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Enhancing Soil Water-physical Properties and Winter Wheat Yield in Rain-fed Regions using Aquasource and Van Polymers

S.V. Sahakyan[1], T.V. Yedoyan[2], T.S. Sahakyan[3], A.Sh. Eloyan[3], S.H. Daveyan[3], G.V. Avagyan[4] **10.18805/IJARe.AF-927**

ABSTRACT

Background: Enhancing productivity in rain-fed soils is crucial for sustainable agriculture. This study evaluates the potential of two newly synthesized water-absorbing polymers, Aquasource and Van, to improve soil water-physical properties and increase winter wheat yields in rain-fed areas.

Methods: Laboratory and field experiments were conducted from 2021 to 2024. Laboratory experiments assessed the effects of polymer doses on hydraulic conductivity, maximum field moisture and water-holding capacity in soils with different textural compositions. Field experiments examined winter wheat yields in response to different doses of polymers and fertilizers, applied separately and in combination.

Result: Aquasource (100-300 kg ha^{-1}) and Van (1,000-2,000 kg ha^{-1}) increased soil hydraulic conductivity by 20-47%. In light-clay soils, Aquasource (100-150 kg ha^{-1}) and Van (1,000-1,500 kg ha^{-1}) increased maximum field moisture by 8.4-8.6% and 8.0-10.5%, respectively. In heavy and medium loamy soils, the application of 300 kg ha^{-1} of Aquasource and 2,000 kg ha^{-1} of Van improved maximum field moisture by 5.0-6.5%. The optimal polymer doses, without fertilizers, were 50 kg ha^{-1} for Aquasource and 500 kg ha^{-1} for Van, resulting in a 21.5% and 38% increase in wheat yield, respectively. When combined with fertilizers, yields increased by 22.0-48.0%. These findings suggest that these polymers can significantly improve soil properties and enhance crop yields, promoting sustainability in rain-fed regions.

Key words: Agricultural productivity, Hydraulic conductivity, Land improvement, Polymer and fertilizers doses, Water-holding capacity, Yield indicators.

INTRODUCTION

The dynamic growth of the agricultural sector requires continuous research to preserve and optimize resources, with a particular focus on water, in the face of global climate change and increasing irrigation demands (Khondoker *et al.,* 2023). The rising global demand for freshwater, coupled with reduced precipitation and increased evaporation, underscores the urgent need for effective water resource management in agriculture (Li *et al.,* 2023). As a result, the adoption of water-conservation technologies has become a critical strategy to enhance crop productivity, particularly in regions facing water scarcity (Klykov *et al.,* 2019; de Clercq *et al.,* 2021; Ghebru, 2007). Polymer hydrogels, known for their exceptional water-absorption characteristics, form soil-polymer complexes that retain substantial water volumes for extended periods (Noorjahan *et al.,* 2019; Azeem *et al.,* 2023; Avagyan *et al.,* 2024). This feature reduces water irrigation needs, extending intervals for both irrigated and rain-fed agriculture and ensuring sufficient moisture for crops (Oladosu *et al.,* 2022). Additionally, polymer hydrogels find diverse applications in agriculture, contributing to improved soil water retention, erosion mitigation and other benefits (Grabowska-Polanowska *et al.,* 2021; Piccoli *et al.,* 2024).

Since 1980, hydrogel-forming polymers have played a crucial role in agriculture, renowned for their efficacy (Azzam, 1980; Khodadadi, 2018; Patra *et al.,* 2022). The interaction between soil and polymers induces changes in the size and shape of soil aggregates, affecting the mechanisms of interaction among soil particles (Abrisham *et al.,* 2018). This interaction primarily occurs on the surfaces of the soil

[1]Faculty of Urban Economy and Ecology, National University of Architecture and Construction of Armenia, 105 Teryan St., Yerevan 0009, Republic of Armenia.

[2]Faculty of Management and Technology, National University of Architecture and Construction of Armenia, 105 Teryan St., Yerevan 0009, Republic of Armenia.

