iVES OENO One vine & wine

DOI: https://doi.org/10.20870/oeno-one.2026.60.1.9466

OPEN ACCESS

VITICULTURE SHORT COMMUNICATIONS

Effect of potassium hydrogel polymer on young grapevine growth and soil properties under controlled conditions

Gonçalo Victorino[1,*], João Lucas Coito[1], Mariana G. Lopes[1], Erika S. Santos[1], Sérgio A. Silva[2], José C. Pinheiro[2], Dora Miranda[2], and Margarida Rocheta[1,3,*]

[1] LEAF-Linking Landscape, Environment, Agriculture and Food Research Center, Associate Laboratory TERRA, Instituto Superior de Agronomia, Universidade de Lisboa, Tapada da Ajuda, 1349-017 Lisboa, Portugal

[2] ME Ativ – Manutenção e Gestão de Ativos S.A., EN10 Edifício Alverca Park, 2619-501 Alverca do Ribatejo, Portugal

[3] Forest Research Centre, TERRA Associate Laboratory, School of Agriculture, University of Lisbon, Tapada da Ajuda, 1349-017 Lisboa, Portugal

Article number: 9466

**correspondence:*
gvictorino@isa.ulisboa.pt
rocheta@isa.ulisboa.pt

Associate editor:
Luigi Bavaresco

Received:
18 June 2025

Accepted:
26 November 2025

Published:
8 January 2026

This article is published under the **Creative Commons licence** (CC BY 4.0).

Use of all or part of the content of this article must mention the authors, the year of publication, the title, the name of the journal, the volume, the pages and the DOI in compliance with the information given above.

ABSTRACT

Potassium polyacrylates (SAPs) are hydrogels capable of retaining and gradually releasing water many times their own weight. When incorporated into soil, they can enhance soil water retention and offer a promising strategy to mitigate drought stress in viticulture. This study evaluated the effects of SAPs on the vegetative development and nutrient dynamics of potted young *Vitis vinifera* cv. Castelão vines in sandy soils under controlled drought conditions. Over two years, SAP-treated and untreated plants were exposed to varying periods of drought to better understand SAP–soil–grapevine interactions. SAP-treated plants showed accelerated phenological development in the second season, progressing faster under both full and deficit irrigation. They also exhibited increased shoot length and leaf area—with significant gains throughout the second year—and greater root biomass, with dry weight increases of 34.4 % and 35.5 % under well-watered and deficit irrigation, respectively. Additionally, SAPs enhanced irrigated water productivity (WP), which increased by 25.5 % under well-watered and 30.0 % under deficit conditions. Minor yet statistically significant differences in soil and leaf potassium and sodium levels were also observed, suggesting enhanced nutrient retention and uptake. Overall, SAPs improved grapevine growth at early stages of development and enhanced resource use efficiency, particularly under water-limited conditions. These findings underscore the potential of SAPs as a sustainable soil amendment in viticulture. Future research should focus on evaluating vine performance and soil health under field conditions to confirm these benefits at the vineyard scale.

KEYWORDS: potassium superabsorbent, water deficit, climate change adaptation, Mediterranean viticulture, *Vitis vinifera* L.

INTRODUCTION

Viticulture holds significant economic and cultural value, especially in Mediterranean regions, where it is central to local livelihoods and traditions. However, increasing climate variability, frequent droughts, and declining soil quality are threatening grapevine productivity and grape quality (Fraga *et al.*, 2016). Water stress, driven by irregular rainfall and high evapotranspiration, can severely impact yield and alter key metabolites essential for wine production (van Leeuwen *et al.*, 2019). Additionally, drought impairs nutrient uptake, compromising vine vigour and fruit quality (Keller, 2005). These challenges underscore the need for sustainable strategies to enhance water and nutrient availability, with superabsorbent polymers (SAPs) emerging as a promising solution in water-limited systems.

Superabsorbent polymers (SAPs) are hydrophilic materials capable of retaining large amounts of water relative to their own mass (Guilherme *et al.*, 2015). Previous studies have explored the positive influence of SAP application on soil hydraulic potential at the root-zone, as a result of their temporal water storage and subsequent gradual release as the surrounding soil dries (Krasnopeeva *et al.*, 2022). The increased root-zone moist period allows lower declines in soil water potential, consequently, maintaining gas exchange by reducing the rate at which the plant shifts into a drought-response state (Yang *et al.*, 2022; Zohuriaan-Mehr & Kabiri, 2008). Furthermore, the incorporation of such soil conditioners can change some physical and biological properties in the soil by improving soil structure and porosity, which positively affects several edaphic processes such as organic matter decomposition and nutrient availability (Awad *et al.*, 2013; Saha *et al.*, 2020). Previous studies have highlighted the effects of superabsorbent polymers (SAPs) in annual crops, such as soybean in sandy soils (Yazdani *et al.*, 2007) and sugarcane in silty soils (Watanabe *et al.*, 2019), with improvements in germination and overall growth. Although less frequently studied, woody perennial crops also show beneficial responses. For instance, the application of SAP in olive trees on sandy soils improved stomatal conductance, water use efficiency, and oil yield (Chehab *et al.*, 2017). Similarly, apple trees grown on silty soils exhibited enhanced growth in the second year when SAPs were used alongside fertilisers and biostimulants (Kapłan *et al.*, 2021). In young citrus, substrate amendment with hydrogel not only increased soil water retention and leaf water potential under drought conditions but also led to greater root biomass (Arbona *et al.*, 2005). The incorporation of superabsorbent polymers (SAPs) into potted grapevines has been shown to significantly improve soil moisture retention (Frioni *et al.*, 2024), improving hydraulic properties and reducing irrigation needs, while enhancing vine growth and yield (Ali *et al.*, 2023). It has recently been demonstrated that root-zone application of both synthetic and organic hydrogels at transplanting, significantly increased soil field capacity and maximum available water, delayed the decline in stem water potential under drought, and improved leaf gas exchange in grapevines (Frioni *et al.*, 2025). Vines treated with hydrogels achieved greater leaf area, shoot growth, internode diameter, and pruning weight after two growing seasons compared to untreated vines, and also transitioned earlier into productive stages (Frioni *et al.*, 2025). These findings reinforce the capacity of SAPs to alleviate water scarcity, a quality that is becoming increasingly valuable in light of the current impact of climate change. Although superabsorbent polymers (SAPs) have shown promise in enhancing grapevine growth under drought conditions, varietal and site-specific responses may vary. Although some studies have demonstrated the positive effects of superabsorbent polymers on perennial crops, under moderate stress, their efficacy may vary according to soil type, climatic conditions, and cultivar. Further research is needed to understand how these materials perform under more extreme conditions and in different viticultural contexts. In this study, we investigated the application of a potassium-based superabsorbent polymer on a Portuguese grapevine variety grown in sandy soil under water-limited conditions, aiming to evaluate its influence on phenological development, vegetative growth, and leaf and soil physical and chemical properties during the plant establishment phase.

