



SPECIAL ISSUE

Effects of applying two new-generation superabsorbent hydrogels to soil on grapevine tolerance to summer stress: physiological validation and potential vineyard applications

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ABSTRACT

Hydrogels are soil-conditioning materials capable of absorbing substantial amounts of water relative to their weight. Their use in agriculture is expanding rapidly, but their effects on grapevines at transplanting has until now not been explored.

This study compared the localised root-zone application to soil of a potassium polyacrylate hydrogel (SH1) and an organic hydrogel (SH2) at vine transplanting, with an untreated control (C) in two experiments: one on potted vines under semi-controlled conditions and the other in a newly established rainfed vineyard.

Both SH1 and SH2 increased soil field capacity and maximum available water. In the potted vines, they improved water status under drought conditions, delaying the decline of stem Ψ (+ 0.25 MPa on the last day before rewatering) and enhancing leaf gas exchange (+ 9 and + 8 $\mu\text{mol m}^{-2} \text{s}^{-1}$ for SH1 and SH2, respectively, as compared to C). By the end of the second season after transplanting, SH1 and SH2-treated vines exhibited greater leaf area, higher yield (+ 29 % and + 26 % relative to C, respectively), and a lower leaf-to-fruit ratio, resulting in reduced TSS (−2.0 and −2.2 °Brix respectively) and anthocyanin levels. In the field, shoot growth and final leaf area after two years were higher in SH1- and SH2-treated vines (+ 25 %). SH1 accelerated the transition to a productive stage, while SH2 reduced the number of vines requiring two-nodes pruning.

Our findings indicate that hydrogels are promising tools for vineyard water management. Their incorporation at transplanting could help shorten unproductive stages and accelerate full crop development.

KEYWORDS: water stress, superabsorbent polymers, soil hydrology, vineyard establishment, water potential, photosynthesis, GiESCO 2025

INTRODUCTION

Water scarcity is one of the main factors affecting yield and fruit composition. High evaporative demand concomitant with reduced soil water availability affects grapevine physiology, and thus the development of vegetative and reproductive organs (Stevens *et al.*, 1995; Tomás *et al.*, 2012). The impacts of water scarcity are even higher in the case of young vines that have a limited root system with a quite poor soil colonisation capacity (Olmstead *et al.*, 2012). In both rainfed or irrigated vineyards, water stress can reduce shoot growth, impair or delay the formation and training of permanent structures, and delay cropping for years, representing significant economic losses (Tomás *et al.*, 2012). Superabsorbent hydrogels are materials capable of absorbing and retaining significant amounts of water or solutions relative to their relative mass. They comprise a network of polymeric chains rich in hydrophilic groups (Guilherme *et al.*, 2015). Depending on their biochemical configuration, they can absorb 9 to 400 times their specific weight in water (*i.e.*, up to 400 mL/g). Even though they have been industrially available for decades, in agriculture their use is limited due to associated costs and environmental concerns about the release of polyacrylamide into the environment (Crous, 2017). This situation has recently changed thanks to the development of new acrylamide-free polymeric hydrogels; some are entirely derived from organic raw materials (ligno-cellulosic or starch-based byproducts) and are less expensive to manufacture. At the same time, climate change pressures are increasing the interest of growers and technicians in the functions of hydrogels (Piccoli *et al.*, 2024). However, scientific literature on the effects of hydrogels on plants is currently very limited, especially concerning tree crops. Several reviews highlight the capability of hydrogels to change soil water retaining properties and increase plant survival under reduced or absent water supply. On the other hand, other authors have expressed concerns about the magnitude of the water absorbed relative to plant evapotranspiration needs, especially those of tree crops, and they are uncertain whether hydrogels make water available to plants or compete with root systems for it (Crous, 2017). Studies on olive and orange trees have shown that hydrogels can help maintain a lower negative midday water potential and improve tree physiological performance. Arbona *et al.* (2005) subjected *citrus* plants to a daily reduction of irrigation as compared to the diurnal evapotranspiration: while the control plants showed a midday leaf water potential as low as -2.8 MPa, those treated with hydrogel maintained a significantly higher water status, never exceeding the threshold of -2.0 MPa, and the recovery of their leaf water potential was more efficient following the morning irrigations. Similarly, Chehab *et al.* (2017) have demonstrated that the application of hydrogels to the root zones of olive trees enhances leaf turgor during periods of water stress, which in turn improves stomatal conductance and the efficiency of the photosynthetic apparatus.

All available data point to soil application at transplanting as the most feasible implementation of hydrogels in tree

crops, taking into account the daily evapotranspiration and root system development of young and mature trees (Arbona *et al.*, 2005; Chehab *et al.*, 2017). However, none of the available literature provides information about the efficacy of hydrogels in improving grapevine water status, physiological performance or vegetative and reproductive development. The only work on the topic evaluated the interactions with different doses of applied fertilisers (Ali *et al.*, 2023).