[3]Department of Amelioration, Scientific Centre of "Soils Science, Agrochemistry and Amelioration after Hrant Petrossyan", branch of the Armenian National Agrarian University, 24 Isakov St., Yerevan 0004, Republic of Armenia.

[4]Faculty of Agronomy, Armenian National Agrarian University, 74 Teryan St., Yerevan 0009, Republic of Armenia.

Corresponding Author: T.V. Yedoyan, Faculty of Management and Technology, National University of Architecture and Construction of Armenia, 105 Teryan St., Yerevan 0009, Republic of Armenia. Email: yedoyantatevik@nuaca.am

ORCIDs: 0000-0001-9605-8183; 0009-0001-8079-8045; 0009-0002-5411-5842; 0000-0002-0539-9829; 0000-0002-1381-2257; 0000-0001-5843-5080

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particles, leading to a significant increase in their overall surface area (Abdallah, 2019; Sroka and Sroka, 2024). Notably, some scholars have suggested that the effectiveness of polymers may be reduced in soils with lighter mechanical compositions, especially in coarse-grained sandy soils compared to clay-based soils (Dehkordi, 2016). It is acknowledged that variations in water-absorption properties depend on both soil types and polymer characteristics (El-Rhman *et al.,* 2017). Consequently, investigating the impact of polymers on water-retention in soils with diverse mechanical compositions holds scientific and practical significance (Kolesnikov *et al.,* 2024).

Challenges related to land and water scarcity and their efficient utilization are prominent in the Republic of Armenia. The mountainous terrain severely restricts agricultural development in Armenia, categorizing the country as extremely risky for land utilization because of poor water-physical properties and inadequate moisture supply. Declining soil moisture in rain-fed conditions reduces both crop yield and quality. A promising solution is the use of water-absorbing polymer hydrogels to improve soil water management. This research aims to evaluate and apply locally produced water-absorbing agents such as Aquasource and the polymer-mineral composition of Van within the agricultural production domain (Sahakyan *et al.,* 2024). These substances are locally produced in the Republic of Armenia, featuring biodegradability, substantial water absorption capabilities and complete safety for humans, avian species and beneficial soil microorganisms.

This study was aimed to determine optimal dosages of recently synthesized polymers for enhancing water-physical properties in soils with varied mechanical compositions. It was essential to conduct empirical investigations under controlled laboratory conditions to substantiate the innovative effectiveness of these polymers in enhancing agricultural production. The novelty lies in enabling effective polymer utilization for regulating soil water regimes, especially in arid regions, with the ultimate objective of enhancing crop yields.

MATERIALS AND METHODS

The research was conducted between 2021 and 2022 at the Soil Melioration Laboratory of the Scientific Centre of Soils Science, Agrochemistry and Amelioration after Hrant Petrossyan, a branch of the Armenian National Agrarian University.

Study area

The experimental soils were collected from the Spitak community of Armenia, located at 44.2730°E longitude and 40.8156°N latitude in the WGS84 coordinate system. This region, within the dry-steppe zone, experiences annual precipitation of 350-500 mm during the warm period, occasionally leading to declines in crop yields due to insufficient moisture.

Soil characteristics

The soils are characterized by typical Chernozems with diverse mechanical compositions, which are slightly alkaline, with pH values ranging from 7.2 to 7.6 and low soluble salt levels and electrical conductivity (EC) ranging from 0.8 to 1.4 dS m^{-1}. The cation exchange capacity (CEC) ranged from 28.2 to 41.7 cmolc kg^{-1} and the exchangeable sodium percentage (ESP) varied from 3.1 to 3.9%. Humus content ranged between 5.4% and 7.6%. Detailed physical, chemical and physiochemical properties are summarized in Table 1.

Polymers used

Two types of polymers were used in this study: Aquasource from the company Aquatechnology and the polymer-mineral composition Van from the yerevan household chemicals plant in Armenia. 1 g of Aquasource absorbs 500 g of water, while 1 g of the polymer-mineral water-absorber of Van, comprising clay minerals and approximately 10% of the polymer, absorbs 78 g of water.

