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Application of hydrogel polymers and fertilizers for increasing winter wheat grain yield in conditions of rain-fed agriculture

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Abstract: This study aims to address the critical issue of water scarcity, which is being intensified by climate change and presents significant challenges to rain-fed agriculture, especially in arid regions. The research focuses on enhancing winter wheat grain yield productivity under rain-fed conditions through the utilization of locally produced, environmentally friendly hydrogel polymers. The methodology involved a field experiment conducted in the Spitak community, Armenia, from 2022 to 2023, covering an area of 630 m^2. Along with control groups, the study had 21 experimental treatments that used Aquasource and Van polymers in different ways, with and without nitrogen, phosphorus, and potassium (NPK) fertilizer. The findings indicated that the application of Aquasource and Van polymers at doses of 50-100 kg ha^{-1} and 750-1000 kg ha^{-1}, respectively, without fertilizers significantly increased soil moisture absorption during the tillering and heading stages by 11.5-12.5% and 5.5-7.5%, compared to the controls. On the other hand, using these polymers with NPK fertilizer ($N_{50}P_{50}K_{50}$ and $N_{100}P_{100}K_{100}$) together made it harder for plants to absorb water, especially when more polymers were used. Soil moisture levels had a substantial impact on winter wheat grain yield metrics during these growth stages, demonstrating a strong correlation ($R = 0.71\text{-}0.91$). Enhanced moisture absorption resulting from polymer application led to a 22-24% increase in winter wheat grain yield. The practical implications of this study lie in its identification of key factors that influence winter wheat yield in rain-fed agriculture, particularly regarding locally sourced polymer dosage and application methods, both independently and in conjunction with fertilizers.

Keywords: *Fertilizer, Polymer dosages, Soil improvement, Tillering and heading stages, Water holding capacity, Winter wheat.*

1. Introduction

Agriculture, as a vital industry for food production, is the primary user of water resources [1, 2]. Evaporation in agricultural areas loses a significant portion, approximately 63%, of this water [3]. The shortage of water resources, especially in arid regions, is consistently worsening due to the impacts of climate change and rising demand. This growing trend raises significant concerns for rain-fed agriculture, where crop yields heavily depend on rainfall for moisture. Insufficient soil moisture inevitably results in reduced yields [4]. To address these challenges, it is essential to implement water conservation techniques that prolong rainwater retention and ensure crop survival [5]. In rain-fed areas, limited water

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availability remains a significant barrier to successful crop cultivation [6]. Hydrogel polymers offer a promising solution by improving soil structure, promoting root growth, and enhancing water penetration into the soil [7]. As soil moisture declines, organic matter decomposition accelerates, leading to reduced soil moisture retention capacity [8]. Using hydrogel polymers is known to enhance soil structure and water-physical properties, thereby boosting irrigation efficiency, reducing water usage, and cutting irrigation costs [9]. Particularly in arid regions and erosion-prone slopes, hydrogel polymers are invaluable for mitigating soil water loss and increasing crop yields [10-12].

A recent review suggested that applying an optimal rate of 100 kg ha^{-1} of superabsorbent polymers (SAP) can result in a 15% increase in yields [13]. The structural configuration of these SAPs and their water-absorption mechanism, facilitated by the formation of multiple hydrogen bonds between water molecules and functional groups within the polymer network, have been clarified [14]. It is established that the absorption capacity increases as soil moisture decreases (pF = 6.5 - 7.0), reaching its peak in water-saturated soils (pF = 0). However, plants can only access a portion of the water below the threshold of pF = 4.2 - 4.5, which coincides with the wilting point of most crops. Studies on SAPs indicate that the water potential bound within SAPs, available for plant uptake, falls within the pF range of 2.0 - 4.2.

It's important to note that as soil moisture decreases, the relationship between energy connection of soil moisture and soil particles becomes stronger. This results in a significant decrease in the water-holding capacity of polymers. Laboratory studies have shown that an increase in osmotic pressure can reduce water absorption by polymers, especially noticeable when using mineralized irrigation water or applying high doses of fertilizers in conditions of relatively low soil moisture, as seen in rain-fed agriculture.

Hence, there is an urgent need for innovative strategies to improve soil water retention capacity, especially in wheat cultivation within rain-fed agricultural systems, to meet yield objectives. Although numerous studies worldwide have emphasized the potential benefits of hydrogels as soil amendments, there is a lack of information regarding their use in rain-fed regions, particularly for field crops [15-17]. Therefore, we need to conduct further research to evaluate the effects of hydrogel polymers on soil characteristics and wheat yield in rain-fed conditions.

In the context of limited transportation routes within Armenia, food security issues have become increasingly significant, especially in recent years. The total arable land area is 446.0 thousand hectares, accounting for 21.8% of agricultural land. Rain-fed agricultural cultivation utilizes 70% of this area. Statistical data from the Armenian Statistical Service [18] reveal a concerning trend: the area dedicated to grain and leguminous crops decreased from 193 thousand hectares in 2015 to 114 thousand hectares in 2022, marking a 41% decline [18]. As a result, grain yield decreased by 59%, followed by a 29% reduction in productivity. Notably, despite its low profitability, grain production remains a priority for government attention, particularly following the discontinuation of state subsidies for these crops since 2018.

The observed decline in recent years underscores the importance of soil moisture levels in rain-fed agricultural systems, which are at risk of depletion due to climate change.

This study aimed to develop strategies for enhancing the productivity and grain yield of winter wheat under rain-fed agriculture conditions by using environmentally safe hydrogel polymers produced locally. The research novelty lies in identifying key factors influencing winter wheat yield in rain-fed agriculture, including the dosage and application of newly developed locally sourced polymers, both independently and in conjunction with fertilizers.

2. Material and Methods

We conducted the field studies in the Lori region of Armenia between 2022 and 2023. The research was specifically situated within the ordinary chernozem soils of the Spitak community, utilizing farmland owned by local farmers. Carbonate characterizes this region's soil profile. The geographical coordinates of the study area are 44.2730° E longitude and 40.8156° N latitude, as referenced in the World Geodetic System 1984 (WGS84) Figure 1.