The objective of this study was to evaluate the effects of locally applying two different superabsorbent hydrogels to the root zone at the time of transplanting on soil hydrology and on grapevine physiological performance. Our general hypothesis was that localised changes in soil hydrology can improve vine water status and vegetative performance, facilitating space filling on support wires and hence shortening the duration of the unproductive stages in the vineyard. Using a multidisciplinary approach, we combined studies on grapevine physiology under semi-controlled conditions and then in the field.

MATERIALS AND METHODS

1. Treatments layout

In this study, the three following treatments were compared: an untreated control (C), the incorporation of a potassium polyacrylate-based hydrogel into the soil (SH1), and the incorporation of a ligno-cellulosic hydrogel (permitted in organic agriculture) into the soil (SH2).

2. Soil hydrology

Samples 5 g of a loamy sandy clay soil (three replicates per treatment) were prepared by adding hydrogels (2.5 mg/g of SH1 and 23 mg/g of SH2) and achieving full hydration status. The hydrogel doses were calculated to ensure that both SH1- and SH2-treated soils received a comparable amount of water potentially absorbable by the hydrogels alone. In a previous study (Frioni *et al.* 2024), we had determined that SH1 could absorb up to 84 g of water per gram of hydrogel, while SH2 had a maximum absorption capacity of 9.2 g of water per gram of hydrogel. Based on these values, the application rates were calibrated so that each treatment provided approximately 210 mL of hydrogel-retained water per kilogram of soil. Then, soil samples were weighed and immediately subjected to water potential (Ψ) measurement using a WP4C Dew Point Potential Meter (Decagon Devices, Pullman WA, USA). This operation was repeated multiple times after keeping samples at 30 °C and 45 % RH for 10 min, until full dehydration was reached. For each sample, field capacity (FC) was calculated as the water concentration after drainage, permanent wilting point (PWP) as the water concentration at $\Psi = -1.5$ MPa, and maximum available water (MAW) as the difference between field capacity and wilting point.

3. Potted vines experiment

The experiment on potted vines was carried out in 2023 and 2024 in Piacenza, Italy. Fifteen one-year-old vines (*Vitis vinifera* L.) cv. Sangiovese clone VCR5/SO4 were planted in 55 L pots and assigned to the three treatments on 23 March 2023. Superabsorbent hydrogels were applied in the following quantities according to Frioni *et al.* (2024): 30 g/vine of SH1 and 100 g/vine of SH2. The vines were standardised by retaining the two best shoots on each plant and removing the others. In the subsequent winter, vines were pruned, retaining 10 buds on one of the two canes. In spring 2024, the canopies were standardised by retaining the eight distal shoots on each vine and thinning the others.

Daily vine evapotranspiration (ET) was gravimetrically measured every week by weighing the pots at 24-hour intervals. In both seasons, a progressive water deficit was imposed by reducing irrigation to 50 % ET and then fully suspending water supply until full stomatal closure was achieved on all vines. In 2023, reduction to 50 % ET started on Day Of Year (DOY) 210, then at DOY 214 irrigation was totally suspended and day of rewatering was DOY 219. In 2024, the water was reduced to 50 % ET on DOY 171 and totally suspended on DOY 180; full irrigation resumed on DOY 183 until the end of the season. Midday stem Ψ was monitored during the imposed water deficit in both years using a Scholander pressure chamber (Soilmoisture Corp., Santa Barbara, CA, USA), and leaf gas exchange parameters were concomitantly measured with an ADC LCi-SD (ADC bioscientific). The measurements were taken at 12:00-13:00 every two to three days on three mature, well-exposed leaves at nodes 3-8 per treatment; the measurements were taken under light-saturating conditions and at ambient temperature and relative humidity. The machine was mounted with a cuvette comprising a 6.25 cm² chamber, and the flow rate was adjusted to 200 mL min⁻¹. Leaf water use efficiency (WUE) was calculated as the ratio between leaf photosynthetic (A) and transpiration (E) rates. Midday stem Ψ was measured at 12:00 on the same dates using a Scholander pressure chamber on three leaves per treatment, which had been wrapped in plastic and aluminium foil 1 h before measurement.

In 2024, ripening was monitored from 20 days after veraison on adjacent Sangiovese vines growing in the same conditions as the experimental vines. When total soluble solids (TSS) in the grapes had reached an average of 20 °Brix, all vines were harvested, the yield was measured and the crop components were determined. Three representative clusters per vine were sampled and brought to the laboratory to determine TSS, pH, titratable acidity (TA), organic acids, anthocyanins, and phenolics.