Laboratory studies

Soil preparation

Soil samples were air-dried, crushed and sieved through a 1 mm sieve. The appropriate amount of polymer absorbents (Aquasource and Van) was added to the soil samples and thoroughly mixed to achieve a homogeneous mixture using a soil mixing technique. The dosages of polymer Aquasource were 50-300 kg ha^{-1} and Van is 500-3,000 kg ha^{-1}.

Experimental design

The experimental investigation was conducted under controlled laboratory conditions, comprising three distinct treatments: I) light-clay soil, II) heavy-loamy soil, III) medium-

Table 1: Some physical, chemical properties and average hydrophysical indicators of 0-0.5 m layer in investigated ordinary Cher nozems, categorized by mechanical composition.

Categories	ESP (%)	EC (dS m^{-1})	MFM (%)	Humus (%)	pH	Physical clay (%)	Porosity (%)	Silt (%)	Volumetric mass (kg m^{-3})
I	3.1	1.4	31.9	7.6	7.6	52.6	54.0	23.7	1,250
II	3.6	1.1	27.4	6.1	7.4	43.4	52.4	18.2	1,260
III	3.9	0.8	22.5	5.4	7.2	35.2	53.5	15.8	1,240

Categories: I- Light-clay soil; II- Heavy-loamy soil; III- Medium-loamy soil.

MFM= Maximum field moisture capacity.

loamy soil. Each treatment was replicated three times, with average values calculated for subsequent statistical analysis. Water-physical characteristics of these soils, such as saturated hydraulic conductivity, maximum field moisture (MFM) capacity and water holding capacity (WHC), were assessed.

Determining of hydraulic conductivity

Hydraulic conductivity was determined using the constant-head method (Amoozegar, 2020). This method involves maintaining a consistent head differential across a soil sample within a disturbed steel ring. Measurements of water volume passing through the sample at specific intervals were taken and hydraulic conductivity was computed from this discharge based on the soil sample size and established head differential.

Determining of maximal field moisture capacity

MFM capacity was determined using the capillary saturation method. Rings (4.0 cm diameter, 1.5 cm height) with fine nylon netting at the bottom were filled with 20 g of air-dried soil (sieved through a 1 mm sieve) and placed in a desiccator with water, maintaining a 1 mm water level above the ring bottoms. The water-saturated soil and rings were periodically weighed until a constant weight was achieved. Then, the rings were transferred to a drying chamber and dried at 105°C.

The impact of polymers on soil MFM capacity was assessed by using:

$$FC = \frac{F - F_0}{F_0} 100\% \quad ....(1)$$

Where:

FC = Relative increase of the MFM capacities (%).

F and F_0 = MFM capacities, respectively, with and without polymers use (%).

Determining of water holding capacity

A laboratory experiment was conducted to investigate the impact of Aquasource and Van on soil WHC using Richard's pressure plate apparatus (Richards, 1948). Preceding the experiment, a soil water sorption curve was meticulously constructed for the experimented soils, employing a ceramic plate and membrane apparatus. Saturated soil samples were placed on a ceramic and cellophane membrane with microscopic pores, which allowed water to pass through while retaining the air pressure applied to the upper surface. Water content measurements were conducted at pressure points of 30, 300 and 1500 kPa.

Field studies

Experimental design

An area of 30 m^2 was allocated for each variant and a total of 630 m^2 for all 21 variants with 3 repetitions. Winter wheat was sown in October 2022. Polymers and fertilizers were applied before sowing using specialized equipment, followed by ploughing to incorporate them into the soil at a depth of 20-25 cm.

The field experiment variants were as follows:

- Application of polymers without fertilization.
- Application of polymers in conjunction with the $N_{50}P_{50}K_{50}$ fertilizer dose.
- Application of polymers in conjunction with the $N_{100}P_{100}K_{100}$ fertilizer dose.