MATERIALS AND METHODS

1. Plant and soil material

At the beginning of the 2022 season, a composite soil sample was collected superficially (maximum 50 cm of depth) from a vineyard located in Pegões (PORVID—Central Pole for the Conservation of Autochthonous Grapevine Variability), Portugal (38° 38.864' N 8° 39.241' O). The soil is classified as Arenosol (IUSS Working Group WRB, 2015).

After collection, the soil was transported to Instituto Superior de Agronomia, Lisbon, where it was air-dried, homogenised, and used in a plastic pot experiment (5 kg soil capacity, pot volume of 7 L). A total of 80 one-year-old vines of *Vitis vinifera* cv. Castelão grafted onto SO4 rootstock, obtained from a commercial nursery, were used in the experiment. Due to their dormant state at the time of planting, selection based on uniformity of size was not feasible. Half of the plants (n = 40) were planted in soil that was mixed with hydrated superabsorbent potassium polyacrylate (SAPs; SOCO® Polymer, SDK205X series) at a concentration of 5 % *(w/w)*. The other half (n = 40) were planted in the same soil without SAPs and served as a control. The experiment setup was conducted in April 2022. Plants were randomly assigned to these two treatments during potting to ensure unbiased distribution and were positioned randomly within the greenhouse to minimise environmental variability (*e.g.*, light, temperature, humidity gradients). No fertilisers or nutrient supplements were applied during the experimental period. Spur pruning was conducted in January 2023, leaving each plant with a single spur bearing two buds. To ensure a standardised shoot number across all plants, shoot thinning was performed closely after budburst, and only one shoot per plant was retained. No shoot trimming was performed.

2. Irrigation treatment and experimental setup

Each group of 40 plants (including SAP-treated and non-treated or control plants) was further subdivided into two irrigation regimes: well-watered and deficit-irrigated. This resulted in the following four treatment groups, each comprising 20 plants:

- **WS**: Well-watered, SAP-treated
- **WC**: Well-watered, Control
- **DS**: Deficit irrigation, SAP-treated
- **DC**: Deficit irrigation, Control.

All plants were irrigated using an automated drip system calibrated to deliver a fixed volume of water per event, which corresponded to the soil's field capacity previously determined in the laboratory. Field capacity (pot capacity) was determined by fully saturating each pot, allowing free drainage until its visual cessation, and calculating the retained water by gravimetric difference between pre- and post-watered weights. Each pot received this volume (~450 mL) at every irrigation event, regardless of the initial moisture levels, and any excess drainage was discarded. This approach ensured full soil hydration, including that of the superabsorbent polymers (SAPs). It was designed to standardise water availability across treatments rather than to mimic conventional irrigation practices, thereby minimising variability and enhancing experimental reproducibility.

Although the irrigation volume per event was fixed across all treatments, deficit-treated plants were irrigated less frequently, resulting in reduced seasonal water input, calculated as the product between irrigation period (s), dripper flow rate (mL/s), and number of irrigation events. This approach also reflects expected climate change scenarios, where longer intervals between rainfall events are anticipated, even though the total rainfall per event may not necessarily decrease. To ensure uniform early vegetative development, all plants followed the same irrigation schedule until BBCH stage 19 (Lorenz *et al.*, 1995), after which treatment-specific irrigation regimes were implemented. In 2022, irrigation started right after plant setup (mid-April) and differentiated irrigation treatments were applied between 1 June and 31 August. Deficit-irrigated plants (DS and DC) received approximately 16 L of water (distributed throughout 35 irrigation events throughout the growing season), approximately 30 % less than well-watered plants (WS and WC), which received approximately 23 L of water (distributed throughout 51 irrigation events throughout the growing season). In 2023, the reduction was adjusted to 15 % to avoid excessive stress observed in the first season, with DS and DC plants receiving approximately 19.5 L (distributed throughout 43 irrigation events) and WS and WC 23 L of water (distributed throughout 51 irrigation events).

Throughout the plant cycle in the first season (March–August 2022), the mean greenhouse temperature was 23.7 °C ± 5 °C, with a relative humidity of 49.2 % ± 3.0 %. In 2023, the mean temperature was recorded at 28.5 °C ± 3 °C, with a relative humidity of 47.0 % ± 2.0 %.

3. Vegetative development measurements

3.1. Phenological monitoring

The plants were monitored every week according to their phenological stage, using the BBCH scale (Lorenz *et al.*, 1995) from budburst to stage 19. Although some inflorescences/bunches were anticipated, only a small proportion of the plants (around three) had them. To ensure a balanced distribution of source and sink organs across all plants, the inflorescences were removed soon after being visible. Therefore, only vegetative stages were considered, excluding the reproductive phase. During this period, all plants were maintained under optimal water conditions to support vegetative growth.

3.2. Leaf area and shoot length

Vegetative development was assessed during the growth cycle by measuring shoot length and total shoot leaf area (LA). Measurements were conducted periodically, approximately every one to two weeks, throughout the growing season. Leaf area was estimated using the non-invasive method described by Lopes and Pinto (2005), which relates shoot LA to the length of the lateral veins of both the largest and smallest leaves (> 3 cm), ensuring accuracy without damaging the plant. As only one shoot was retained per vine, the estimated shoot leaf area was obtained once for each vine. Shoot length was measured directly with a standard ruler to follow growth dynamics over time.

3.3. Vegetative biomass and water productivity

At the end of the trial (13 July, 2023), the final pruning weight was documented. Roots and leaves were subsequently collected and dried until a constant weight was achieved, enabling the determination of their dry biomass. Total plant biomass was calculated as the sum of leaf, root, and pruning dry weights. As this assessment was destructive, it was only possible to conduct it at the end of the trial.

Water productivity (WP) is determined by the balance between biomass gain and the volume of water consumed. Since the young plants in this study developed almost entirely under the applied treatment, their WP was calculated using Equation 1 (adjusted from Pereira *et al.*, 2012).

$$\mathrm{WP}\ (\mathrm{g/L}) = \frac{\text{Leaf biomass (g)} + \text{Root biomass (g)} + \text{Shoot biomass (g)}}{\text{Total water irrigated (L)}} \quad (1)$$

Leaf and root biomass were determined as dry weight at the end of the season, while shoot biomass was measured based on pruning weight. Total water irrigated corresponded to the volume of water used for each treatment.

4. Soil and leaf physicochemical analysis

The deficit irrigated plants (DC and DS) showed a high percentage of senescence at the end of the season. As a result, it was not possible to obtain a robust leaf sample from these treatments and therefore not possible to compare it with the corresponding soil sample. Therefore, at the end of the trial, leaf and soil samples were collected from five randomly selected plants only within the well-watered treatments (WC and WS).