At the end of the second year, total leaf area was determined separately for main and lateral shoots, then biomass allocated above-ground and below-ground was quantified measuring fresh and dry weight of roots, trunk, two-year-old wood and one-year-old wood (separating main and lateral shoots) on each vine.

4. Field experiment

The field experiment was conducted on cv. Sauvignon blanc grafted onto 1103 Paulsen rootstock planted on 12 April 2023 in a vineyard in Prato Ottesola, Lugagnano Val d'Arda (PC), Italy. A section of 120 plants (five rows of 24 plants each, 40 replicates per treatment) was selected and, at transplanting, vines were assigned to the three treatments in a RCBD layout. Holes about 50 cm in depth and 50 cm in diameter were dug for each vine to be planted. When transplanting the SH1 and SH2 vines, hydrogels were added to the portion of soil that was 5 to 35 cm below the root systems, uniformly distributing them in a volume of soil of about 0.027 m³ and in doses of 30 g/plant and 100 g/plant respectively. In spring 2023, the vines were standardised by retaining the two best shoots developing on each plant and removing the others. In the subsequent winter, considering the low average diameter of the canes, all the vines were pruned retaining two buds on one of the two canes. In spring 2024, plants were again standardised retaining the two best shoots.

In both years, main shoot growth was measured at varying intervals on each vine during the season.

At the end of 2024, the vine leaf area of the main shoots and lateral shoots separately was determined on each vine. Before pruning, the third internode diameter was measured on each vine and the most highly-developed cane retained and shortened at 10 mm in diameter. Subsequently, all the vines were assigned to the following four classes depending on the length of the retained cane: A) vines with limited development and 2 to 6 nodes on the retained cane, B) vines with 7 to 12 nodes on the retained cane and which reached the intersection with the first wire, C) vines with more than 12 nodes but that did not fill the inter-vine gap in the same row, and D) vines with more than 12 nodes and that filled the inter-vine gap in the same row. This method allowed the vines that had reached the productive stage in 2025 (*i.e.*, classes C and D) to be differentiated from the vines being still under training. Pruning weight was concomitantly determined for each vine.

5. Statistical analysis

The soil hydrology and potted vines experiment data were subjected to one-way analysis of variance (ANOVA). Field experiment data was subjected to a two-way ANOVA (treatment and year). When a significant difference was detected, means were separated by Student-Newman-Keuls (SNK) post-hoc test per $P < 0.05$.

RESULTS

1. Changes in soil hydrology

SH1 and SH2 affected soil hydrology, increasing field capacity (+87 % and +75 % respectively) and wilting point (from 1 % soil moisture in the pure soil to 3 % soil moisture in SH1 and 8 % soil moisture in SH2) (Table 1) However, in both SH1 and SH2, the increase in field capacity was proportionally higher than that of the wilting point, and consequently, the

TABLE 1. Field capacity (FC), permanent wilting point (PWP), and maximum available water (MAW) of a sandy loamy soil containing a potassium polyacrylate based hydrogel (SH1) or an organic based hydrogel (SH2).

	FC (Soil moisture %)	PWP (Soil moisture %)	MAW (Soil moisture %)
Soil	24 b*	1	23 c
Soil + SH1	45 a	3	42 a
Soil + SH2	42 a	8	34 b
<i>P</i>	0.003	0.007	0.004

*Different letters indicate significant difference between treatments ($P < 0.05$) (SNK).

maximum plant available water significantly increased in SH1 and SH2 relative to the control soil (+83 % in SH1 and +48 % in SH2).

2. Potted vine experiment

2.1. Vine water status and leaf gas exchange parameters

Under full irrigation, midday stem Ψ remained comparable between treatments in both years (Figures 1A and 1B). In 2023, after the reduction of irrigation to 50 % ET, stem Ψ decreased from -0.43 MPa to -0.64 MPa in C vines (Figure 1A), while in SH1 and SH2 it was significantly higher (-0.31 MPa on DOY 212 and -0.49 MPa on DOY 214, pooling SH treatments). When irrigation was fully suspended, stem Ψ dramatically decreased in all treatments, but in SH1 and SH2 stem Ψ was again higher than in C vines (-1.25 MPa pooling SH1 and SH2, vs -1.50 MPa in C). In 2024, stem Ψ decreased significantly when irrigation was reduced to 50 % ET, which was due to the larger canopy size and increased vine transpiration losses (Figure 1B); nonetheless, SH1 and SH2 both displayed higher stem Ψ than C vines ($+0.27$ MPa and $+0.20$ MPa respectively on DOY 182). Leaf photosynthetic rates reflected vine water status in both seasons, with SH1 and SH2 showing consistently higher leaf A than the control under reduced or null irrigation, as well as a better resumption of leaf gas exchange parameters at rewatering. Interestingly, while SH1 showed higher leaf A ($+9 \mu\text{mol m}^{-2} \text{s}^{-1}$ relative to C) at the end of the experiment in 2023 (Figure 1C), SH2 had higher post-rewatering photosynthetic rates ($+8 \mu\text{mol m}^{-2} \text{s}^{-1}$ than C) in 2024 (Figure 1D). SH1 and SH2 both showed higher leaf WUE than C for a stem Ψ between -0.8 MPa and -1.2 MPa (Figures 1E and 1F).