After performing the necessary agrotechnical procedures, winter wheat was sown using an inter-row planter, with the seeds embedded in the soil to a depth of 4-5 cm. Ammophoska ($N_{16}P_{16}K_{16}$) was used as the fertilizer at a dose of 625 kg ha^{-1}. For the $N_{100}P_{100}K_{100}$ dose, 1.875 kg of fertilizer was required per variant and for the $N_{50}P_{50}K_{50}$ dose, 0.938 kg per variant. The total amount of Ammophoska used for all experiments was 19.7 kg.

In the field experiments, winter wheat yield was measured using the metric method, with 3 replications for each variant. To assess the effect of polymers on the winter wheat yield the precipitation data for the vegetation period are studied. The field experimental data of 2023 and 2024 were analyzed using the method of curvilinear regression and the results are presented in the form of a cubic parabola.

$$G = AX^3 + BX^2 + CX + D \quad ....(2)$$

Where:

G = Relative winter wheat yields.

X = Polymer doses.

A, B, C, D = Parameters of the equation.

Statistical analysis

Data were analyzed using the Duncan multiple range test to identify significant differences between treatment means. The analysis was conducted at a significance level of $p \leq 0.05$.

The relationship between polymer doses and winter wheat yield was analyzed by comparing the relative yield (G), calculated as:

$$G = \frac{Y - Y_0}{Y_0} 100\% \quad ....(3)$$

Where:

Y = Yield of winter wheat under the application of different measures.

Y_0 = Yield of the control variant.

Statistical significance was assessed using origin 6.1 software.

RESULTS AND DISCUSSION

Laboratory experiments

The effect of polymers on soil hydraulic conductivity

The experimental results (Fig 1a) showed that Aquasource at 100 kg ha^{-1} significantly improved soil filtration, increasing hydraulic conductivity (K, m d^{-1}) by 47% in light-clay soils. However, higher doses (300 kg ha^{-1}) reduced conductivity by 15%. Conversely, in heavy-loamy soils, higher

Aquasource dosages increased hydraulic conductivity by 44% at 300 kg ha^{-1}, while medium-loamy soils exhibited a 22% increase.

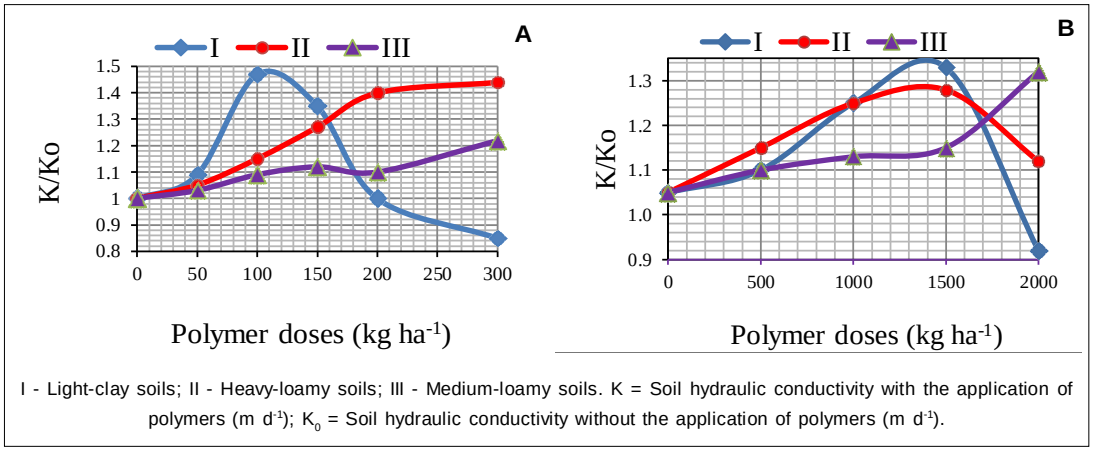
Fig 1b shows the effect of Van doses on relative hydraulic conductivity. In light-clay soils (curve I), 1500 kg ha^{-1} of Van increased filtration by 28%, while a further increase to 2,000 kg ha^{-1} led to a 13% decrease. In heavy-loamy soils (curve II), 2,000 kg ha^{-1} resulted in a 27% improvement, the highest observed. The maximum increase in medium-loamy soils (curve III) was 23% with 1500 kg ha^{-1}, but a 2,000 kg ha^{-1} dose reduced conductivity to 1.07 times. Notably, in medium-loamy soils, the highest increase (1.27 times) was achieved with 2,000 kg ha^{-1} of Van.

