16 and 0.13 g kg^{-1}, respectively. Potassium leaching (Figure 2C) decreased from 2.51 to 0.1 g kg^{-1} with the application of 2.0 g kg^{-1} of hydrogel compared to the treatment without application.

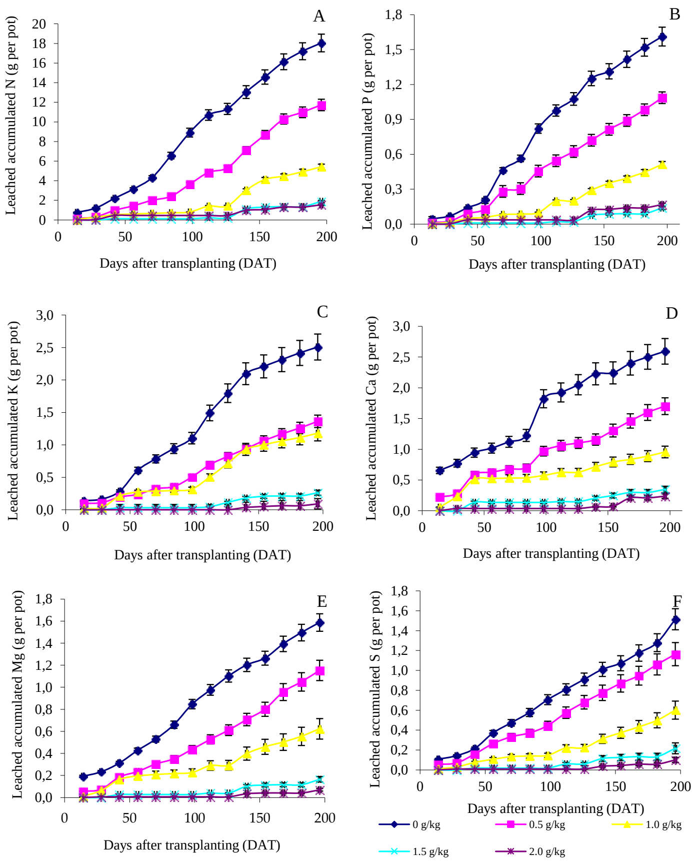

Figure 2. Nutrient leaching accumulation (g per pot) during sugarcane crop cycle every 14 days until 196 days after transplanting (DAT) as a function of hydrogel polymer doses.

Calcium (Figure 2D) showed the highest leaching, after nitrogen, on the last evaluation day, with 2.60 g kg^{-1}. Magnesium (Figure 2E) exhibited 1.59 g kg^{-1}, and sulfur (Figure 2F) had 1.51 g kg^{-1} at 196 DAT. These nutrients, by 196 DAT, displayed leaching of 0.24, 0.07, and 0.1 g kg^{-1}, respectively, with all nutrients leaching less than 3.00 g kg^{-1}. Nutrient leaching decreased with increasing hydrogel doses (Figure 3).