2.2. Vine yield and fruit composition

SH1 and SH2 produced significantly higher vine yield than C (+29 % and +26 % respectively), with higher bunch weight (+25 % in SH1 and +23 % in SH2) (Table 2) and berry mass ($+0.3$ g/berry). In 2024, SH1 and SH2 vines had higher vine leaf areas at harvest (data not shown) due to a more abundant growth of lateral shoots (Table 3). Consequently, SH1 and SH2 had a significantly lower leaf to fruit ratio than C (-0.20 and -0.26 m^2/kg). However, SH1 and SH2 showed lower TSS at harvest than C (-2.0 and -2.2 °Brix respectively). pH and TA did not differ between treatments.

C had significantly higher concentration of total anthocyanins and phenolics than SH1 ($+0.203$ mg/g and $+0.378$ mg/g) and SH2 ($+0.215$ mg/g and $+0.406$ mg/g).

2.3. Biomass allocation

SH2 had a significantly higher root fresh weight than C (+12.4 %) (Table 3). While no difference was found in the permanent wood (*i.e.*, 2- and 3-year-old wood in our study), the vigour of the main canes was significantly higher in SH1 than in C and SH2 ($+34$ g/vine and $+37$ g/vine respectively). The biomass allocation to lateral shoots was significantly higher in SH1 than in C ($+43$ g/vine), with SH2 setting at intermediate levels. Conversely, the biomass allocation to leaves was significantly higher in SH1 than C ($+128$ g/vine), and no difference was found between SH1 and C. No differences were found in the ratio of total aboveground and belowground biomass accumulation.

3. Field experiment

No differences between treatments in terms of shoot growth were observed in 2023 (Figure 2A). In 2024, the sum of the two retained shoots was similar between treatments until DOY 152. SH1 showed significantly higher shoot growth than C from DOY 184, and a significant difference between C and SH2 can be seen as from DOY 214 (Figure 2B). At the end of the second season, the main shoot leaf area (Table 4) was higher in SH1 ($308 \text{ cm}^2/\text{vine}$) and SH2 ($309 \text{ cm}^2/\text{vine}$) vines than in C vines ($231 \text{ cm}^2/\text{vine}$). SH1 had the highest leaf area on the lateral shoots ($339 \text{ cm}^2/\text{vine}$), and SH2 showed a significantly higher leaf area on lateral shoots than C ($+37 \text{ cm}^2/\text{vine}$); thus, the SH1 and SH2 vines had higher total vine leaf area than C (+28 % and +22 % respectively). SH1 had a significantly higher third internode diameter than C ($+1.7$ mm). SH1 had the highest pruning weight (369 g/vine) and C the lowest one-year-old-wood mass (256 g/vine).

Two years after transplanting, 34.1 % of C vine were still in non-productive stages (*i.e.*, Class A + Class B vines). Meanwhile, 84 % of the SH1 vines had reached their productive stages (*i.e.*, Class C + Class D vines) and none of the vines had to be pruned back to two nodes (Class A). A significantly lower number of SH2 vines belonged to Class A (4.4 %) as compared to C (9.1 %).