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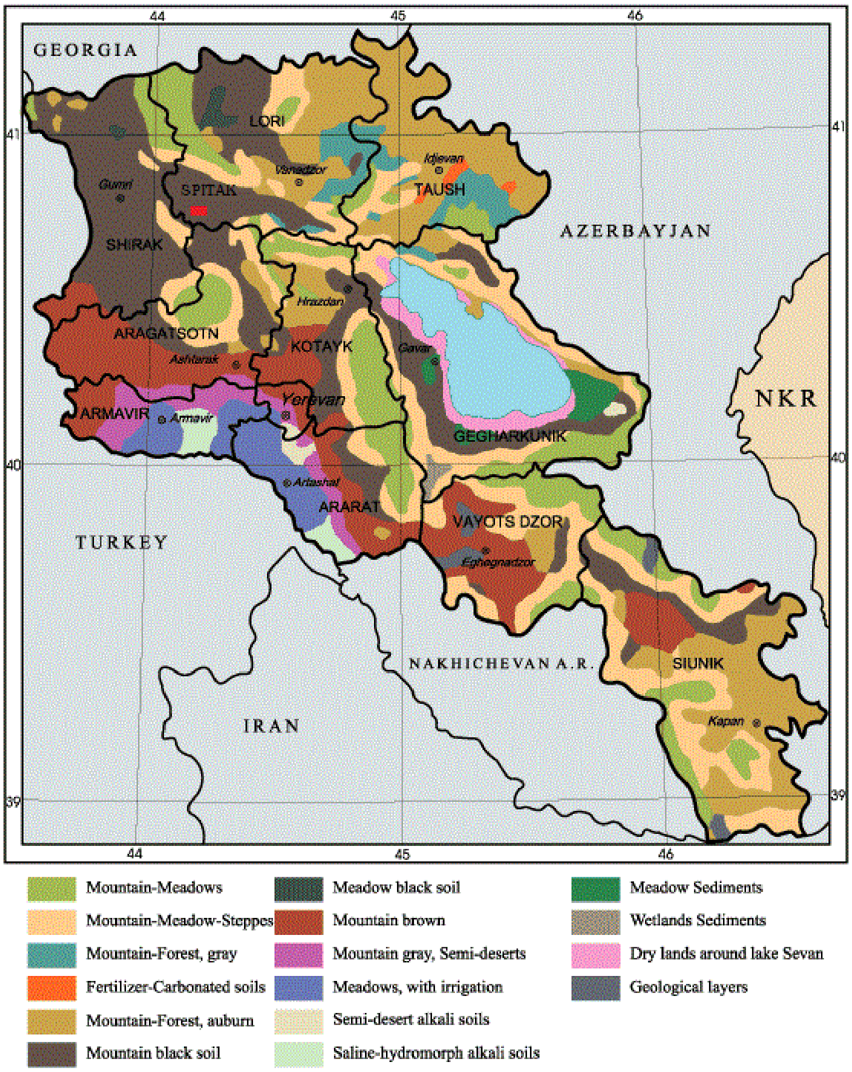

Figure 1.
Distribution of key soil types in Armenia.
Source: EU-JRC and FAO [19].

Within the Spitak subregion, ordinary chernozems cover an area of 37.8 thousand hectares. These soils have developed in dry steppe zone, characterized by an annual average temperature ranging from 2 to 5ºC. Notably, June temperatures average between 13 and 16ºC, with maximum positive temperatures reaching 34ºC and maximum negative temperatures dropping to -46ºC. Annual precipitation levels range from 550 to 750 millimeters, with a smaller range of 350 to 500 millimeters during the vegetation period. Table 1 provides some physical, chemical, and physicochemical parameters that characterize the experimental field.

The examination of the data in table reveals that the soil pH values within the humus horizons are weakly alkaline, ranging between 7.4 and 7.6. Conversely, in the C1 and C2 horizons, pH values increase to a range of 7.9 to 8.0. The humus content is notably elevated in the plow horizon (Ap), reaching 7.4%, whereas it decreases to 5.9-4.2% in the A and B horizons.

The soil exhibits a homogeneous light clay mechanical composition, characterized by silt content ranging from 23.6% to 25.6%, physical clay content from 50.7% to 57.4%, and carbonate content from

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4.2% to 18.9%. The soil's exchangeable complex is mostly full of Ca ions, with levels between 28.7 to 38.7 cmol$_c$ kg^{-1} in the humus horizons. The magnesium level is between 2.4 to 3.6 cmol$_c$ kg^{-1}. Exchangeable sodium percentage (ESP) remains notably low, ranging from 1.6% to 2.3% in horizons A and B. We measure the easily hydrolysable nitrogen, mobile phosphorus, and exchangeable potassium content in the plow horizon at 6.05, 2.30, and 28.00 mg/100 g, respectively. Table 2 provides a number of physical and water-physical parameters of the experimental soils. Bulk density, soil densities, and total porosity within humus horizons exhibit a range of 2.5-2.6 g/cm^3, 1.15-1.23 g/cm^3, and 52-54%, respectively. Due to the clay mechanical composition of the soil, both maximum hygroscopic moisture and moisture at steady wilting point register relatively high values (16.7-18.7% and 22.8-25.2%, respectively), while the range of active moisture is notably lower (7.0-10.5%).

Table 1.
Some properties of ordinary chernozems.

Horizons, depth (cm)	pH	Humus	Silt	Physical clay	CaCO$_3$	Exchangeable cations				
						Ca	Mg	Na	Total	ESP
		(%)				(cmol$_c$ kg^{-1})				%
Ap 0-25	7.6	5.4	25.1	57.4	4.2	38.7	3.1	1.0	42.8	2.3
A 25-42	7.4	3.9	24.0	54.6	11.3	31.4	3.6	0.8	35.8	2.2
B 42-61	7.5	3.2	25.6	50.7	16.1	28. 7	2.4	0.5	31.6	1.6
C1 61-85	7.9	0.7	23.6	53.9	18.9	18.3	1.4	0.2	19.9	1.0
C2 85-111	8.0	0.3	25.0	53.1	14,6	14.9	1.0	0.2	16.1	1.2

Table 2.
Some physical and water-physical properties of soils of the experimental site.