All leaves were collected from each plant, washed with distilled water, and dried in a laboratory oven at 60 °C for 72 h. Dried material was then finely ground using a mortar and pestle for nutrient analysis. The concentration of total N was determined by the Kjeldahl method (Bremner, 1960) while other nutrients were extracted by an acid microwave digestion and determined by flame atomic absorption spectroscopy (AAS-F; Ca, Cu, Fe, K, Mg, Mn, Na, and Zn, Jones & Case, 1990) and UV-VIS spectrophotometry (P, molybdenum blue method, Murphy & Riley, 1962).

After removing the plant, the soil was homogenised, and a sample was collected for physicochemical analysis. Samples were air-dried and the fraction < 2 mm was used for analysis of pH and electrical conductivity in water (1:2.5 *m*:*V*), cation exchangeable capacity (extraction with 1 M ammonium acetate at pH 7 and determination of non-acid exchange cations by AAS-F), total N (Kjeldahl method), extractable P and K (Egner–Riehm method) and other nutrients in available fraction (extraction by DTPA method, Lindsay & Norvell, 1978).

5. Data analysis

Descriptive statistics were performed using Microsoft Excel® for Microsoft 365 (version 2406, Microsoft, Redmond, WA, USA). All data were inserted in GraphPad Prism® (version 10.0, Boston, Massachusetts, USA). A one-way ANOVA was performed within each irrigation treatment, considering SAP application as the main factor. This structure was selected to focus comparisons on SAP effects under consistent water regimes. Post-hoc multiple mean comparisons were conducted using Tukey's test, and statistical significance was established at $p \leq 0.05$. For phenological and vegetative parameters, analyses were performed separatel y for each observation date. Quality control of the analyses was made by analytical replicate samples, blanks, the use of certified standard solutions, and laboratory standards.

RESULTS

1. Phenological development

In the first season (Figure 1A), late potting in mid-April 2022 led to budburst in early May, with rapid progression to BBCH stage 19 within five weeks. In contrast, the second season (Figure 1B) showed slower development, with budburst occurring in mid-February 2023 and stage 19 reached by late March. All plants were kept under optimal water conditions, in both seasons, before budburst and BBCH 19, with irrigation treatments initiated only after reaching the aforementioned phenological stage.

No significant variations were observed during the initial season (Figure 1A), as plants across all treatments exhibited comparable growth patterns. However, during the second season (Figure 1B), results indicate an accelerated development of plants subjected to the SAP treatment, which exhibited higher average phenological development rates from the time of budburst (Figure 1). This difference was particularly relevant between DC and DS plants, which showed statistical significance at all analysis dates. For WC and WS plants, differences were only significant on the second (22/02/2023) and third (02/03/2023) moments of analysis, with WS plants presenting two to three extra fully expanded leaves than WC plants. In the case of deficit irrigation (DC), plants exhibited a delayed budburst and demonstrated a reduced initial growth rate in comparison to those subjected to full irrigation (DS). It is noteworthy that the development of deficit irrigation SAP plants (DS) closely mirrored that of well-watered SAP plants (WS).

2. Leaf area and shoot length

As the reproductive phenological stages were not recorded due to the absence of inflorescences or clusters in the studied plants, leaf area became the main indicator of plant development (Figure 2).

In the 2022 season, significant differences in leaf area (Figure 2A) were observed on the first analysis date, with WC plants exhibiting higher values than WS plants. However, this difference became non-significant in the following weeks. A similar pattern was observed for shoot length (Figure 2B), where control plants had greater values than SAP-treated plants across both irrigation treatments. Unlike leaf area, these differences in shoot length persisted for a longer period, remaining significant up to 42 days after BBCH 19 for both WC and WS treatments.

In the 2023 season, significant differences in leaf area were observed throughout most of the growing season, with SAP-treated plants showing higher values in both irrigation treatments (Figure 2C). A similar trend was observed for shoot length, particularly in DS and DC plants, with DS plants maintaining a significantly higher shoot length average almost to the end of the season (Figure 2D).

3. Final biomass and water productivity

At the end of the trial, plants were pruned and their leaves and roots collected for weighing (Figure 3). No significant differences in leaf dry weight were observed between treatments (Figure 3A), suggesting that variations in the number of primary and secondary leaves between untreated (WC, DC) and SAP-treated (WS, DS) plants did not significantly affect total biomass. In relation to root development, the SAP treatment exerted a favourable influence on both irrigation regimes, with increases of 16.0 g (34.4 %) for WS *vs* WC and 11.6 g (35.5 %) for DS *vs* DC (Figure 3B).

Pruning wood also made a notable contribution to total biomass, with a significant increase of 3.4 g (25.3 %) observed under water stress conditions (DS *vs* DC), while a positive trend was observed under full irrigation (WS *vs* WC) (Figure 3C). Together, these effects resulted in significant differences in total biomass between SAP-treated and untreated plants within each irrigation regime, with a 25.0 % and 28.3 % enhancement in total biomass observed in SAP well-watered and water-deficient plants, respectively (Figure 3D).