In summary, the application of 1 500 kg ha^{-1} of Van, combined with up to 100 kg ha^{-1} of Aquasource in light clay soils, significantly improved soil filtration properties, increasing relative hydraulic conductivity by 1.28 to 1.47 times (28-47%) compared to untreated soils. The maximum increase in relative hydraulic conductivity (1.22 to 1.27 times) was achieved in heavy and medium-loamy soils with 200-300 kg ha^{-1} of Aquasource and 1,500-2,000 kg ha^{-1} of Van.

Thus the application of polymers Aquasource and Van in soil management has demonstrated a significant impact on improving soil hydraulic conductivity, which is essential for enhancing moisture retention in mountainous regions and mitigating water runoff and erosion on gentle slopes. These findings are consistent with previous studies, including those by Renkuan *et al.* (2016) and Abrisham *et al.* (2018).

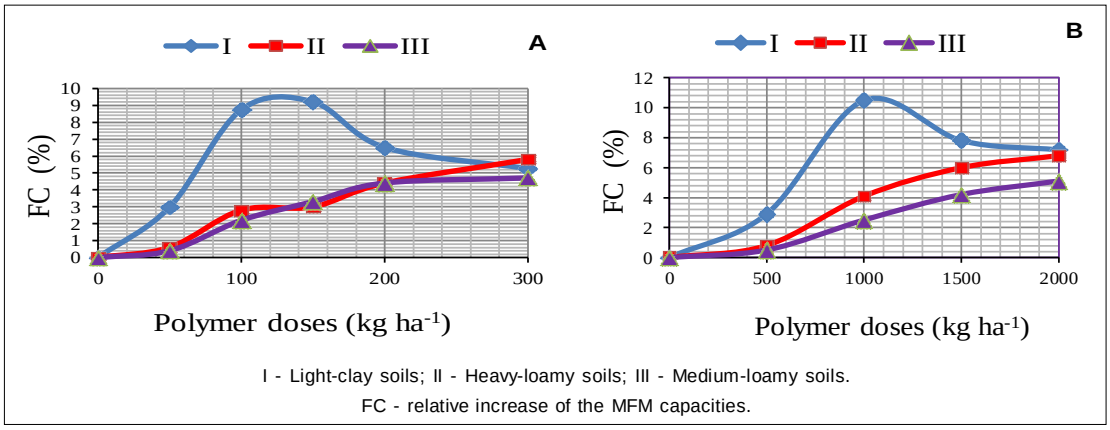
The impact of polymers on the MFM capacity of soil

Aquasource application improved field moisture capacities in light-clay soils (curve I) by 8.4% to 8.6% at polymer doses of 100-150 kg ha^{-1} (Fig 2a). Increasing the dosage to 300 kg ha^{-1} led to a decrease in FC to 5.0%. In heavy-loamy (curve II) and medium-loamy (curve III) soils, field moisture capacities increased gradually with polymer doses, reaching 6.0% and 4.5% at 300 kg ha^{-1}, respectively, 1.4-1.9 times lower than in light-clay soils. Fig 2b shows that Van, a polymer-mineral composition, achieved peak FC (10.5%-8.0%) at 1,000-1,500 kg ha^{-1}, with a decrease to 7.0% at 2,000 kg ha^{-1}. In heavy-loamy and medium-loamy



I - Light-clay soils; II - Heavy-loamy soils; III - Medium-loamy soils. K = Soil hydraulic conductivity with the application of polymers (m d^{-1}); K_0 = Soil hydraulic conductivity without the application of polymers (m d^{-1}).

Fig 1: The impact of different dosages of Aquasource (A) and Van (B) polymers on the relative hydraulic conductivity of soils with different mechanical compositions.