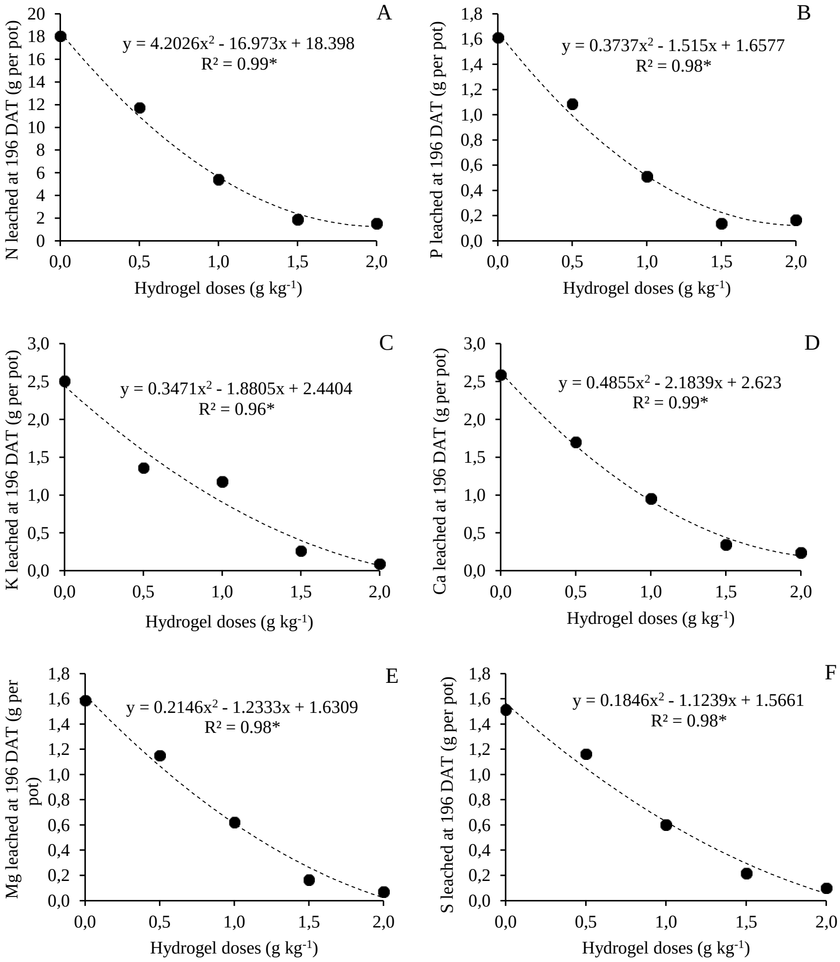

Figure 3. Average accumulated nutrient leaching during the sugarcane cycle at 196 DAT as a function of increasing hydrogel doses.

Figure 3 presents reduction equations for nutrient leaching at the end of the production cycle. Total reduction in nitrogen leaching (Figure 3A) was 89.52 and 91.43% with doses of 1.5 and 2.0 g kg^{-1} of soil over 30 weeks compared to the treatment without hydrogel. Phosphorus leaching reduction (Figure 3B) was 91.44 and 89.64% for doses of 1.5 and 2.0 g kg^{-1} of soil, respectively. Potassium showed reductions of 98.55 and 99.49% for treatments with 1.5 and 2.0 g kg^{-1} of soil compared to the control (Figure 3C). For calcium (Figure 3D), reductions were 86.58 and 90.82%, magnesium (Figure 3E) exhibited 93.64 and 97.30%, and sulfur (Figure 3F) showed reductions of 91.63 and 96.14% for doses of 1.5 and 2.0 g kg^{-1} of soil, respectively.

Significant differences were not observed up to 112 DAT, but from 126 DAT onward, the treatment effects became evident (Figure 4). At the end of the experiment (196 DAT), a significant difference was observed, with an increase in hydrogel dose leading to a 43.95% increase in sugarcane stem height compared to the control.

Figure 5 indicates that stem diameter was less affected by hydrogel doses compared to stem height. No significant differences were observed in periodic analyses up to 168 DAT, but from 182 DAT onward, the effect of hydrogel application became apparent. At the end of the experiment (196 DAT), the highest dose resulted in a 13.94% increase in stem diameter compared to the control.

At the end of the experiment, as shown in Figure 6, hydrogel application significantly increased stem and leaf mass. Increasing doses correlated with greater fresh leaf mass, stem fresh mass, and stem dry mass. The two highest doses of the polymer outperformed the others, displaying increases of 47.59 (Figure 6A), 79.84 (Figure 6B), and 69.51% (Figure 6D) for fresh leaves, stem fresh mass, and stem dry mass, respectively, at the 1.5 g kg^{-1} dose.

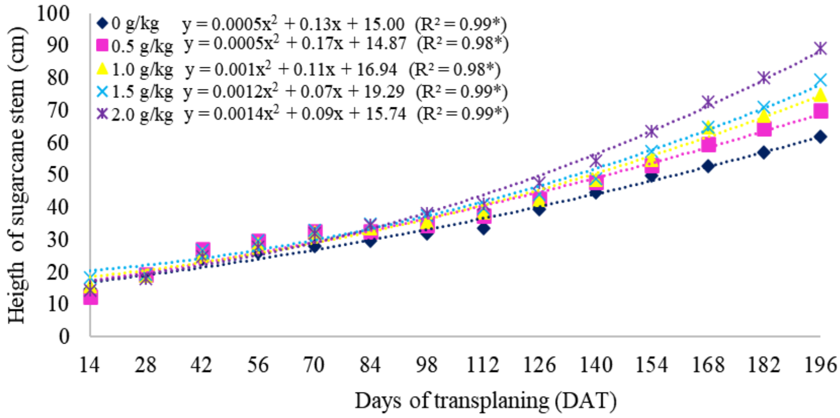

Figure 4. Sugarcane stem height (cm) during the growth process for different hydrogel doses.