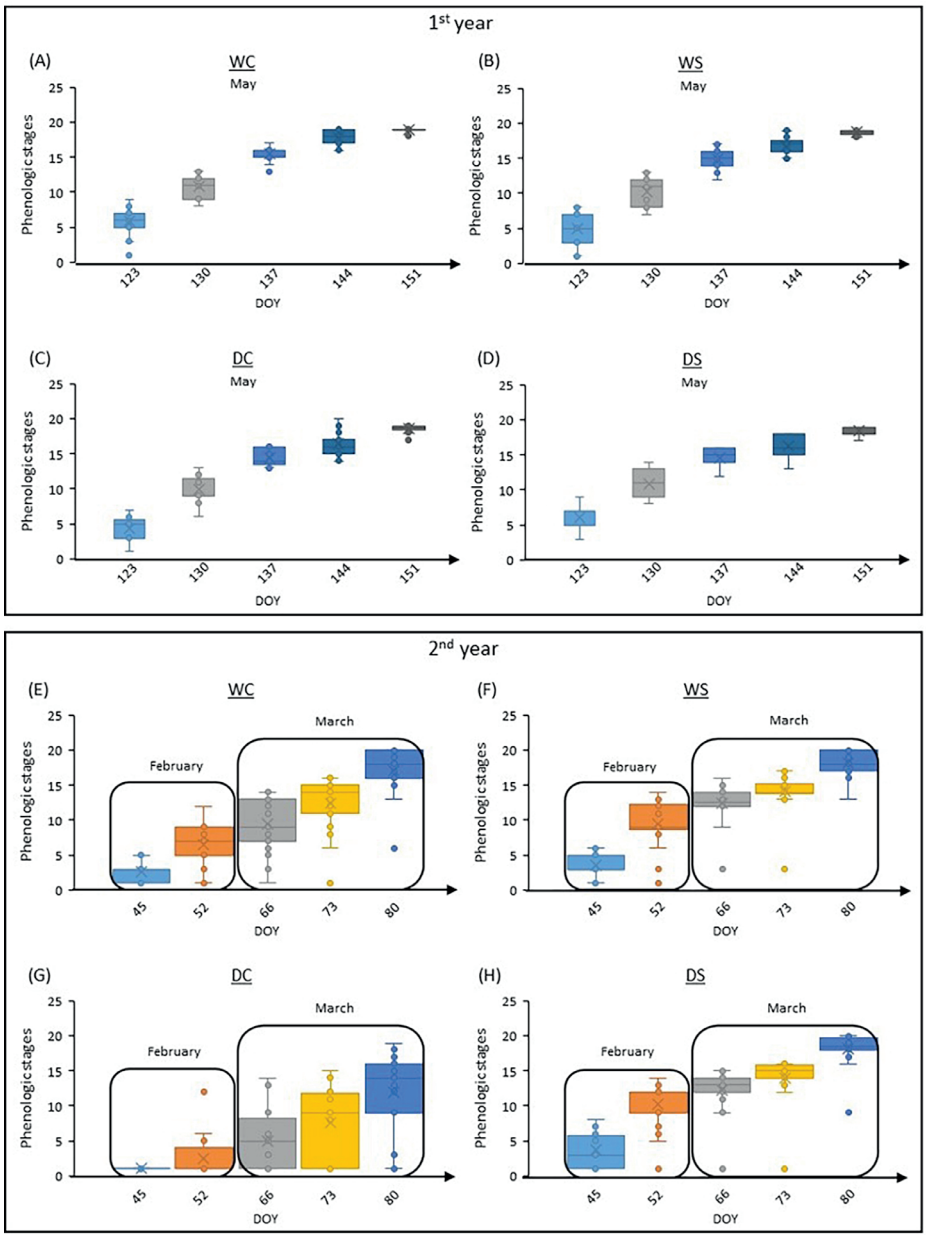


FIGURE 1. Phenological development of the plants from the different treatments during the first (2022) and second (2023) growing seasons of the trial, according to the BBCH scale (Lorenz *et al.*, 1995). Mean values ± standard error (n = 20 per treatment). DOY: Day of the year. A and E: WC (Well-watered irrigation control); B and F: WS (Well-watered irrigation with added SAPs); C and G: DC (Deficit irrigation control); D and H: DS (Deficit irrigation with added SAPs).

After measuring the dry weight of leaves, roots, and pruning wood, water consumption in the greenhouse during 2023 was analysed, and water productivity (WP) was determined (Figure 4).

The presence of SAPs had a highly significant effect on both years of the study, with DS plants surpassing WC plants in terms of WP (Figure 4). Throughout the 2023 analysis period, DC and DS plants received 15 % less water than WC and WS plants. Notably, DS plants achieved the same biomass as WC plants, indicating that under the studied conditions, SAPs effectively compensated for reduced irrigation, promoting efficient growth even under water deficit conditions.

4. Nutritional composition of soil and leaves

Considering the comparison of soil characteristics between WC and WS, only the values of electrical conductivity and some macronutrients were significantly different. For electrical conductivity, the WS soil had higher values compared to the WC soil (Table 1). The WC soil presented significantly higher P concentration than WS, while the opposite trend was observed for K. Among the other available nutrient concentrations, only Na was statistically different, with a higher concentration in the WC soil (Table 1).

Phenotypically, no symptoms of nutritional deficiency or phytotoxicity were observed throughout the experiment.

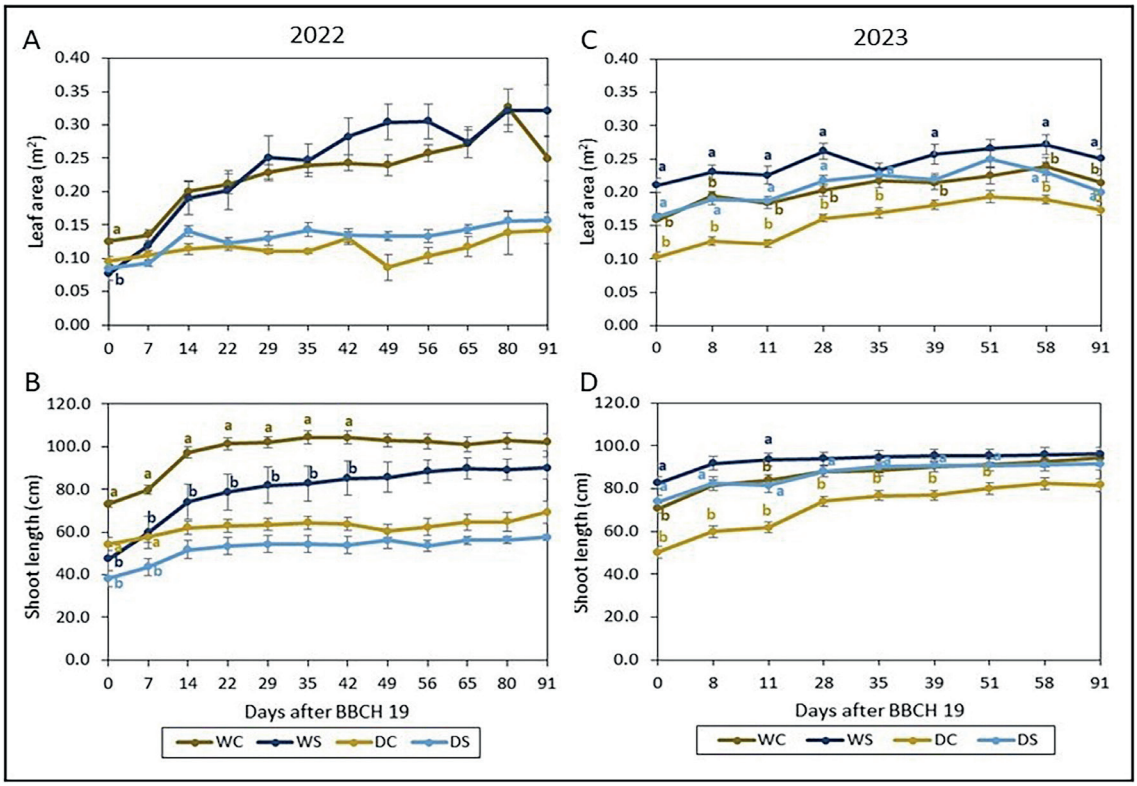


FIGURE 2. Grapevine leaf area (A, C) and shoot length (B, D) across water treatments during two growing seasons (2022 and 2023). Mean values ± standard error (n = 20 per treatment). WC: Well-watered irrigation treatment control; WS: Well-watered irrigation treatment with added SAPs; DC: Deficit irrigation control; DS: Deficit irrigation with added SAPs. Different letters (a and b) represent statistical significance observed for each irrigation regime at the same date of analysis ($p < 0.05$).