Horizons, depth, cm	BD	SD	TP	MHM	MSW	FMC	AMR
	(g/cm^3)		(%)				
Ap 0-25	2.5	1.15	54	16.9	22.8	33.3	10.5
A 25-42	2.5	1.21	52	16.7	23.0	33.4	10.4
B 42-61	2.6	1.23	53	18.7	25.2	32.2	7. 0

Note: BD-Bulk density, SD-Soil density, TP-Total porosity, MHM-Maximum hygroscopic moisture, MSW-Moisture of steady wilting, FMC-Field moisture capacity, AMR-Active moisture range.

Two polymers were used in the experiment: Aquasource, sourced from the Armenian company "Aquatechnology," and the polymer-mineral composition Van, manufactured by the "Yerevan Household Chemicals" plant. 1 g of Aquasource absorbs 500 g of water, while 1 g of the polymer-mineral composition Van, comprising clay minerals and approximately 10% of polymer, absorbs 78 g of water.

This field experiment marked the introduction of Aquaource and the Van polymer-mineral composition for the first time. The biodegradability, large water absorption, and complete non-toxcity to humans, birds, and soil-beneficial microorganisms are what make these polymers stand out.

For the experiment, an area of 30 m^2 was allocated for each treatment, resulting in a total area of 630 m^2 across all 21 variants, each replicated three times. The sowing of winter wheat was carried out in October 2022. Using specialized equipment, we uniformly distributed both polymers and fertilizers over the appropriate field options prior to sowing. Subsequently, the soil was plowed, embedding polymers and fertilizers into the soil to a depth of 20-25 cm. Subsequently, the soil was plowed to a depth of 20-25 cm, facilitating the incorporation of polymers and fertilizers. We sowed winter wheat seeds using an inter-row seeder, adhering to appropriate agronomic practices and ensuring their embedment to a depth of 4-5 cm within the soil. Amofoska ($N_{16}P_{16}K_{16}$) was applied as a fertilizer at a rate of 625 kg ha^{-1}. As a result, one treatment variant necessitated 1875 kg of fertilizer at the $N_{100}P_{100}K_{100}$ dose, whereas another treatment variant required only 0.938 kg at the $N_{50}P_{50}K_{50}$ dose. The cumulative amount of Amofoska fertilizer utilized for all experimental treatments amounted to 19.7 kg. We assessed soil moisture level using the weighing method at key stages of winter wheat development, including the tillering, heading, and ripening phases, throughout the experimental period. We conducted phenological assessments during the field experiments, which included measurements of plant height, head length, the number of grains per head, and the weight of 1000 grains. These observations were derived from an average of 40-45 plants sampled from each treatment variant within the field. We determined the yield of winter wheat using a metric method, collecting data from three replicates of each treatment variant. To identify the relationship between soil moisture levels and winter wheat yields, the latter were expressed as relative values using:

$$M = \frac{W-W_0}{W_0}100\% \qquad (1)$$

$$G = \frac{Y-Y_0}{Y_0}100\% \qquad (2)$$

Where W denotes the soil moisture level following the implementation of various interventions, W_0represents the soil moisture level of the control treatment, M signifies the relative soil moisture index, Y denotes the yield of winter wheat following the application of various interventions, Y_0represents the yield of the control treatment, and G is the relative yield indicator.

The relationship between soil moisture levels and the various growth stages of winter wheat was investigated through three experimental conditions: 1: application of polymers without fertilization; 2: application of polymers in conjunction with the $N_{50}P_{50}K_{50}$ fertilizer dose; 3: application of polymers in conjunction with the use of $N_{100}P_{100}K_{100}$ fertilizer dose.

The experimental results were analyzed using Origin 6.1 mathematical statistics software.

We conducted laboratory experiments to determine the polymer doses. Results indicated that the ideal doses for Aquasource and Van ranged between 50-150 kg ha^{-1} and 500-1500 kg ha^{-1}, respectively. Table 3 outlines these experimental conditions and polymer dosages.

Table 3.
Application of deferent doses of polymers and fertilizers.

Treatments	**Polymer doses (kg ha^{-1})**	**Fertilizer doses (kg ha^{-1})**
Polymer aquasource		
I	50	0
II	100	0
III	150	0
IV	50	$N_{50}P_{50}K_{50}$
V	100	$N_{50}P_{50}K_{50}$
VI	150	$N_{50}P_{50}K_{50}$
VII	50	$N_{100}P_{100}K_{100}$
VIII	100	$N_{100}P_{100}K_{100}$
IX	150	$N_{100}P_{100}K_{100}$
Polymer van		
X	500	0
XI	1000	0
XII	1500	0
XIII	500	$N_{50}P_{50}K_{50}$
XIV	1000	$N_{50}P_{50}K_{50}$
XV	1500	$N_{50}P_{50}K_{50}$
XVI	500	$N_{100}P_{100}K_{100}$
XVII	1000	$N_{100}P_{100}K_{100}$
XVIII	1500	$N_{100}P_{100}K_{100}$
Controls		
XIX	0	0
XX	0	$N_{50}P_{50}K_{50}$
XXI	0	$N_{100}P_{100}K_{100}$

3. Results and Discussion

3.1 The Relationship Between Soil Moisture Absorption and the Varying Doses of Applied Polymers

Figure 2 illustrates two primary factors influencing soil moisture dynamics: average monthly temperatures (1, °C) and precipitation levels throughout the crop-growing season (2, mm) in the Spitak subregion. The air temperature in April was 9 °C, gradually rising and reaching its peak (21 °C) in August. Meanwhile, the precipitation levels in April began at 66 mm and steadily rose, culminating in a maximum of 108 mm in June. Subsequently, precipitation levels decreased to 84 mm in July before experiencing a sharp decline to 20 mm in August. Consequently, the total precipitation during the vegetation period amounted to 373 mm, representing an average indicator for the region.