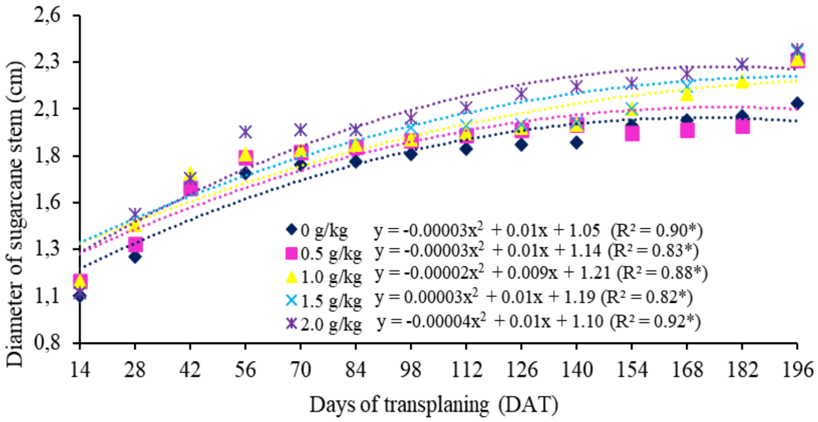

Figure 5. Sugarcane stem diameter (cm) during the growth process for different hydrogel doses in the sugarcane crop.

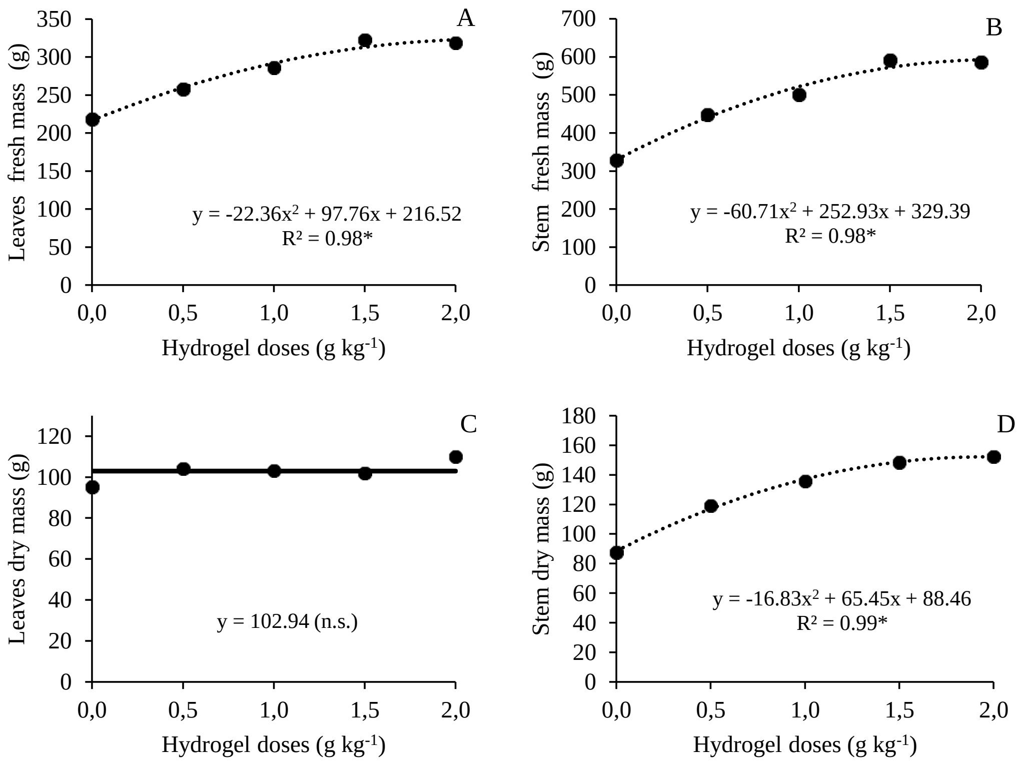

Figure 6. Fresh leaf mass (A), stem fresh mass (B), leaf dry mass (C), and stem dry mass (D) of sugarcane as a function of different hydrogel doses at 196 DAT.