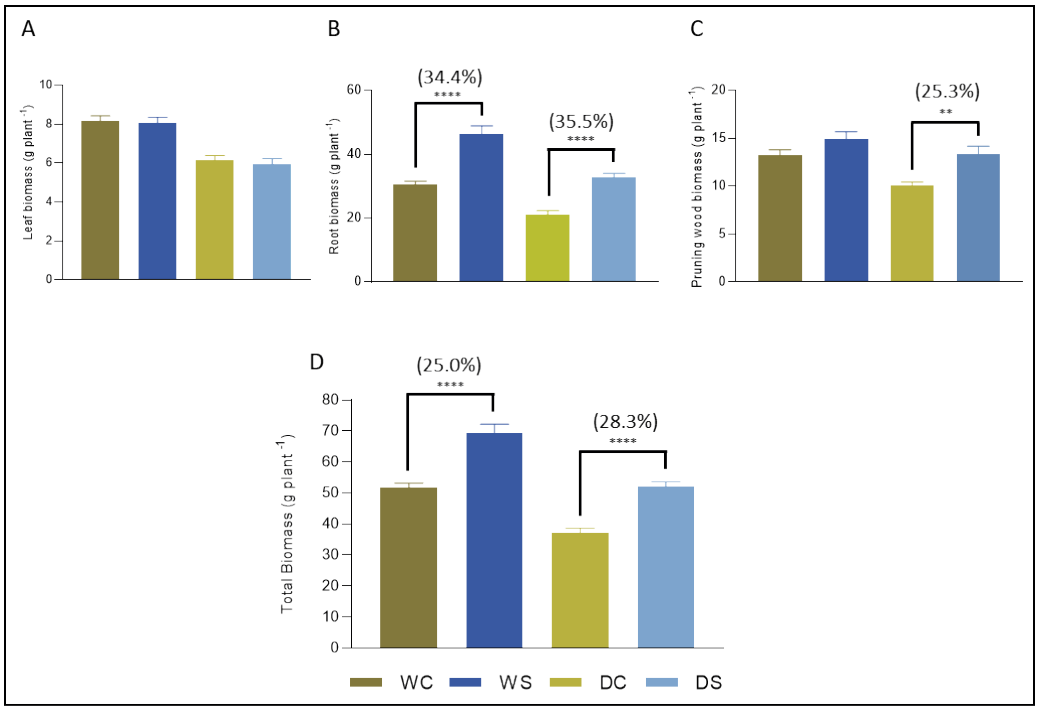


FIGURE 3. Dry weight of plant components by treatment at the end of the experiment. Values are mean ± standard error of dry weight of leaves (A), roots (B), wood (C), and total biomass (D) per plant, categorised by treatment. Statistical significance is shown as follows: **** $p < 0.0001$; ** $p < 0.01$. WC: Well-watered irrigation treatment control; WS: Well-watered irrigation with added SAPs; DC: Deficit irrigation control; DS: Deficit irrigation with added SAPs.

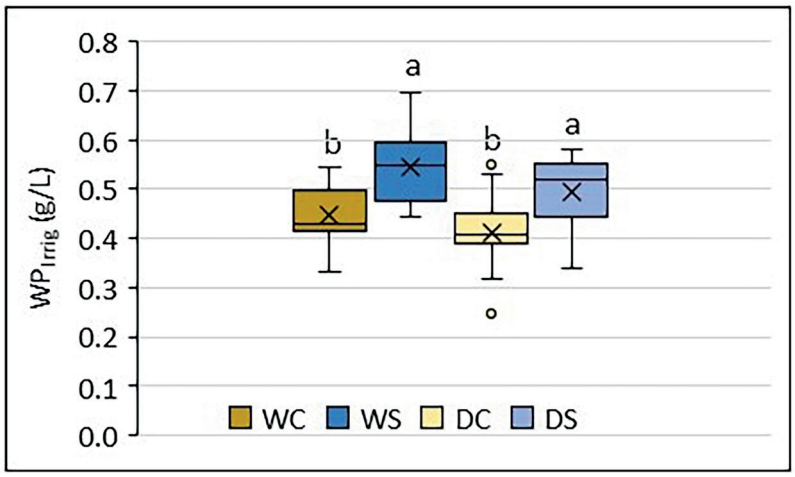


FIGURE 4. Water productivity (WP_{irrig}) by treatment at the end of the trial. Mean ± standard error (n = 20 per treatment). WC: Well-watered irrigation treatment control; WS: Well-watered irrigation with added SAPs; DC: Deficit irrigation control; DS: Deficit irrigation with added SAPs. Different letters (a and b) represent statistical significance observed for each irrigation regime ($p < 0.05$).

TABLE 1. Soil physicochemical characteristics from treatments well-watered plants growing without (WC) and with SAPs (WS) at the end of the trial. Mean ± standard deviation (n = 20 per treatment). Statistical significance is shown as follows: ** $p < 0.01$; *** $p < 0.001$).

Parameter	Treatment	
	WC	WS
pH	5.9 ± 0.4	6.8 ± 0.3
Electric conductivity*** (µS cm^{-1})	660.3 ± 80.8	730.3 ± 74.9
Cation exchange capacity (cmolc kg^{-1})	4.36 ± 0.44	4.26 ± 0.49
Total N (mg kg^{-1})	248.54 ± 25.7	252.53 ± 23.9
Macronutrient concentration in available fraction (mg kg^{-1})		
P**	50.5 ± 12.1	24.6 ± 7.5
Ca	443.0 ± 90.9	432.6 ± 88.0
Na***	924.9 ± 74.1	853.1 ± 65.2
K**	20.7 ± 4.4	40.2 ± 9.0
Mg	85.3 ± 5.1	83.3 ± 16.1
Micronutrient concentration in available fraction (mg kg^{-1})		
Fe	43.8 ± 4.4	41.6 ± 6.7
Mn	11.4 ± 2.2	7.7 ± 1.1
Zn	8.0 ± 0.8	5.3 ± 1.3
Cu	22.4 ± 2.6	19.0 ± 2.5

Considering leaf nutrient concentrations, significant differences were only observed for K and Na. Regarding K concentration, WS plants had significantly higher values than WC plants. The opposite was observed for Na concentration, with WC showing significantly higher values (Table 2). As previously outlined, an insufficient quantity of healthy leaves was available in the deficit irrigation treatments due to leaf senescence. Consequently, this analysis was conducted solely on well-irrigated plants (Table 2).

DISCUSSION

The early phenological development observed in the SAP-treated plants in the 2023 season could be explained by the development of a more extensive root system during 2022, due to their effect on water and nutrient dynamics, consequently, facilitating a more stable and improved mobilisation of reserves for budburst (Zapata *et al.*, 2004). A beneficial effect of SAPs on root biomass was observed at

TABLE 2. Nutrient composition in leaves obtained from plants growing in well-watered conditions without (WC) and with SAPs (WS). Mean ± standard deviation (n = 20 per treatment). Statistical significance is shown as follows: ** $p < 0.01$; *** $p < 0.001$.