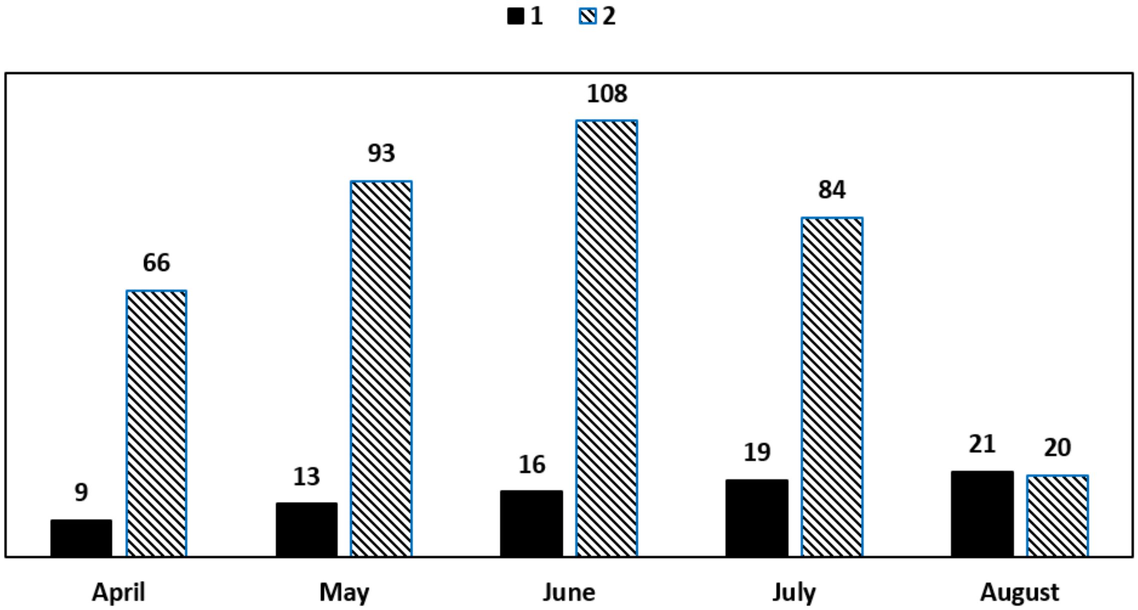

Figure 2.
Monthly mean air temperatures.

Table 4 presents the soil moisture levels at different growth stages of winter wheat. Analysis of the data reveals notable patterns.

Table 4.
Soil moisture levels (% of the soil weight).

Treatments	Tillering stage	Heading stage	Ripening stage
Polymer Aquasource			
I	29.65	22.01	20.20
II	29.43	22.58	23.01
III	27.15	20.46	20.62
IV	27.67	22.26	18.22
V	27.17	19.23	20.93
VI	30.93	17.95	22.52
VII	28.18	18.88	20.54
VIII	26.00	17.99	20.41
IX	29.79	19.23	23.64
Polymer van			
X	29.43	20.16	19.23

Treatments	Tillering stage	Heading stage	Ripening stage
XI	32.96	17.83	24.14
XII	22.15	22.77	21.93
XIII	27.90	19.29	17.84
XIV	31.85	19.33	21.12
XV	26.83	18.90	22.73
XVI	28.43	23.16	18.64
XVII	28.43	17.30	20.71
XVIII	26.37	18.22	18.03
Controls			
XIX	26.96	22.62	20.72
XX	27.76	18.19	17.75
XXI	27.22	17.34	21.64

During the tillering stage, characterized by relatively low air temperatures (ranging from 9 to 13 °C) and heavy precipitation (ranging from 63 to 93 mm), the soil exhibits high moisture content, ranging from 26.00% to 31.85%. Conversely, in June (heading stage), with an increase in air temperature (ranging from 13 to 16 °C) and heightened evapotranspiration rates, soil moisture levels decrease significantly, ranging from 17.30% to 23.16%. However, during the ripening stage, despite further increases in air temperature (ranging from 19 to 21 °C), the presence of precipitation in July (84 mm) and reduced water demand from plants lead to a slight rise in soil moisture levels, observed to increase by 2-3% compared to the heading stage, particularly in treatments utilizing polymers.

Figure 3 illustrates the influence of different polymer application dosages on relative soil moisture without the application of fertilizer at various growth stages of winter wheat. Analysis of soil moisture indicators during the tillering stage reveals that the application of 50–100 kg ha^{-1} of Aquasource results in the most significant moisture absorption, leading to soil moisture levels heightened by 9–10% compared to the control treatment. Conversely, the application of Van at doses ranging from 750 to 1000 kg ha^{-1} yields a moisture absorption of 4-5% relative to the control treatment during the same stage.

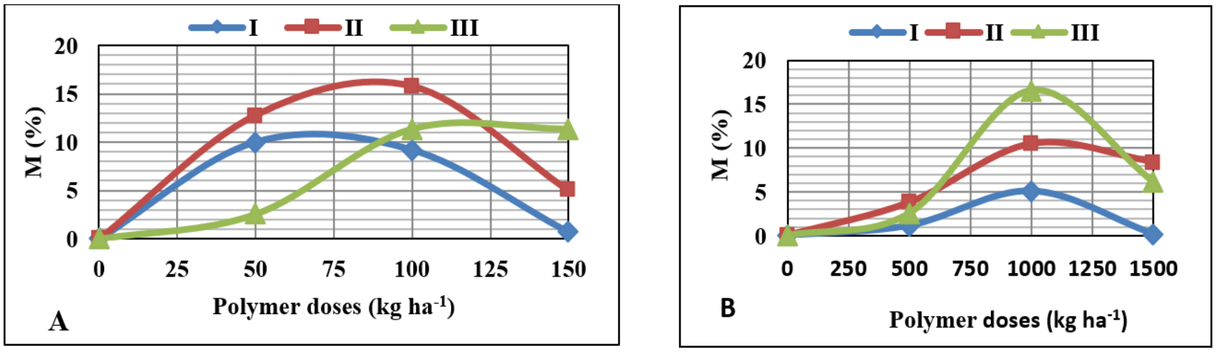

Figure 3.
Polymer dosages impact on soil moisture without fertilizers.
Note: A –using Aquasource, B –using Van, I - Tillering stage, II - Heading stage, III - Ripening stage.