Discussion

Among different soil types, sandy soil presents various challenges due to its physical, hydrological, chemical, agronomic, ecological, and biological characteristics. Investigating techniques that can mitigate these challenges, particularly in sandy soils, is crucial for environmental sustainability and conservation (Huang & Hartemink, 2020). This research demonstrates that the application of hydrogel, at specific doses, can enhance soil water retention, reduce leaching of six crucial macronutrients (N, P, K, Ca, Mg, and S), and promote the growth of sugarcane.

The use of hydrogel at a dose of 2 g kg^{-1} significantly increased soil water retention by 17.71%. This increase in soil moisture is attributed to the hydrophilic properties of the polymer, which can absorb and retain a substantial amount of water within its molecular chains. Additionally, hydrogel can function as a controlled-release material, slowly releasing substances such as fertilizers (Liu et al., 2022; Watanabe et al., 2019). Similar results were reported by Zhao et al. (2022), where the use of superabsorbent polymers decreased soil water leaching loss by 12.6 - 22.7%, leading to reduced leaching of N, P, and K.

Hydrogel can also serve as an alternative to address water scarcity, which can negatively impact plant development, causing reduced growth and productivity. Its ability to act as a soil conditioner is critical in retaining water and nutrients, creating more favorable conditions for sugarcane growth. The water retained within the hydrogel's chains, due to the expansion and separation of hydrophilic groups, plays a pivotal role in mitigating water scarcity (Oladosu et al., 2022).

Higher water retention values in treatments with greater hydrogel doses, compared to the control treatment, contributed to the reduction of nutrient leaching during the crop cycle. Enhanced water retention minimizes nutrient loss as less water drains from the soil, resulting in increased availability of both water and nutrients for plant uptake. This favored the growth of sugarcane stems, leading to a 43.95% increase in height and a 13.94% increase in diameter at the end of the cycle.

The reduction in nutrient leaching is particularly important for sugarcane management, especially for potassium (K), as it is the most required nutrient in sugarcane cultivation (Orlando Filho, 1993). Additionally, sandy and irrigated soils, as studied in this work, are more susceptible to K losses through leaching (Silva, Furtini Neto, Fernandes, Curi, & Vale, 2000; Teixeira, Natale, Bettiol Neto, & Martins, 2007). While phosphorus (P) is less mobile in soil and not typically subject to leaching, its movement can be influenced by soil texture and water flow, particularly in sandy soils (Faria & Pereira, 1993).

The ability of hydrogel to act as a reservoir for plant-available water, improving soil water retention by up to 30%, is linked to its physical and mechanical properties, such as hydrophilicity, stability, and porosity. These properties make it an effective soil conditioner, optimizing fertilizer release and promoting better crop development under drought conditions. For instance, it has been shown to increase bean growth rates by 20% (Durpekova, Bergerova, Hanusova, Dusankova, & Sedlarik, 2022) and enhance corn yields by over 30%, while also improving water use efficiency (Zhao et al., 2022).

In this study with sugarcane, hydrogel application not only reduced nutrient leaching but also increased productivity. Notably, there was a substantial increase in stem height and diameter, which in turn led to greater stem fresh mass—a key economic product obtained from sugarcane. These positive outcomes are attributed to improved nutrient availability and soil properties, which enhanced plant development.

Conclusion

The application of hydrogel in soil effectively reduced nutrient leaching losses, with lower concentrations of N, P, K, Ca, Mg, and S in the leachate under hydrogel treatments compared to the control. The nutrient N exhibited the highest absolute losses through leaching, but the use of the hydrogel polymer Hydroplan-EB™ effectively mitigated nutrient leaching in sandy soil. The greatest efficiency was observed with doses of 1.5 and 2.0 g kg^{-1} of soil.

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