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Rainfed Wheat Productivity: Assessing the Efficacy of Hydrogel Intervention for Improved Soil Moisture Conservation

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Abstract

Soil moisture scarcity is a major constraint to achieving potential soil productivity in arid and semi-arid regions. Hydrogel application has shown promise in addressing this issue, but its benefits for crop improvement and soil moisture retention require further exploration. This study evaluated the impact of hydrogel on soil moisture retention, soil characteristics, and wheat yield in a rainfed agricultural system in Jand, Attock. A randomized complete block design (RCBD) experiment with four replications was conducted from 2018 to 2021, comprising three treatments: control (no hydrogel), hydrogel application via seed drill, and hydrogel application via broadcast. Results revealed significant enhancements in relative soil moisture contents (up to 33.25%) and wheat yield (3960 kg ha^{-1}) with hydrogel application. Increase in nutrient availability (2.57 to 3.43 mg kg^{-1} of P_2O_5, 51.26 to 76 K_2O) and soil organic matter contents (0.62 to 0.77) were also observed. This study demonstrated the potential of hydrogel as a strategy to improve crop productivity in rainfed regions.

***Keywords*: Soil amendment; Water holding capacity; Rainfed area; Water use efficiency**

1. Introduction

Wheat is the staple crop and backbone of food security and faces significant challenges in rainfed areas of Pakistan, including uncertain rainfall patterns and dry spells. Climate change predictions suggest reduced winter rainfall in Pakistan, potentially delaying wheat sowing (Hussain et al., 2021). However, this reliance clashes with the inherent water scarcity of arid and semi-arid regions facing irregular rainfall and dwindling water resources. This makes understanding and mitigating water stress in wheat absolutely crucial. The confluence of rapid population growth and diminishing water resources, particularly in regions dominated by coarse-textured soils, presents a significant threat to food security and environmental sustainability (Abrisham et al., 2018; El- Asmar et al., 2017). Coarse-textured soils, primarily sandy soils, have large particle sizes and a coarse structure. This allows water to drain quickly, leading to low water and nutrient holding capacity. Crops in these soils are highly susceptible to drought as they struggle to retain sufficient moisture. To compensate for poor retention, more frequent and often larger volumes of water are required for growing crops like wheat, gram, and pulses. This puts immense pressure on dwindling water resources, especially in arid and semi-arid regions. Soil in arid and semi-arid regions faces low organic matter and often low clay content, which severely limits their ability to hold water and nutrients. Coupled with minimal annual rainfall, results in very low available water for plants, making agriculture a significant challenge in these areas (Xu et al., 2018; Yu et al., 2011, 2012).

In rainfed regions, water scarcity poses a significant threat to crop production, with soil moisture being a critical limiting factor in addition to the benefit of increasing available water. The success of crops in these areas relies on rainfall, and soil moisture stress can lead to drought stress. The chemical hydrogels cross-linked polymers as a potentially innovative solution, especially for areas grappling with water scarcity and challenging soil conditions like those found in the Potwar region (Ali et al., 2024). The soil chemical, physical, and biological properties improved in semi-arid and arid regions and serve as a potential chemical to lessen drought impact on crops (Abd El-Aziz et al., 2022). Under the long, irregular dry spells and scant rainfall areas, especially in semi-arid and arid areas where evapotranspiration rates are high, hydrogels improved soil physico-chemical properties (Guo et al., 2020). Despite management efforts, including the use of conventional soil amendments, a truly sustainable solution for mitigating moisture stress and fertility depletion in these challenging soils remains hard to find. This technique of application of superabsorbent in agriculture preserves moisture content and improves soil bio-chemical health, which reduces stresses in plants and ultimately enhances crop yield. Moreover, by promoting water resources management and mitigating soil moisture stresses, hydrogel use is committed to sustainable agriculture (Changela et al., 2022).

The use of polymers as soil conditioners has shown promise in conserving soil moisture (Krasnopeeva et al., 2021). However, the most effective solution for crop survival is to implement appropriate water conservation techniques that prolong the retention of rainwater, while various soil amendments have been proposed for soil moisture conservation and soil productivity, but their acceptance in the farmer's field failed due to high costs and short-term benefits. The field capacity of soil was altered by the use of hydrogels, which stimulated plant growth due to enhanced soil moisture content. The improved dissolved nutrients in soil and water contents due to hydrogels prolonged water retention in the rhizosphere, which is crucial for seed germination and root development. Keeping in view the above facts, the study was designed to investigate the potential of hydrogels as a soil conditioner for soil moisture conservation in arid areas of Pakistan to increase the productivity of wheat.