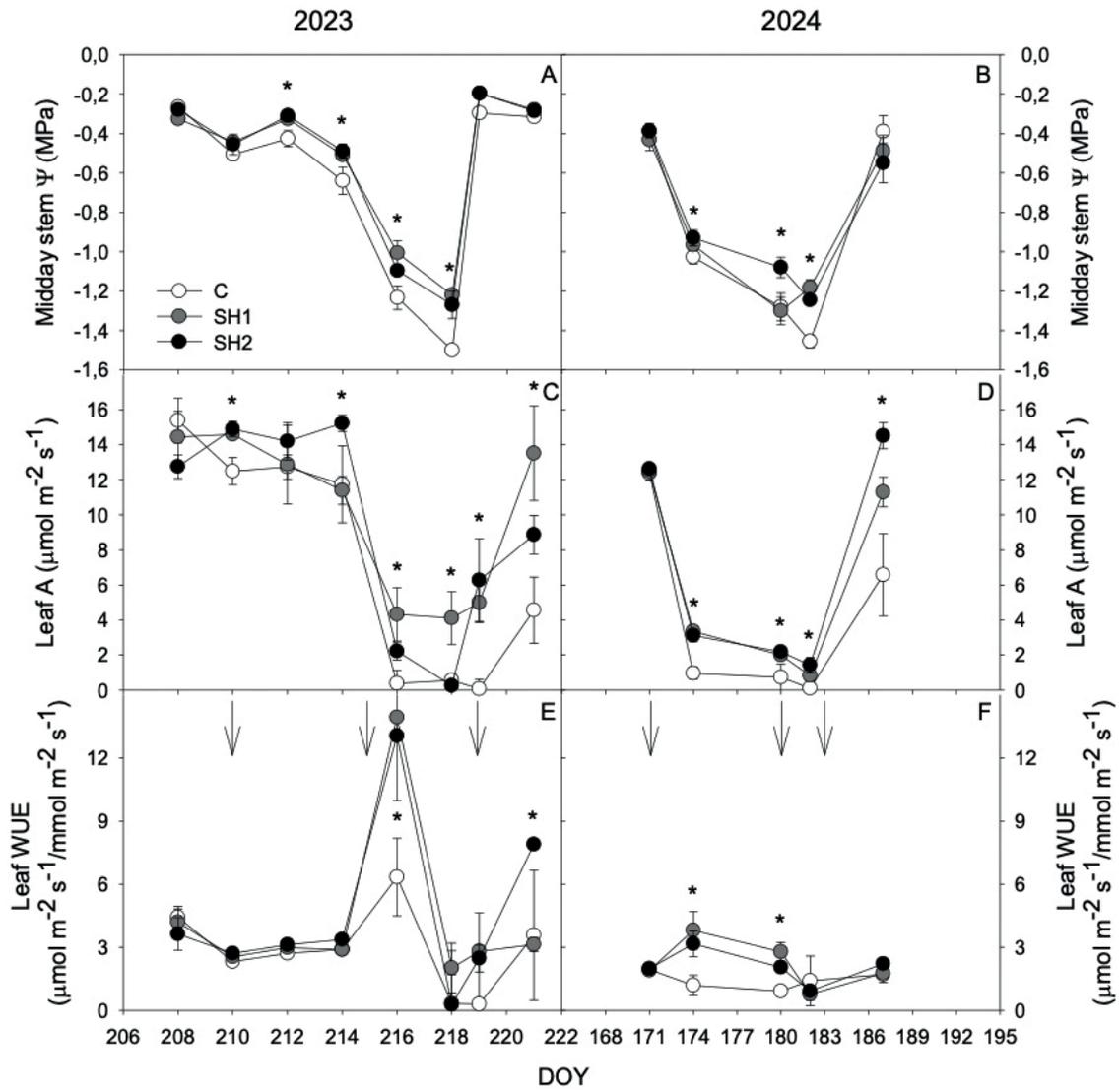


FIGURE 1. Seasonal trend of midday stem water potential Ψ (panels A and B), leaf photosynthesis (A) (panels C and D), and leaf water use efficiency (WUE) (panels E and F), in 2023 (panels A, C and E) and in 2024 (panels B, D and F) in pot-grown vines subjected to the soil incorporation of a potassium polyacrylate based hydrogel (SH1) and of an organic based hydrogel (SH2), as compared to untreated control vines (C). Means \pm standard errors ($n = 3$). Asterisks indicate significant differences between treatments ($P < 0.05$). From left to right, arrows in panels E and F indicate the day of reduction of irrigation to 50 % ET, the day water supply was fully suspended, and the day of rewatering in 2023 and 2024.

TABLE 2. Vine yield, vine balance, bunch size, and fruit composition in vines subjected to the soil incorporation of a potassium polyacrylate based hydrogel (SH1) and of an organic based hydrogel (SH2), as compared to untreated control vines (C).

	Vine yield (kg/vine)	Bunches per vine (n./vine)	Bunch weight (g)	Leaf to fruit ratio (m ² /kg)	Total soluble solids (°Brix)	pH	Titrateable acidity (g/L)	Total anthocyanins (mg/g)	Total phenolics (mg/g)
C	3.5 b*	12	291 b	0.95 a	20.9 a	3.31	6.2	0.425 a	1.765 a
SH1	4.5 a	12	365 a	0.75 b	19.0 b	3.32	6.5	0.222 b	1.387 b
SH2	4.4 a	12	357 a	0.69 b	18.7 b	3.29	6.5	0.210 b	1.359 b
P	0.002	0.912	0.009	0.008	0.006	0.874	0.916	0.003	0.002

*Different letters indicate significant difference between treatments ($P < 0.05$) (SNK).

TABLE 3. Biomass allocation at the end of 2024 in vines subjected to the soil incorporation of a potassium polyacrylate based hydrogel (SH1) and of an organic based hydrogel (SH2), as compared to untreated control vines (C).