Moving on to the heading stage, using 50 and 100 kg ha^{-1} of Aquasource increases the rate at which the soil absorbs water by 13 to 16 percent compared to the control treatment.

Applying the Van polymer at doses ranging from 750 to 1000 kg ha^{-1}, results in a maximum soil moisture absorption of 7.5–10.0% compared to the control treatment. During the ripening stage of winter wheat, the highest soil moisture level of 11% is attained with doses of 100–150 kg ha^{-1} of Aquasource. Conversely, when Van is applied, this indicator ranges from 10 to 16% at doses of 750–1000 kg ha^{-1}.

Notably, an increase in Van doses up to 1500 kg ha^{-1} results in a decrease in soil moisture absorption by up to 6.0%. These findings underscore the optimal polymer doses of 50–100 kg ha^{-1} and 750–1000 kg ha^{-1} for Aquasource and Van applications, respectively.

Figure 4 shows how the soil's moisture changes during different stages of winter's wheat growth when different amounts of polymer are used along with different amounts of $N_{50}P_{50}K_{50}$ fertilizer. Analysis of the provided data suggests that fertilizer application reduces soil moisture absorption. Specifically, during the tillering stage of winter wheat, applying 50 and 100 kg ha^{-1} of Aquasource leads to a slight increase in moisture absorption (1.0–2.5%) compared to the control treatment (application of $N_{50}P_{50}K_{50}$ doses without polymer application), with a notable increase of 11.5% observed only when applying 150 kg ha^{-1}. When Van was used, the highest increase in soil moisture (5%) was observed with a dose of 1000 kg ha^{-1} of polymer. The maximum increase in moisture absorption during the heading stage, relative to the control (10.0%), was noted with the application of 50 kg ha^{-1} of Aquasource. On the other hand, the application of Van led to increases in moisture absorption at doses of 1000 and 1500 kg ha^{-1}, which ranged from 6.0 to 4.0%. At the ripening stage, the greatest increases in soil moisture (16–17%) were observed with the application of Aquasource at doses of 100–150 kg ha^{-1} and with Van (19.0–20%) at doses of 1000–1500 kg ha^{-1}. Figure 5 shows soil moisture dynamics during winter wheat growth stages under different polymer doses of $N_{100}P_{100}K_{100}$ fertilizer. When Aquasource was used, the soil was able to absorb (14.0%) more water during the tillering stage of winter wheat compared to the control treatment. This was especially true at a dose of 150 kg ha^{-1}. Likewise, the application of Van demonstrated an 8.0% rise in soil moisture absorption at a dose of 1000 kg ha^{-1}.

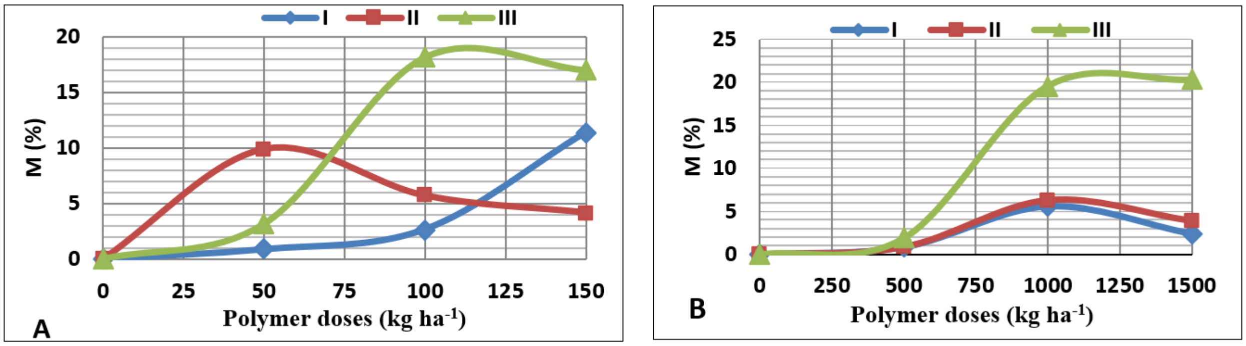

Figure 4.
Polymer dosages impact on soil moisture with $N_{50}P_{50}K_{50}$ fertilizer.
Note: A –using Aquasource, B –using Van, I - Tillering stage, II - Heading stage, III - Ripening stage.

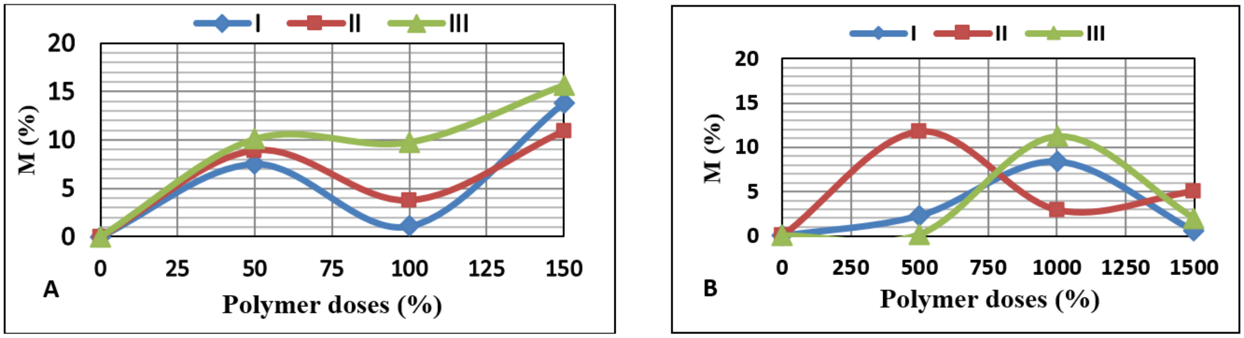

Figure 5.
Polymer dosages impact on soil moisture with $N_{100}P_{100}K_{100}$ fertilizer.
Note: A –using Aquasource, B –using Van, I - Tillering stage, II - Heading stage, III - Ripening stage.