I - Light-clay soils; II - Heavy-loamy soils; III - Medium-loamy soils.
FC - relative increase of the MFM capacities.

Fig 2: The impact of varied dosages of Aquasource (A) and Van (B) polymers on the relative maximum field moisture capacity of soils with different mechanical compositions.

soils, maximum field moisture capacities occurred at 2,000 kg ha^{-1}, reaching 6.5% and 5.0%, respectively.

In summary, the effect of polymers on the MFM capacity was notably more pronounced in heavier soils compared to lighter soils. This suggests that the soil texture plays a significant role in the efficacy of polymer treatments, with higher doses of polymer required for significant improvements in heavy soils. This observation aligns with the findings of Dehkordi (2016).

The impact of polymers on soil WHC

Table 2 shows that Aquasource and Van applications under high soil moisture saturation (30 kPa) increased soil WHC by 5.2%-3.1% and 6.2%-3.1%, respectively, compared to untreated soil. Maximum WHC was achieved at polymer doses of 100 kg ha^{-1} (Aquasource) and 1,000 kg ha^{-1} (Van), with higher doses reducing WHC. Under lower moisture saturation (300 kPa), this trend persisted, though the effect was weaker (4.0%-2.4% for Aquasource and 4.8%-2.2% for Van).

At 1,500 kPa, polymer efficacy decreased significantly, with only a 2% increase observed at 100 kg ha^{-1} and 1,000 kg ha^{-1} doses and no positive effect at higher doses.

Thus, the efficiency of polymers Aquasource and Van was highest under conditions of high soil moisture saturation. This is in agreement with Sivapalan's (2001) findings.

Statistical analysis

The statistical parameters for soil hydraulic conductivity, MFM and WHC were analyzed. The data indicated that Aquasource at 50 kg ha^{-1} did not significantly affect hydraulic conductivity ($p > |t| > 0.05$). However, the Van polymer only showed a significant difference at 500 kg ha^{-1}, indicating its limited impact on improving soil hydraulic conductivity compared to Aquasource.

Regarding MFM capacity, Aquasource significantly affected MFM at doses of 100, 150 and 200 kg ha^{-1} compared to the control, with no significant differences observed among other doses. For the Van polymer, significant effects on MFM, compared to the control, were observed at doses of 1,000, 1,500 and 2,000 kg ha^{-1}. Significance was also noted when doses of 1,000 and 2,000 kg ha^{-1} were compared to the 500 kg ha^{-1} dose. These results demonstrate that the Van polymer has a more pronounced impact on increasing soil MFM.

In terms of WHC, under 30 kPa pressure, Aquasource doses of 100, 150 and 200 kg ha^{-1} significantly enhanced soil absorption properties compared to the control, with no significant differences among these doses. At 1,500 kPa, only the 100 kg ha^{-1} dose showed a significant difference from the control, indicating a decreased efficacy of the polymer in enhancing WHC at lower moisture levels.

Thus, the statistical analysis of the experimental data attests to the reliability of the laboratory experiments and the validity of the obtained results.

Field experiments

Effect of polymers on winter wheat yield without fertilizers

The analysis of the impact of Aquasource and Van polymers on relative winter wheat yields (expressed as the percentage yield increase compared to the control) revealed the following:

- **Aquasource (Fig 3a):** The maximum relative yield increase (21.5%) was observed at a 50 kg ha^{-1} dose. Increasing the dose to 100 kg ha^{-1} had no effect, while 150 kg ha^{-1} reduced the yield increase to 13.5%.

Table 2: Dependence of the applied pressure on the volumetric moisture of light-clay soil under various polymer dosages.