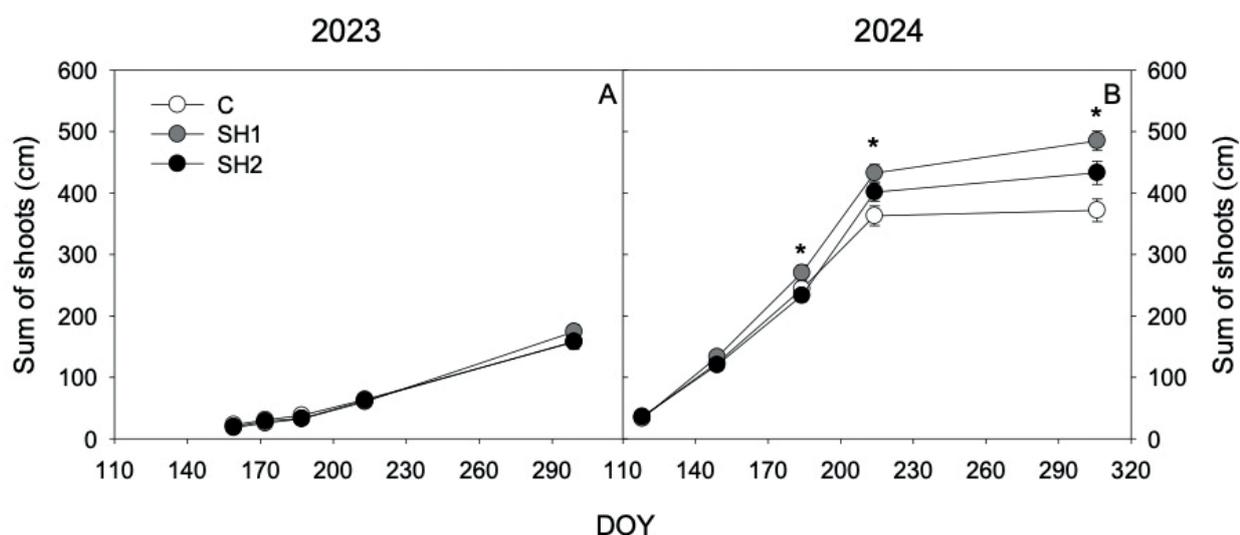
	Roots (g/vine)	Trunk (g/vine)	Main canes (g/vine)	Lateral shoots (g/vine)	Leaves (g/vine)	Aboveground (%)	Belowground (%)
C	921 b*	305	317 b	110 b	481 b	83.6	16.4
SH1	965 ab	289	351 a	153 a	524 ab	85.6	14.4
SH2	1035 a	305	314 b	122 ab	609 a	84.7	15.3
<i>P</i>	0.032	0.723	0.047	0.006	0.004	0.987	0.923

*Different letters indicate significant difference between treatments ($P < 0.05$) (SNK).

TABLE 4. Vine leaf area and pruning weight at the end of 2024 in vines subjected to the soil incorporation of a potassium polyacrylate-based hydrogel (SH1) and of an organic-based hydrogel (SH2), as compared to untreated control vines (C).

	Main shoots leaf area (cm ² /vine)	Lateral shoots leaf area (cm ² /vine)	Total vine leaf area (cm ² /vine)	3rd internode diameter (mm)	Pruning weight (g/vine)
C	231 b*	302 c	533 b	12.68 b	256 c
SH1	308 a	375 a	683 a	13.26 a	369 a
SH2	309 a	339 b	648 a	12.88 ab	306 b
<i>P</i>	0.008*	0.006	0.004	0.046	0.004

*Different letters indicate significant difference between treatments ($P < 0.05$) (SNK).

**FIGURE 2.** Seasonal trend of shoot growth in 2023 (panel A) and in 2024 (panel B) in field-grown vines subjected to the soil incorporation of a potassium polyacrylate based hydrogel (SH1) and of an organic based hydrogel (SH2), as compared to untreated control vines (C). Means \pm standard errors ($n = 3$). Asterisks indicate significant differences between treatments ($P < 0.05$).

DISCUSSION

Modifying soil hydrological constants is one of the most challenging tasks in vineyard management. FC and PWP are primarily influenced by soil texture, making their control particularly complex for growers. The only viable approach to partially managing these parameters is the application of soil conditioners, such as manure or compost. However, their effectiveness is limited due to the substantial quantities required for meaningful impact (Carter, 2007); for instance, in order to increase maximum soil water retention by 1.2 to 2.6 %, Ramos (2017) applied 1 t/ha of composted manure. Both FC and PWP are correlated with soil organic carbon (SOC), but their increase is minimal for a significant increase in SOC (Carter, 2007). Moreover, at present, the application of hydrogels does not appear to be feasible for full-field use on adult vines. However, their properties show promise for improving the hydrological characteristics of the soil in the root zone at transplanting. Such localised applications could improve vine establishment and accelerate its growth during the unproductive stages. In our study, the localised application of SH1 nearly doubled FC and MAW, while SH2 increased MAW by 50 % (Table 1). These results are in line with findings from Savi *et al.* (2014), and they suggest that such amendments could serve as a transformative tool for improving agricultural water management.