Nutrient	Treatment	
	WC	WS
Macronutrient concentration (g kg^{-1})		
N	20.2 ± 1.1	18.0 ± 2.1
P	2.6 ± 0.5	2.9 ± 0.6
Ca	8.0 ± 1.6	6.7 ± 0.8
K***	13.6 ± 2.1	25.3 ± 1.7
Mg	2.7 ± 0.6	2.2 ± 0.2
Micronutrient concentration (mg kg^{-1})		
Na**	341.52 ± 50.0	323.31 ± 30.9
Fe	90.6 ± 8.7	84.0 ± 10.1
Mn	108.8 ± 28.3	121.8 ± 24.7
Zn	17.7 ± 2.1	19.3 ± 2.9
Cu	30.2 ± 11.5	27.5 ± 8.2

the end of the trial and has been previously reported for citrus plants (Arbona *et al.*, 2005). It is possible that this effect was already present at the end of the first season, although due to the destructive nature of its inspection, it was not possible to perform. As the initial growth phase transitioned to being primarily driven by photosynthesis, phenological development stabilised, with untreated plants reaching similar stages to those treated with SAPs. Notably, the phenological advancement observed in SAP-treated plants has not been previously reported in perennial crops. This finding is particularly relevant under climate change scenarios. The higher uniformity in phenological development observed in WS and DS plants when compared to their control counterparts (reduced standard deviation, Figure 1) could be considered a positive output (Costafreda-Aumedes *et al.*, 2025) as it may improve synchronisation with management practices, potentially increasing yields and reducing biotic stress (Keller, 2015). However, earlier phenological development can also have negative implications, considering abiotic stresses, shifting the timing of sensitive stages, possibly exposing them to extreme weather events such as frost damage during early spring and warm temperatures near harvest (*e.g.*, De Rosa *et al.*, 2021), depending on the variety's cycle length and the region. Nevertheless, the present study was conducted in a greenhouse under above-average temperatures, where earlier budburst was expected. A conclusive assessment of this effect would require field trials conducted across different regions and with varieties susceptible to temperature extremes. Nevertheless, when implementing SAPs, growers should account for regional climate and varietal cycle length, as both may influence how phenological timing responds to the altered soil conditions.

Considering vegetative growth, during the 2022 season, WC grapevines demonstrated increased shoot length when compared to WS plants, yet regarding leaf area, significant differences were only found at the first date of analysis. This pattern may be attributed to transient variations in root development shortly after potting, when the hydrated SAP hydrogel occupied space within the root zone before fully integrating into the soil. This could have temporarily constrained early root and vegetative growth compared to control plants, an effect that was no longer significant later in the season. In the second year, however, the opposite trend was observed with SAP-treated plants presenting higher values for both shoot length and leaf area throughout the majority of the season. The higher values for these two parameters in SAP-treated plants, particularly at earlier stages, may be a reflection of their earlier phenological development, as discussed above. During this season, however, no substantial increase in shoot length and leaf area was observed over time, within each treatment. This result can possibly be associated with abnormally high temperatures (reaching values of up to 50 °C) that were periodically felt in the greenhouse during this season, which may have limited plant growth by surpassing the grapevine temperature tolerance threshold (*e.g.*, Bernardo *et al.*, 2018).

It is challenging to predict whether an increased vegetative regrowth would remain significant over the years. However, when growing conditions are unfavourable, the benefit of the presence of SAP may be cumulative and, over the years, SAP-treated plants may reserve more carbohydrates, giving them a greater advantage over untreated plants (Gatti *et al.*, 2016; Grechi *et al.*, 2007). Nevertheless, a longer-term study would be necessary to clarify the most likely scenario and achieve conclusive results.

Regarding water productivity, the values obtained by adding SAPs indicated that WS plants are 25.5 % more efficient in water use (Figure 4), with an increase in total biomass of 17.6 g for the same amount of water (Figure 3D). In a more restrictive scenario, water productivity values for DS plants were 30.0 % higher when compared with plants without SAPs (Figure 4), with an average increase in total biomass of 14.8 g (Figure 3D). The improved water productivity in SAP-treated plants likely reflects a moderated physiological response to water deficit. By delaying declines in soil water content, SAPs help maintain transpiration and photosynthesis for longer periods, reducing the rate at which vines shift into drought-response modes (stomatal closure) and corresponding decrease in carbon assimilation (Yang *et al.*, 2022).

When comparing water regimes, values from WC plants had a lower water productivity than DS plants (Figure 4) (Ali *et al.*, 2023). Improvements in WP under SAP treatments offer several agronomic and environmental advantages. By enhancing the plant's ability to produce more biomass or yield per unit of water used, SAPs contribute to more sustainable water management, particularly in arid and semi-arid regions (Alharbi *et al.*, 2024). Higher WP can lead to reduced irrigation requirements, lowering both water costs and pressure on local water resources. Additionally, improved WP often supports better drought tolerance, promoting crop resilience under water-limited conditions and ensuring more stable agricultural productivity (Ma *et al.*, 2025).

The application of SAPs influenced both soil chemical properties and nutrient dynamics. In WS treatment, increased available K in soil was strongly correlated with higher leaf K concentrations (r = 0.71), supporting adequate vine concentrations (de Varennes, 2003) and aligning with prior findings (Ali *et al.*, 2023). While available P concentrations were higher in WC soils, no significant differences were observed in leaf P concentrations between treatments, which remained within adequate ranges (de Varennes, 2003). SAPs also led to a slight increase in soil pH, likely due to cation exchange between SAP counter-ions and acidic soil cations (Qu & de Varennes, 2010) and contributed to a modest rise in electrical conductivity linked to enhanced K availability. Notably, SAP-treated soils exhibited lower Na concentrations, possibly due to K–Na exchange or improved leaching through enhanced water movement (Situ *et al.*, 2023; Al-Taey & Al-Ameer, 2023). Beyond their chemical interactions, SAPs are also known to improve soil physical structure by increasing porosity and aggregation, particularly in coarse-textured soils, which reduces bulk density and enhances aeration and microbial activity (Zhao *et al.*, 2022; Li *et al.*, 2022). These structural changes can indirectly support nutrient availability and uptake. Combined with the results of this study, these findings suggest that SAPs can enhance soil fertility while potentially reducing nutrient leaching (Ekebafe *et al.*, 2011).

Considering the complexity of the water–SAP–soil interaction, future research should prioritise long-term field studies to assess SAP persistence, degradation, and their cumulative effects on soil health and vine performance. Optimising application rates and placement methods across soil textures and climatic conditions remains essential. In the context of vineyard establishment, early application at planting appears particularly promising for improving vine establishment and survival under limited water availability. Additionally, exploring the combined use of SAPs with organic amendments or fertilisers may further enhance nutrient availability and soil structure, supporting more sustainable vineyard management.