Polymer doses	Applied pressure (kPa)		
(kg ha^{-1})	30	300	1500
		Aquasource (%)	
0	60.2	45.1	13.6
100	65.4	49.1	16.6
200	64.1	48.1	11.9
300	63.3	47.5	10.9
		Van (%)	
0	60.2	45.1	13.6
1,000	66.5	49.9	16.5
2,000	64.5	48.4	14.5
3,000	63.1	47.3	12.8

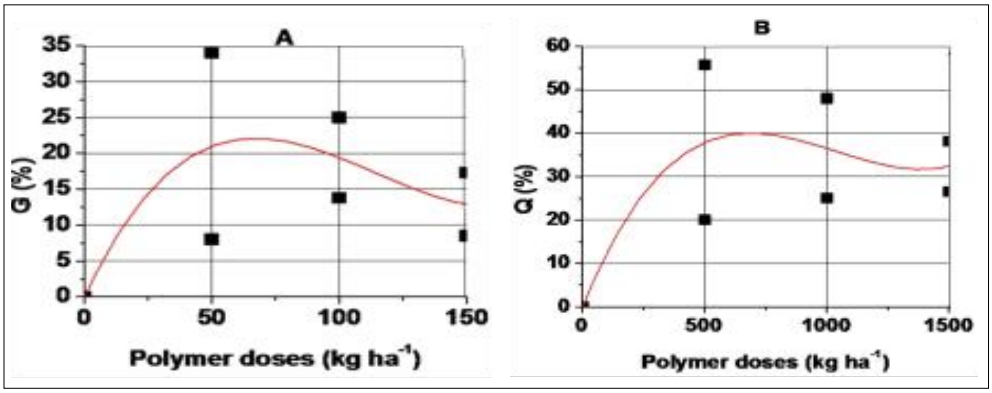


Fig 3: The impact of varied dosages of Aquasource (A) and Van (B) polymers on the relative winter wheat yields (G, %) without application of fertilizers (by the data 2023-2024).

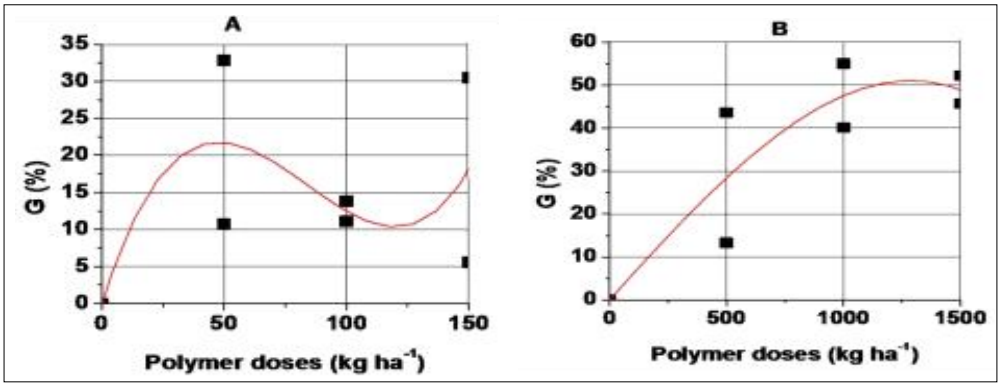


Fig 4: The impact of varied dosages of Aquasource (A) and Van (B) polymers on the relative winter wheat yields (G), with the application of $N_{50}P_{50}K_{50}$ fertilizers (2023-2024).