2. Materials and Methods

2.1 Experiment conditions and setup

The research experiment was conducted at the farmer field at Pindsultani (Jand) district, Attock (2018-2021), to assess the efficacy of hydrogel intervention for soil moisture conservation and enhanced wheat yield in a rainfed agricultural system. The experiment consists of different application methods of hydrogels, i.e., (i) hydrogel application (seed drill), hydrogel application (broadcast), and control (no hydrogel) treatment. The experiment was laid out in an RCBD arrangement with three replications. Net plot size measured 4m × 5m, and uniform rates of hydrogel @10 kg/ha were applied in treated plots at the start of the experiment, once during the whole study period. The recommended dose of chemical fertilizers (NPK @ 120, 80, 60 kg ha^{-1}) was applied before sowing every year. The fertilizers were applied in the form of SOP, DAP, and Urea, respectively. The approved wheat variety Ujala-2016 was sown every year in the 2nd week of November. All the cultural practices were performed uniformly throughout the growing period of wheat. The study area receives rainfall of 350-500 mm (Fig. 1). The climate is semiarid, warm, subtropical winter/monsoon. The runoff and soil erosion are vigorous in the Potwar region (Ahmad et al., 2006).

2.2 Data collection

Soil classifications are shown in Table 1 (Hillel, 1987). Before the start of the experiment, soil samples were collected and dried by a 2mm sieve. Soil properties examined before sowing and after harvesting of the crop are given in Table 2-4. The pH and EC_e of soil were determined by McLean (1982) and Richards (1954), SOM was determined by Walkley (1947), K_2O by Rhoades (1982), P_2O_5 by Watanabe and Olsen (1965), and soil particle size by Gee and Bauder (1986). The plots were harvested at maturity in every cropping season, and data were collected from a one square meter area to record grain and biomass yield. The treatments were statistically analyzed using Statistix 8.1 software for ANOVA and LSD calculation. Rainfall (mm) was recorded at the experimental site shown in Figure 1.

Table 1: Steady-state infiltration rates*

Soil Type	Steady-state infiltration rate
Sand	>0.80
Sandy and Silty soils	0.40-0.80
Loam	0.20-0.40
Clayey Soils	0.04-0.20
Sodic Clayey Soils	<0.04

*Hillel (1987), USDA-NRC soil classifications.

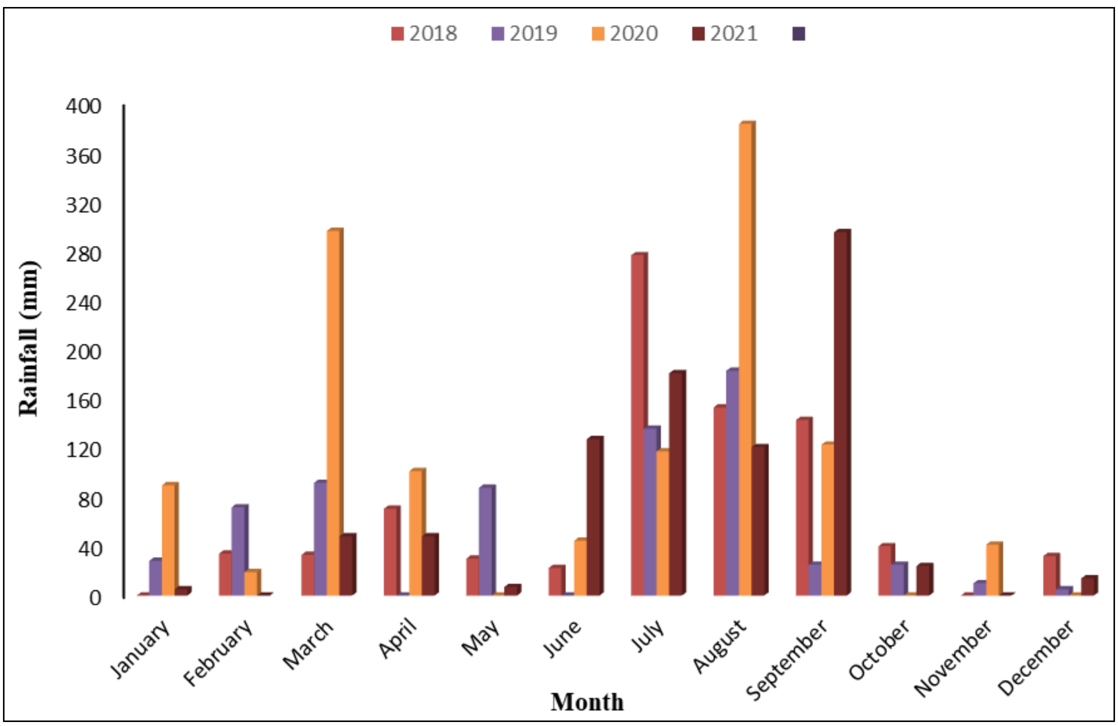

Fig. 1. Rainfall (mm) at experimental site (2018-2021).