The data from the potted vines align with the observed changes in soil hydrology. Under reduced water availability, both SH1 and SH2 helped maintain higher stem Ψ across both years of the study (Figures 1A and 1B). Leaf A and water use efficiency (WUE) followed a similar trend (Figures 1C, 1D, 1E and 1F). Notably, when water was completely withheld, both vine water status and leaf gas exchange parameters declined significantly, even in SH1 and SH2. However, the effects were substantial enough for a significantly better recovery of these parameters upon rewatering in both years. This aligns with the findings of Arbona *et al.* (2005) and Chehab *et al.* (2017), who reported improved leaf water potential in citrus and olive trees following hydrogel root-zone soil application. Notably, in our study, the organic-based SH2 hydrogel produced effects comparable to those of the traditional SH1. To date, no studies have directly compared organic and synthetic hydrogels for improving plant performance under limited conditions. Our work demonstrates the efficacy of the root-zone application of natural hydrogels on grapevine physiological performance, provided that doses are appropriately calibrated. Interestingly, in 2024, the positive effects of hydrogels on the water status and physiological performance of potted vines were comparable to, or even greater than, those observed in 2023 in the first summer following their incorporation into the soil. There are two possible explanations for this: i) the hydrogels continued to enhance root-zone soil hydrology in the second year, or ii) the direct effects of the hydrogels in the second year were limited, but the observed improvements in the first year (such as enhanced root development, vegetative growth, and overall vine vigour) played a key role in ensuring improved plant functioning in the subsequent

season. The existing literature on hydrogel application in perennial plants is limited, and even fewer studies have investigated their effects beyond the first year of application. The biodegradability of hydrogels is a complex factor that directly influences both their long-term efficacy and environmental sustainability. While slower degradation will extend their functional lifespan in the soil, it is essential for hydrogels to fully degrade within a defined time-frame to prevent the accumulation or release of potentially harmful degradation by-products into the environment. In this context, the reviews by Kaur *et al.* (2023) and Adjuik *et al.* (2023) provide a comprehensive overview of hydrogel degradation patterns. Regardless of their origin, hydrogels are broken down by soil microorganisms, with degradation rates that are influenced by soil moisture and temperature. Polyacrylate-based hydrogels degrade slowly, ranging from 16 % to 31 % over nine months, depending on their molecular weight (Arredondo *et al.*, 2023; Oksinska *et al.*, 2016). Organic-based hydrogels exhibit highly variable degradation rates depending on their source: cotton- or cellulose-based hydrogels degrade rapidly, with complete breakdown within 25 days, while lignosulfonate-based hydrogels show only about 20 % degradation over four months (Yoshimura *et al.*, 2006; Kono *et al.*, 2012; Song *et al.*, 2020). Further investigation is needed to determine whether the observed effects in 2024 were due to ongoing hydrogel activity or residual benefits from improvements achieved in 2023; a combined influence of both factors cannot be excluded.

One of the first expected effects of increased FC and MAW and improved vine water status is enhanced vegetative growth. In potted vines at the end of 2024, SH1 promoted biomass allocation to the main canes and lateral shoots, while SH2 exhibited the most significant root system development (Table 3). In the field, shoot growth remained unchanged in 2023, but in the following year, both of the hydrogels stimulated shoot growth, particularly during the summer, and they increased the final leaf area, internode diameter and pruning weight (Table 4). Overall, both of the hydrogels enhanced vine vegetative growth at the end of the season, aligning with improved water status under stress conditions. This finding is consistent with previous research on *Citrus* and annual plants (Arbona *et al.*, 2005; Das *et al.*, 2025), but it has until now not been reported in grapevines. Das *et al.* (2025) found that the influence of organic hydrogels on annual plant root-to-shoot allocation differed depending on the species: in *Cucumis* and *Lycopersicon*, hydrogels were found to initially favour shoot growth after germination, but after 30 days, root growth predominated more than in the controls; no significant differences were observed in *Vigna*. In our study, the aboveground to belowground ratio remained unchanged at the end of the potted experiment (Table 3), aligning with findings by Orikiriza *et al.* (2009), who reported parallel increases in shoot and root length across nine forest species treated with soil hydrogels. However, a dynamic assessment of shoot elongation throughout the season is needed to fully understand this response.