During the heading stage, significant increases in moisture absorption of 8.5% and 11.0% were observed with Aquasource at dosages of 50 and 150 kg ha^{-1}, respectively. On the other hand, the use of Van resulted in soil moisture absorption of 12.0% at a dosage of 500 kg ha^{-1}. The ripening stage presents a different scenario, characterized by reduced water demand from plants and significant precipitation (84 mm in July). Here, the maximum increase in soil moisture absorption relative to the control treatment (16.0%) was noted with Aquasource at a dose of 150 kg ha^{-1} and with Van (11.0%) at a dose of 1000 kg ha^{-1}. Notably, when fertilizers were introduced into the soil alongside polymers, the highest soil moisture absorption was observed only with the application of elevated doses (150 and 15000 kg ha^{-1}) of Aquasource and Van. Additionally, the degree of soil moisture absorption appeared slightly higher with Aquasource.

3.2. Study of the Parameters Affecting Winter Wheat Yield Indicators with the Application of Different Doses of Polymers, Both with and Without the Use of Fertilizers

Table 5 presents the winter wheat yield indicators after applying different doses of polymers and fertilizers. The average statistical indicators of winter wheat grain yield under the rain-fed agricultural conditions of the Spitak subregion range from 18 to 20 C ha^{-1}. Analyzing the data in Table 5, it is evident that in the control versions, without the use of polymers, the grain yield does not exceed 18-20 C ha^{-1}. However, the application of Aquasource and Van polymers at doses of 500-100 and 500-1000 kg ha^{-1}, respectively, resulted in an increase in winter wheat yield compared to the control version, by 5-7 and 3-4 C ha^{-1}. It should be noted that with an increase in the mentioned polymer doses (150 and 1500 kg ha^{-1}), there was no significant contribution to increasing the grain yield; in some cases, it even decreased.

The use of polymers together with fertilizers at doses of $N_{50}P_{50}K_{50}$ showed a decrease in yield compared to the version without the use of fertilizer, but this decrease was less in comparison to the control variant, at 6 C ha^{-1} with a dose of 50 kg ha^{-1} of Aquasource, and 1-2 kg ha^{-1} at doses of 100-150 kg ha^{-1} only. When using the polymer Van, the maximum yield increase observed was 7 C ha^{-1}, at doses of 1000-1500 kg ha^{-1}.

Table 5.
Yield with varied polymer and fertilizer rates.

Polymer aquasource												
Doses (kg ha^{-1})	**Without fertilizer application**				**Together with $N_{50}P_{50}K_{50}$ doses of fertilizer**				**Together with $N_{100}P_{100}K_{100}$ doses of fertilizer**			
	1	2	3	4	1	2	3	4	1	2	3	4
0 (cont.)	20	6	26	34	18	6	32	37	20	7	32	36
50	27	9	35	38	24	10	36	42	25	9	34	39
100	25	7	38	40	20	8	35	41	27	10	36	38
150	22	7	31	39	19	7	34	40	26	8	37	37
Polymer van												
0 (cont.)	20	6	26	34	18	6	32	37	20	7	32	36
500	24	7	34	40	20	8	38	41	23	8	37	41
1000	23	7	31	38	25	8	37	38	21	10	37	42
1500	23	7	32	38	25	8	36	40	20	7	36	40

Note: 1- grain yield (C ha^{-1}), 2- stem height (cm), 3- number of grains per head (Piece), 4- weight of 1000 grains (g).

Similarly, the use of polymers together with fertilizers at a dose of $N_{100}P_{100}K_{100}$ indicated that when using Aquasource at doses of 50-150 kg ha^{-1}, the winter wheat grain yield exceeded the control version by 5-7 kg ha^{-1}, while when using Van polymer, the excess yield was only 1-3 kg ha^{-1}, at doses of 500-1000 kg ha^{-1}. Thus, the decrease in the water-absorbing capacity of polymers explains why the use of of polymers together with the fertilizers in rain-fed agricultural conditions did not lead to an additional positive effect.

It is well known that under rain-fed agricultural conditions, the main determinant of winter wheat grain yield is soil moisture. Therefore, establishing the correlational dependence between the yield of winter wheat grain and soil moisture is of significant importance.

3.2.1. Discussion of Research Results Regarding the use of Polymers Without Fertilizer Application

Figure 6 illustrates a linear correlation between soil moisture and relative grain yield of winter wheat. Analyzing the data presented in Figure 6, it is evident that there exists a strong correlation between soil moisture (W, %) and the relative yield of winter wheat grains (G, %) during the tillering and heading stages. Table 6 presents harvest indicators such as grain yield, stem height, number of grains in the head, and weight of 1000 grains, along with the values of parameters A and B of linear dependence at different stages of plant growth.

After looking at the information in the table, we can say that the correlation between soil moisture (W) and grain yield (G) in winter wheat during the tillering and heading stages is high enough, ranging from 0.71 to 0.91, with a significance level of $p < 0.05$. This indicates that the observed dependencies are reliable and statistically significant. We note an exception in the correlation between soil moisture and the weight of 1000 grains, where the correlation coefficient R is relatively low (0.34-0.61). This suggests that there is not a close relationship between these indicators. The dependency is expressed in the form of a linear regression equation:

$$G = A + BW \qquad (3)$$

$$G = 7.78W - 201.6, \qquad (4)$$

$$G = 4.75W - 78.2, \qquad (5)$$

Where the coefficients A and B are presented in Table 6.