CONCLUSION

This study investigated the effects of potassium-based superabsorbent polymers (SAPs) on young grapevine growth and soil nutrient dynamics under controlled conditions. The results demonstrate the potential of SAPs to enhance water productivity, support earlier and more uniform phenological development, and improve soil fertility, particularly in sandy soils under Mediterranean conditions or regions prone to water deficit. A temporary reduction in early vegetative growth was observed during the first season, likely due to partial occupation of the root zone by hydrated SAPs before their full integration into the soil. However, this effect was no longer evident in the following season, when SAP-treated plants showed anticipated phenology and improved shoot growth and leaf area. SAP influence on soil and leaf nutrients highlights the importance of calibrating application rates and integrating SAP use with balanced fertilisation strategies to prevent potential nutrient imbalances. While these findings provide insight into the short-term effects of SAPs, further long-term studies across different regions and grapevine varieties are necessary to fully assess their cumulative effects on soil health, vine physiology, and productivity, thereby clarifying their overall potential for sustainable vineyard management.

ACKNOWLEDGEMENTS

This work was supported by FCT—Fundação para a Ciência e a Tecnologia, I. P., to UID/04129 LEAF-Linking Landscape, Environment, Agriculture and Food, Research Center and to UID/00239 CEF-Forest Research Centre. We would like to thank Mota-Engil ATIV for their collaboration and logistical support throughout the project, including the provision of resources and coordination assistance. We also acknowledge PORVID for its valuable support. Finally, we would like to thank Ana Graça for her assistance in collecting the data on the hottest days.

REFERENCES

Alharbi, S., Felemban, A., Abdelrahim, A., Al-Dakhil, M. (2024). Agricultural and Technology-Based Strategies to Improve Water-Use Efficiency in Arid and Semiarid Areas. *Water*, *16*(13). https://doi.org/10.3390/w16131842

Ali, M., Mohamed, M., Eid, M., & Mostafa Omar, A. (2023). Effect of Superabsorbent Polymer Application on Soil Hydraulic Properties, Growth, Yield, and Water Use Efficiency of 'Early Sweet' Grapevine *(Vitis vinifera)* under Different Irrigation Levels. *Egyptian Journal of Horticulture*, 50(2), 209-229. https://doi.org/10.21608/ejoh.2023.196613.1232

Al-Taey, D. K., & abd Al-Ameer, A. (2023). Effect of Salinity on the Growth and Yield of Grapes: A review. In *IOP Conference Series: Earth and Environmental Science*, *IOP Publishing*, Vol. 1262, Nº 4, p. 042038. https://doi.org/10.1088/1755-1315/1262/4/042038

Arbona, V., Iglesias, D. J., Jacas, J., Primo-Millo, E., Talon, M. & Gomez-Cadenas, A. (2005). Hydrogel substrate amendment alleviates drought effects on young citrus plants. *Plant and Soil*, *270*, 73–82. https://doi.org/10.1007/s11104-004-1160-0

Awad, Y. M., Blagodatskaya, E., Ok, Y. S., & Kuzyakov, Y. (2013). Effects of polyacrylamide, biopolymer and biochar on the decomposition of ^{14}C-labelled maize residues and on their stabilization in soil aggregates. *European Journal of Soil Science*, 64(2), 488–499. https://doi.org/10.1111/ejss.12034

Bernardo, S., Dinis, L. T., Machado, N., & Moutinho-Pereira, J. (2018). Grapevine abiotic stress assessment and search for sustainable adaptation strategies in Mediterranean-like climates. A review. *Agronomy for Sustainable Development*, *38*(6), 66. https://doi.org/10.1007/s13593-018-0544-0

Bremner, J. M. (1960). Determination of nitrogen in soil by the Kjeldahl method. *The Journal of Agricultural Science*, *55*(1), 11-33. https://doi.org/10.1017/S0021859600021572

Chehab, H., Tekaya, M., Mechri, B., Jemai, A., Guiaa, M., Mahjoub, Z., Boujnah, D., Laamari, S., Chihaoui, B., Zakhama, H., Hammami, M., & del Giudice, T. (2017). Effect of the super absorbent polymer Stockosorb® on leaf turgor pressure, tree performance, and oil quality of olive trees cv. *Chemlali* grown under field conditions in an arid region of Tunisia. *Agricultural Water Management*, *192*, 221–231. https://doi.org/10.1016/j.agwat.2017.07.013

Costafreda-Aumedes, S., Leolini, L., Menz, C., Yang, C., Argenti, G., Dibari, C., ... & Moriondo, M. (2025). Uncertainties in predicting the medium-term future occurrence of grapevine budburst in Europe: the role of phenological models and climate scenarios. *OENO One*, *59*(2). https://doi.org/10.20870/oeno-one.2025.59.2.8056

De Rosa, V., Vizzotto, G., & Falchi, R. (2021). Cold hardiness dynamics and spring phenology: climate-driven changes and new molecular insights into grapevine adaptive potential. *Frontiers in plant science*, *12*, 644528. https://doi.org/10.3389/fpls.2021.644528

de Varennes, A. (2003). *Produtividade Dos Solos e Ambiente*. Escolar Editora: Lisbon, Portugal. ISBN 978-972-592-156-2.

Ekebafe, L., Ogbeifun, O., Okieimen, F. (2011). Polymer applications in agriculture. *Biokemistri*, *23*, 81–89.

Fraga, H., García de Cortázar Atauri, I., Malheiro, A. C., & Santos, J. A. (2016). Modelling climate change impacts on viticultural yield, phenology and stress conditions in Europe. *Global Change Biology*, *22*(11), 3774-3788. https://doi.org/10.1111/gcb.13382

Frioni, T., Bonicelli, P. G., Ripa, C., Tombesi, S., & Poni, S. (2024). Superabsorbent hydrogels: A new tool for vineyard water management? *Agricultural Water Management*, *306*, 109145. https://doi.org/10.1016/j.agwat.2024.109145

Frioni, T., Bonicelli, P. G., Tiwari, H., Gatti, M., & Poni, S. (2025). Effects of applying two new-generation superabsorbent hydrogels to soil on grapevine tolerance to summer stress: physiological validation and potential vineyard applications. This article is part of the special issue of the GiESCO 2025 meeting. *OENO One*, *59*(3). https://doi.org/10.20870/oeno-one.2025.59.3.9305

Gatti, M., Pirez, F. J., Chiari, G., Tombesi, S., Palliotti, A., Merli, M. C., & Poni, S. (2016). Phenology, canopy aging and seasonal carbon balance as related to delayed winter pruning of *Vitis vinifera* L. cv. Sangiovese grapevines. *Frontiers in Plant Science*, *7*, Article 659. https://doi.org/10.3389/fpls.2016.00659

Grechi, I., Vivin, P., Hilbert, G., Milin, S., Robert, T., & Gaudillère, J.-P. (2007). Effect of light and nitrogen supply on internal C:N balance and control of root-to-shoot biomass allocation in grapevine. *Environmental and Experimental Botany*, *59*(2), 139–149. https://doi.org/10.1016/j.envexpbot.2005.11.002

Guilherme, M. R., Aouada, F. A., Fajardo, A. R., Martins, A. F., Paulino, A. T., Davi, M. F. T., Rubira, A. F., & Muniz, E. C. (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

IUSS Working Group WRB. (2015). World Reference Base for Soil Resources 2014, International soil classification system for naming soils and creating legends for soil maps, Update 2015. *World Soil Resources Reports*, Nº 106, Rome: FAO. E-ISBN 978-92-5-108370-3.