The primary objective of this study was to determine whether root-zone hydrogels application can help shorten the unproductive phase following transplanting. By the end of the second year of the field experiment, four out of five SH1-treated vines had reached a productive stage, while SH2 had reduced the number of vines that needed to be pruned back to two nodes (Table 5). Along with the generally higher vigour observed in SH1- and SH2-treated field vines, these results suggest that the impact on the 2025 vine yield could be substantial. The potted vines experiment provides an early indication of this trend. Although initial differences between treatments were minimal (*i.e.*, all control vines reached Class D at pruning, similar to SH1 and SH2) yield at harvest was significantly higher in SH1 and SH2 due to increased bunch and berry size (Table 2). Fruit composition reflected the leaf area-to-fruit ratio. Since SH1 and SH2 produced higher yields with a lower leaf-to-fruit ratio, sugar and anthocyanin levels were accordingly reduced. Additionally, the higher sugar and anthocyanin concentrations in C vines may be due to a concentration effect resulting from reduced berry growth, likely caused by the lower stem Ψ levels reached during stress imposition. While the SH1 and SH2 reduced sugars and anthocyanins may seem disadvantageous, in rainfed field conditions, maintaining a leaf-to-fruit ratio closer to the 0.8 m²/kg threshold and slowing down ripening can be beneficial (Kliwer & Dokoozlian, 2005; Poni *et al.*, 2018). Finally, the lower sugar levels exhibited by SH1 and SH2 is a particularly desirable trait for white and sparkling wine production in the current context (Poni *et al.*, 2018). Overall, data from both the field and potted-vine experiments suggest that localised hydrogel application at transplanting can support and potentially accelerate the transition of vineyards to full productivity. While comprehensive field trials are still needed to quantify the extent of any yield increase during the first post-transplanting years, these preliminary findings provide some initial insight into the sustainability and practical aspects of their use.

The current cost of applying either SH1 or SH2 hydrogels at transplanting is approximately 0.25 € per vine; therefore, at a planting density of 3,000 vines per hectare, the cost would be around 750 €/ha. In order for the practice to be economically sustainable, this investment would need to generate returns exceeding this amount. Assuming a minimum market price of 42 € per 100 kg of wine grapes (Unioncamere, 2024), the cost would be offset by an additional yield of at least 1.79 t/ha over the first two years after transplanting. Based on the yield increases observed in the potted vine experiment, when extrapolated to a per-hectare basis, the first productive year alone could potentially see a yield increase of approximately 3 t/ha, which would be a favorable return on investment. In this regard, the mechanised application of hydrogels at transplanting appears to be the only viable strategy for reducing costs. In the future, a different approach to applying hydrogels in productive vineyards may become feasible. If costs can be reduced, one potential strategy could involve the incorporation of hydrogels in inter-row soil at depths of 10-30 cm. A low dosage would be tailored to soil texture to increase FC and MAW while minimising any impact on the PWP.

Regarding the environmental sustainability of hydrogels, further research is required. While organic-based hydrogels generally raise fewer concerns, their influence on soil biology, particularly through changes in microclimatic conditions, still warrants investigation. By contrast, the primary concern regarding potassium polyacrylate hydrogels is their potential contribution to soil microplastic pollution through the degradation by-products. This concern has been raised by Buchmann *et al.* (2024), although other studies (*e.g.*, Guan *et al.*, 2014; Kaur *et al.*, 2023) report that such formulations can fully degrade into nitrogen dioxide, water, ammonia nitrogen, and sodium ions under soil conditions.

TABLE 5. Stage of development at the end 2024 in vines subjected to the soil incorporation of a potassium polyacrylate based hydrogel (SH1) and of an organic based hydrogel (SH2), as compared to untreated control vines (C). Class A = vines with limited development that had 2 to 6 nodes on the retained cane; Class B = vines with 7 to 12 nodes on the retained cane, reaching the intersection with the first wire; Class C = vines with more than 12 nodes but not filling the inter-vine gap in the same row; Class D = vines with more than 12 nodes and filling the inter-vine gap in the same row.

	Class A (%)	Class B (%)	Class C (%)	Class D (%)
C	9.1 a*	25.0 a	22.7 ab	43.2 b
SH1	0.0 c	15.9 b	29.5 a	54.5 a
SH2	4.4 b	24.4 a	24.4 ab	46.7 ab
P	0.000	0.041	0.009	0.037

*Different letters indicate significant difference between treatments ($P < 0.05$) (SNK).

CONCLUSION

In the near future, the application of hydrogels to the soil could represent a strategic tool in the adaptation of agriculture to climate change.

Our work demonstrates that new hydrogels can be used to locally control soil hydrology and improve vine tolerance to water deficit after transplanting, thus accelerating the transition to full crop production. Although studies in relation to different soils and pedoclimatic conditions are needed, this work paves the way for the implementation of this technique in vineyards.

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