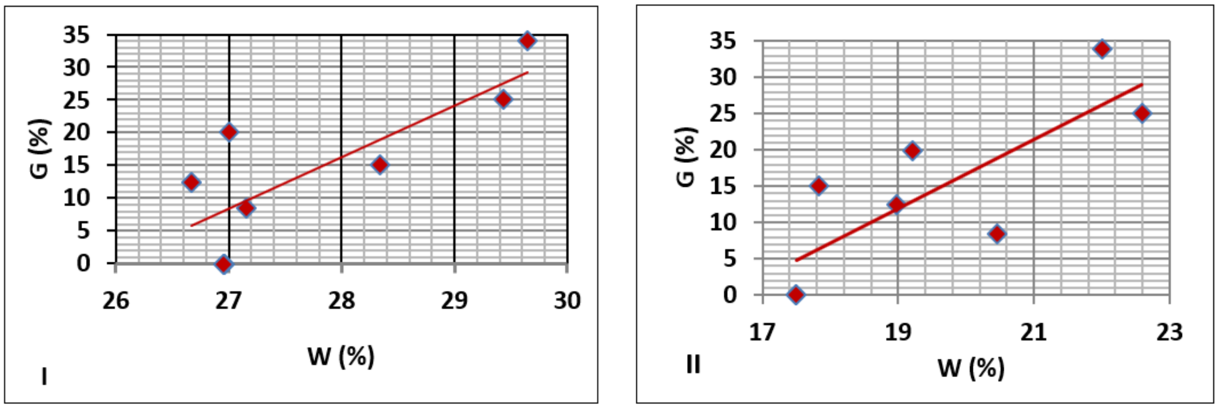

Figure 6.
Linear correlation: Soil moisture and relative yield without fertilizers.
Note: I-Tillering stage, II- Heading stage.

Placing these coefficients in the stages of tillering and heading, we obtained correlative dependencies 3 and 4 between relative grain yield and moisture. The regression equations for the moisture interval ranging from 26.0 to 28.8% for the tillering stage are accurate, with the maximal relative growth of winter wheat grain yield being 22.4%. For the heading stage, the moisture interval is 16.5-21.5%, with the maximal relative growth of grain yield being 23.9%. Observing the dependence between the relative index of winter wheat harvest and soil moisture in the ripening stage, it can be stated that there is no close dependence between G and W (R = -0.08 – 0.18).

Summarizing the given data, it can be concluded that the indicators of the winter wheat harvest are significantly affected by soil moisture in the stages of tillering and heading, while soil moisture in the ripening stage of the plants does not have a significant effect on the quantitative indicators of the harvest.

Table 6.
Statistics: Soil moisture and yield relationship.

The yield indicators	R	SD	N	P	A	B
Tillering stage						
1	0.79	7.78	8	0.019	-201.62	7.78
2	0.76	11.42	8	0.028	-272.14	10.33
3	0.71	13.26	8	0.046	-266.33	10.44
4	0.34	6.85	8	0.416	-42.02	1.88
Heading stage						
1	0.80	7.58	8	0.016	-78.24	4.75
2	0.71	12.38	8	0.048	-98.85	5.82
3	0.91	7.84	8	0.002	-132.83	8.01
4	0.61	5.79	8	0.110	-29.72	2.05
Ripening stage						
1	0.06	12.72	8	0.895	5.54	0.42
2	-0.08	17.57	8	0.842	33.15	-0.86
3	0.18	18.67	8	0.677	-17.36	1.91
4	0.13	7.22	8	0.767	-0.94	0.52

Note: 1- grain yield (C ha-1), 2 - stem height (cm), 3- number of grains in head (Piece), 4- weight of 1000 grains (g). R- Correlation coefficient, SD-Standard deviation, N-Number of selections, P- Probability, A and B- Coefficients of the regression equation (3),

3.2.2. The Discussion of Research Results Using Polymers in Conjunction with N$_{50}$P$_{50}$K$_{50}$

The relationship between soil moisture (W, %) and the relative grain yield of winter wheat (G, %) is represented through a linear correlation, as depicted in Figure 7. Upon examining the data presented in Figure 7, it becomes apparent that there is not a strong correlation between soil moisture (W, %) and relative yield (G, %) of winter wheat grains during the tillering and heading stages. Table 7 presents harvest indicators, including the values of parameters A and B of the linear dependence, observed at various stages of plant growth.

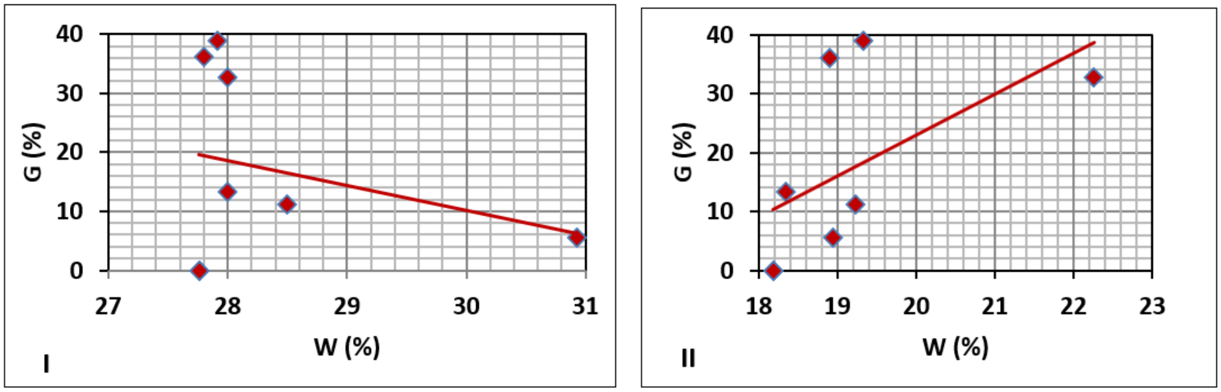

Figure 7.
Linear correlation: Soil moisture and yield with polymer and N$_{50}$P$_{50}$K$_{50}$ fertilizer.
Note: I-Tillering, II- Heading stage.

Table 7.
Statistics: Soil moisture and yield with polymer and $N_{50}P_{50}K_{50}$ fertilizer.