3. Results and Discussion

3.1 Soil Moisture Contents

The data revealed a significant ($p < 0.05$) increase in soil moisture contents at wheat harvest each year in hydrogel treatments compared to the control. Notably, seed application of hydrogel outperformed broadcast application during each year, except 2021. The results of the study indicated that hydrogel application increased relative soil moisture contents by up to 29.65% in seed drill vs control, 7.98% in seed drill vs broadcast and 20.06% in broadcast vs control during the year 2018-19; 6.31% soil moisture contents in seed drill vs Broadcast; 33.25 % in seed drill vs control and 25.33% in broadcast vs control during 2019-18 and 6.07% soil moisture contents in seed drill vs broadcast, 28.98% in seed drill vs control and 21.59% in broadcast vs control during 2020-21 (Fig. 2). The results indicated that soil moisture contents decreased overtime in next two consecutive years because of degradation ability of hydrogels. As shown in Figure 2, the improved soil moisture contents following hydrogel application can be attributed to the diffusion of water molecules into the hydrogel network through pores and channels in the polymer matrix. Hydrogels absorb large amounts of water, generally 400 times their weight (Kaur et al., 2022). The water molecules enter the hydrogel network, and the polymer chains swell due to osmotic pressure, causing the network to expand and create more space for water molecules to enter. This mechanism enables hydrogels to retain water in the soil, reducing the need for irrigation. The hydrogels have the capacity to decrease the frequency of irrigation, enhance soil quality, and lessen the leaching of fertilizer (Palanivelu et al., 2022). The data indicated that the application of hydrogel improved soil moisture contents, which decreased the frequency of irrigation and delayed wilting of plants under high evapotranspiration.

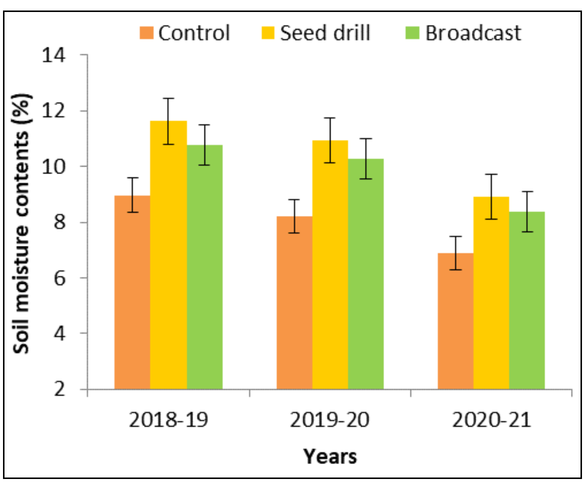

Fig. 2. Effect of hydrogels on soil moisture contents (%) during 2018-19 to 2020-21.

Numerous studies have investigated the effects of hydrogel application in agricultural systems on plant growth, soil moisture contents, nutrient availability, and herbicide efficacy. The results also indicated that hydrogel performance decreased over time, with the highest moisture contents recorded in 2019 and the lowest in 2021. The results of the study, supported by Abd El-Naby et al. (2024), stated that the potential benefits of hydrogel technology for sustainable agricultural practices include improving soil moisture content.

3.2 Soil fertility attributes

3.2.1 Soil pH

The application of hydrogels can have a modest impact on soil pH. According to Patel et al. (2023), hydrogel application had no significant effect on soil pH. However, other studies have reported slight decreases in soil pH, ranging from 0.08 to 0.18 units, following hydrogel application. These decreases are relatively small and may not have substantial agronomic implications. The results of the study, presented in Table 2, showed that hydrogel application methods resulted in slight variations in soil pH. Specifically, a dropping effect was observed in hydrogel-treated soil compared to the control. Over the three-year study period, the pH of the control soil was 7.78, while the hydrogel-treated soil (via seed drill application) showed a decrease to 7.68 by the third year (Table 2-4).