Jones, J. B., Jr., & Case, V. W. (1990). Sampling, handling, and analyzing plant tissue samples. *Soil testing and plant analysis*, *3*, 389-427. https://doi.org/10.2136/sssabookser3.3ed.c15

Kapłan, M., Lenart, A., Klimek, K., Borowy, A., Wrona, D., & Lipa, T. (2021). Assessment of the possibilities of using cross-linked polyacrylamide (Agro hydrogel) and preparations with biostimulation in building the quality potential of newly planted apple trees. *Agronomy*, *11*(1), 125. https://doi.org/10.3390/agronomy11010125

Keller, M. (2005). Deficit irrigation and vine mineral nutrition. *American Journal of Enology and Viticulture*, *56*(3), 267-283. https://doi.org/10.5344/ajev.2005.56.3.267

Keller, M. (2015). *The Science of Grapevines: Anatomy and Physiology*. 2nd ed., Elsevier Academic Press: Amsterdam, The Netherlands.

Krasnopeeva, E. L., Panova, G. G., Yakimansky, A. V. (2022). Agricultural Applications of Superabsorbent Polymer Hydrogels. *International Journal of Molecular Sciences*, *23*(23), 15134. https://doi.org/10.3390/ijms232315134

Li, R., Hou, X., Li, P., & Wang, X. (2022). Multifunctional Superabsorbent Polymer under Residue Incorporation Increased Maize Productivity through Improving Sandy Soil Properties. *Advances in Polymer Technology*, 6554918, 12 p. https://doi.org/10.1155/2022/6554918

Lindsay, W. L. & Norvell, W. A. (1978). Development of DTPA soil test for zinc, iron, manganese, and copper. *Soil Science Society of America Journal*, *42*, 421–428. https://doi.org/10.2136/sssaj1978.03615995004200030009x

Lopes, C. M., & Pinto, P. A. (2005). Easy and accurate estimation of grapevine leaf area with simple mathematical models. *Vitis*, *44*(2), 55-61.

Lorenz, D. H., Eichhorn, K. W., Bleiholder, H., Klose, R., Meier, U., & Weber, E. (1995). Growth Stages of the Grapevine: Phenological growth stages of the grapevine (*Vitis vinifera* L. ssp. *vinifera*)—Codes and descriptions according to the extended BBCH scale. *Australian Journal of Grape and Wine Research*, *1*(2), p. 100–103. https://doi.org/10.1111/j.1755-0238.1995.tb00085.x

Ma, Y., Lv, H., Wang, Y., Wang, Y., Yin, M., Kang, Y., Qi, G., Zhang, R., Wang, J., Chen, J. (2025). Study on the Synergistic Regulation Model for *Lycium barbarum* Berries Under Integrated Irrigation and Fertigation in Northwest Arid Regions. *Agronomy*, *15*, 73. https://doi.org/10.3390/agronomy15010073

Murphy, J., & Riley, J. P. (1962). A Modified Single Solution Method for Determination of Phosphate in Natural Waters. *Analytica Chimica Acta*, *27*, 31–36. https://doi.org/10.1016/S0003-2670(00)88444-5

Pereira, L. S., Cordery, I., & Iacovides, I. (2012). Improved indicators of water use performance and productivity for sustainable water conservation and saving. *Agricultural water management*, *108*, 39-51. https://doi.org/10.1016/j.agwat.2011.08.022

Qu, G., & de Varennes, A. (2010). Use of hydrophilic polymers from diapers to aid the establishment of *Spergularia purpurea* in a mine soil. *Journal of Hazardous Materials*, volume 178, issues 1–3, p. 956-962. https://doi.org/10.1016/j.jhazmat.2010.02.031

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

Situ, Y., Yang, Y., Huang, C., Liang, S., Mao, X., & Chen, X. (2023). Effects of several superabsorbent polymers on soil exchangeable cations and crop growth. *Environmental Technology & Innovation*, *30*, 103126. https://doi.org/10.1016/j.eti.2023.103126

van Leeuwen, C., Destrac-Irvine, A., Dubernet, M., Duchêne, E., Gowdy, M., Marguerit, E., Pieri, P., Parker, A., de Rességuier, L., & Ollat, N. (2019). An Update on the Impact of Climate Change in Viticulture and Potential Adaptations. *Agronomy*, *9*, 514. https://doi.org/10.3390/agronomy9090514

Watanabe, K., Saensupo, S., Na-iam, Y., Klomsa-ard, P., & Sriroth, K. (2019). Effects of Superabsorbent Polymer on Soil Water Content and Sugarcane Germination and Early Growth in Sandy Soil Conditions. *Sugar Tech*, *21*, 444–450. https://doi.org/10.1007/s12355-018-0672-5

Yang, Y., Zhang, S., Wu, J., Gao, C., Lu, D., & Tang, D. (2022). Effect of long term application of super absorbent polymer on soil structure, soil enzyme activity, photosynthetic characteristics, water and nitrogen use of winter wheat. *Frontiers in Plant Science*, *13*. https://doi.org/10.3389/fpls.2022.998494

Yazdani, F., Allahdadi, I., & Akbari, G. A. (2007). Impact of superabsorbent polymer on yield and growth analysis of soybean (*Glycine max* L.) under drought stress condition. *Pakistan Journal of Biological Sciences*, *10*(23), 4190-4196. https://doi.org/10.3923/pjbs.2007.4190.4196

Zapata, C., Deléens, E., Chaillou, S., & Magné, C. (2004). Partitioning and mobilization of starch and N reserves in grapevine (*Vitis vinifera* L.). *Journal of Plant Physiology*, *161*(9), 1031-1040. https://doi.org/10.1016/j.jplph.2003.11.009

Zhao, C., Zhang, L., Zhang, Q., Wang, J., Wang, S., Zhang, M., & Liu, Z. (2022). The effects of bio-based superabsorbent polymers on the water/nutrient retention characteristics and agricultural productivity of a saline soil from the Yellow River Basin, China. *Agricultural Water Management*, volume 261, 107388. https://doi.org/10.1016/j.agwat.2021.107388

Zohuriaan-Mehr, M. J., & Kabiri, K. (2008). Superabsorbent polymer materials: A review. *Iranian Polymer Journal*, *17*(6), 451-477.