The yield indicators	**R**	**SD**	**N**	**P**	**A**	**B**
Tillering stage						
1	-0.27	16.91	8	0.515	133.65	-4.11
2	-0.06	21.96	8	0.882	59.22	-1.19
3	-0.11	7.33	8	0.795	28.99	-0.70
4	0.22	5.57	8	0.603	-23.6	1.08
Heading stage						
1	0.57	14.39	8	0.137	-117.66	7.04
2	0.86	11.31	8	0.006	-227.40	13.18
3	0.36	6.88	8	0.380	-26.60	1.86
4	0.63	4.43	8	0.091	-41.77	2.54
Ripening stage						
1	0.41	16.04	8	0.317	-42.32	3.00
2	0.12	21.84	8	0.775	3.18	1.11
3	0.17	7.27	8	0.687	-1.32	7.27
4	0.19	5.62	8	0.651	-2.23	0.46

Note: 1- grain yield (C ha^{-1}), 2- stem height (cm), 3- number of grains in head (pieces), 4- weight of 1000 grains (g).

By summarizing these indicators, we conclude that the use of fertilizers as an additional factor significantly influences the linear dependency. As a result, there is no linear correlation between moisture and the growth of the relative indicators of the winter wheat crop at all stages of plant growth (R = 0.11-0.63). Exceptions include the dependencies during the tillering stage, where the correlation coefficient is high (0.86).Upon discussing the data presented in Figure 8, it is evident that there is not a strong correlation between soil moisture and the relative yield of winter wheat grains in the tillering stage. However, the heading stage shows a good linear relationship. Harvest indicators, including the values of parameters A and B of linear dependence at various stages of plant growth, are provided in Table 8.

Observing the data presented in Table 8, it can be stated that there is no strong correlation between relative yield and soil moisture across all stages of plant growth (R = -0.06 – 0.67). We note an exception when we consider the correlation between soil moisture and grain yield in the heading stage (R = 0.78), and the number of grains in the head (R = 0.84) in the ripening stage. In summary, the results suggest that using fertilizers as an additional factor does not have a significant effect on the winter wheat yield indicators in rain-fed conditions.

3.2.3. Discussion of Research Results Using Polymers in Conjunction with $N_{100}P_{100}K_{100}$

The relationship between soil moisture and the relative grain yield is depicted in Figure 8.

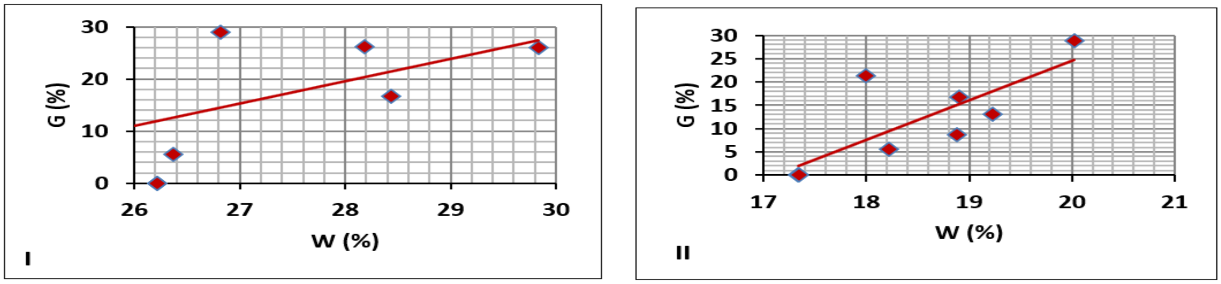

Figure 8.
Linear correlation: Soil moisture and yield with polymer and $N_{100}P_{100}K_{100}$ fertilizer.
Note: I-Tillering, II- Heading stage.

Table 8.
Statistics: Soil moisture and yield with polymer and $N_{100}P_{100}K_{100}$ fertilizer.

Yield indicators	R	SD	N	P	A	B
Tillering stage						
1	0.46	12.18	8	0.248	-98.60	4.22
2	0.46	21.33	8	0.257	-181.18	7.24
3	0.54	5.30	8	0.168	-55.68	2.25
4	0.19	6.71	8	0.659	-15.62	0.84
Heading stage						
1	0.78	6.89	8	0.022	-144.83	8.47
2	0.33	22.70	8	0.420	-123.61	7.92
3	0.38	5.81	8	0.350	-38.04	2.36
4	0.67	5.08	8	0.070	-75.72	4.49
Ripening stage						
1	0.24	10.70	8	0.567	-14.76	1.34
2	0.32	22.82	8	0.441	-54.68	3.90
3	0.84	3.39	8	0.009	-47.57	2.68
4	-0.06	6.82	8	0.886	11.55	-0.21

Note: 1- grain yield (C ha^{-1}), 2- stem height (cm), 3- number of grains in head (Pieces), 4- weight of 1000 grains (g).

4. Conclusion

- Application of polymers Aquasource and Van at doses ranging from 50-100 and 750-1000 kg ha^{-1}, respectively, without the use of fertilizers, enhances moisture absorption by approximately 11.5-12.5% and 5.5-7.5%, on average, during the tillering and heading stages of winter wheat compared to the control version.
- The use of polymers alongside $N_{50}P_{50}K_{50}$ and $N_{100}P_{100}K_{100}$ doses reduces the water absorption capacity of polymers. This capacity only increases with higher Aquasource and Van polymer doses of 100-150 and 1000-1500 kg ha^{-1}, respectively, which is economically inefficient. Consequently, in rain-fed agriculture conditions characterized by relatively low soil moisture levels, it is advisable to avoid applying high doses of fertilizers in conjunction with polymers.
- During the tillering and heading stages, when the correlation is very high ($R = 0.71-0.91$) and shows itself as a straight line, soil moisture has a big effect on the relative indicators of winter wheat yield.
- Additional absorption of 3-5% of soil moisture during the tillering and heading stages, facilitated by polymer application without fertilizers, results in a 22-24% increase in winter wheat grain yield compared to the control version.
- Fertilizer application significantly affects the linear relationship between soil moisture and yield indicators across all growth stages, leading to a very low linear dependence ($R < 0.5$).

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Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

Competing Interests:

The authors declare that they have no competing interests.

Authors' Contributions:

Supervision, Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, S.S.; funding acquisition, project administration, conceptualization, G.A.; writing - reviewing and editing, validation, visualization, T.Y.; investigation; data curation, S.D.; formal analysis, investigation, A.E. All authors have read and agreed to the published version of the manuscript.

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