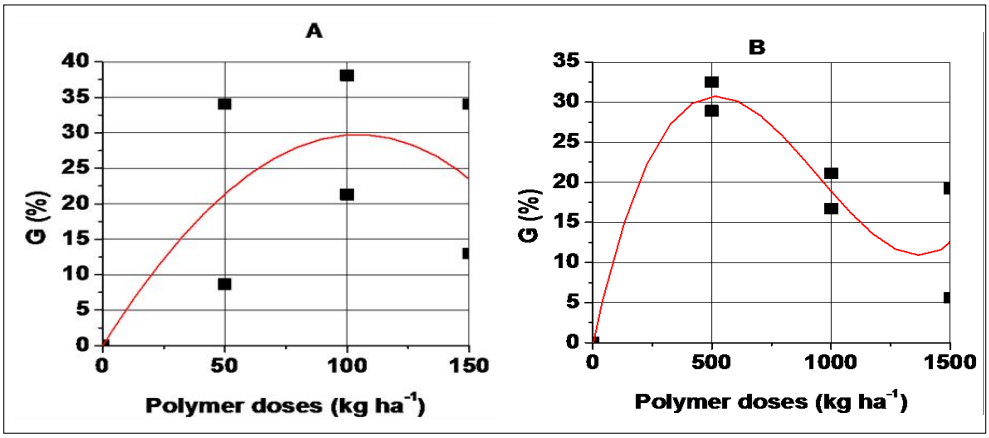


Fig 5: The impact of varied dosages of Aquasource (A) and Van (B) polymers on the relative winter wheat yields (G), with the application of $N_{100}P_{100}K_{100}$ fertilizers (2023-2024).

- **Van (Fig 3b):** The maximum relative yield increase (38%) occurred at 500 kg ha^{-1}, which was 43.4% higher than the maximum increase seen with Aquasource at 50 kg ha^{-1}. A further increase to 1,500 kg ha^{-1} reduced the yield increase to 31.5%.

Overall, Aquasource and Van polymers increased winter wheat yields by 21% to 48% compared to the control, aligning with similar studies like Ghasemi and Khoshkhou (2008), who reported a 15% increase with 100 kg ha^{-1} of superabsorbent polymers.

Effect of polymers on winter wheat yield with fertilizers

When combined with $N_{50}P_{50}K_{50}$ fertilizer (Fig 4), the maximum relative yield increase with Aquasource (21%) was observed at 50 kg ha^{-1}, while higher doses resulted in a reduction in yield increase. For Van, the yield increase increased almost linearly up to 1,000 kg ha^{-1}, reaching 48%, which was 56.2% higher than Aquasource at 50 kg ha^{-1}. Further increases in Van's dose did not produce significant additional increases.

With $N_{100}P_{100}K_{100}$ fertilizer (Fig 5), the maximum yield increase with Aquasource (30%) was obtained at 100 kg ha^{-1}, while further increases in dose led to a decrease in yield (24%). The Van polymer also showed a peak yield increase of 30.5% at 500 kg ha^{-1}, with a decline to 12% at 1,500 kg ha^{-1}.

In summary, the optimal application doses of Aquasource (50 kg ha^{-1}) and Van (500 kg ha^{-1}) resulted in a yield increase of 21.5% and 38%, respectively, compared to the control. The combined applications with fertilizers (50 and 100 kg ha^{-1}) led to yield increases ranging from 22.0% to 48%, with the highest increase of 30% observed with 100 kg ha^{-1} of fertilizer and 100 kg ha^{-1} of Aquasource.

CONCLUSION

The findings demonstrate that the application of Aquasource at 100-300 kg ha^{-1} and Van at 1,000-2,000 kg ha^{-1} significantly enhanced soil hydraulic conductivity by 20-47%. Additionally, Aquasource (100-150 kg ha^{-1}) and Van (1,000-1,500 kg ha^{-1}) improved maximum field moisture (MFM) capacity in light-clay soils by 8.4-8.6% and 8.0-10.5%, respectively, while in heavy and medium loamy soils, MFM capacity increased by 5.0-6.5% for Aquasource at 300 kg ha^{-1} and 2,000 kg ha^{-1} for Van. Regarding winter wheat yield, the optimal application doses of Aquasource (50 kg ha^{-1}) and Van (500 kg ha^{-1}) resulted in a yield increase of 21.5% and 38%, respectively, compared to the control. Furthermore,

combined applications with fertilizers (50 and 100 kg ha^{-1}) led to yield increases ranging from 22.0% to 48%, with the highest increase of 30% observed with 100 kg ha^{-1} of fertilizer and 100 kg ha^{-1} of Aquasource.

These results highlight the potential of Aquasource and Van polymers in regulating soil water regimes, particularly in arid regions, thus supporting sustainable agricultural productivity.

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Disclaimers

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this article. No funding or sponsorship influenced the design of the study, data collection, analysis, decision to publish or preparation of the manuscript.

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