These results are consistent with Mahgoub's (2020) study, which investigated the impact of hydrogel application on the tomato crop in sandy soil using drip irrigation. The study found that adding hydrogel at rates of 2 g and 4 g per plant resulted in a decrease in soil pH by 0.08 to 0.18 units, likely due to the dissociation of H^+ ions from the hydrogel, increasing soil acidity. The lowest pH was recorded in T1 (7.23), while the control had the highest pH (7.53). Notably, despite these decreases, the soil pH levels may be due to high Cation Exchange Capacity (CEC), meaning they can attract and hold positively charged ions from the soil solution, i.e., calcium, magnesium, and potassium. In doing so, they may release H^+ ions that were initially part of their structure or that they have absorbed and degraded in soil, releasing organic acids. This exchange of basic cations for H^+ ions can contribute to a decrease in soil pH, which favours crop cultivation.

3.2.2 Soil EC

Hydrogel application can impact soil electrical conductivity (EC), although the effects vary depending on hydrogel type, concentration, and soil conditions. Patel (2023) observed a reduction in soil EC following hydrogel incorporation, highlighting the complexity of this relationship. The variability in findings suggests that hydrogel composition, application rate, soil type, and environmental conditions all influence the impact of hydrogel on soil EC. In this study, the initial EC of the sandy soil was 0.90 dS m^{-1} (Table 2). However, after one month of hydrogel application, EC decreased, potentially due to plant nutrient uptake. The EC values ranged from 0.98 to 0.88 (dS m^{-1}) (Table 2). The data presented in this study revealed a gradual decrease in electrical conductivity of the extract (EC) with hydrogel application, primarily because their ability to absorb and retain large amounts of water resulted in a lower concentration of soil solution. The highest EC value (0.91dSm^{-1}) was recorded in the control treatment during the first year, while the lowest EC value (0.77 dSm^{-1}) was observed in the treatment with hydrogel application by broadcast method during the second year. These findings are in accordance with (Pawar et al., 2018), who reported a decrease in EC with increasing organic matter in soil.

3.3 Soil Organic Matter

The application of hydrogel resulted in an increase in soil organic matter compared to the control. Specifically, the maximum organic matter content (0.75) was observed in T2 (seed drill application) during the second year of study, while the lowest organic matter content (0.62) was recorded in the control treatment (Table 2-4). A gradual increase in organic matter was noted with hydrogel application, likely due to enhanced soil moisture retention, creating a more favorable environment for plant growth and microbial activity. Hydrogel application has been shown to enhance soil organic matter content by improving water retention, plant nutrition, and soil protection, as well as stimulating microbial activity (Wei et al., 2023). These benefits can accumulate over time, contributing to improved soil health. Similar findings have been reported by Mellelo (2019), highlighting the positive impact of hydrogel application on soil organic matter.

3.4 Available P_2O_5

Hydrogel application can enhance phosphorus (P) availability in soil by improving water retention around the root zone, which increases P solubility and diffusion, particularly in dry soils where P mobility is limited. Hydrogels create moist environments that promote microbial activity, including phosphate-solubilizing bacteria (PSB). The results indicated that hydrogel application methods increased available phosphorus in the soil compared to the control. The data showed that the maximum available phosphorus (3.60 mg kg^{-1}) was recorded in the third year of the experiment in T3 (Table 4), where hydrogel was applied via broadcast method. In contrast, the lowest available phosphorus (2.57 mg kg^{-1}) was recorded in the control during the first year (Table 2). These results are consistent with previous research, such as Mahgoub (2020), which demonstrated that hydrogel application positively influences soil P dynamics. In this study, adding hydrogel to sandy soil increased available phosphorus content from 2.45 mg kg^{-1} to 3.60 mg kg^{-1} when combined with half the recommended fertilizer amount.

3.5 Extractable K_2O

The application of hydrogel significantly increased extractable potassium in the soil. The results of the study showed that the maximum extractable potassium (85 mg kg^{-1}) was recorded in the broadcast hydrogel application treatment during the first year of study (Table 2), while the minimum value (57.00 mg kg^{-1}) was observed in the control treatment during the same year (Table 2). Improved potassium availability in soil can enhance crop quality and yield. Hydrogels, as superabsorbent polymers, can retain water and nutrients in the soil, influencing the availability and mobility of nutrients like potassium (K). By minimizing K fixation in clay-rich soils, hydrogels can optimize potassium utilization (Saha et al., 2020). Similar findings have been reported by Huang (2023), highlighting the potential of superabsorbent hydrogels (SAHs) as a soil improvement under drought conditions and soil health improvement.

3.6 Grain yield

The influence of hydrogel application on the grain yield of wheat is illustrated in Figure 3. The results of the study indicated that hydrogel-treated plots significantly enhanced wheat grain yield compared to the control. Among the hydrogel application methods, the seed drill method (T2) yielded the highest mean grain yield (3960 kg ha^{-1}), while the control treatment (T1) had the lowest mean grain yield (2375 kg ha^{-1}).

Table 2: Physicochemical characteristics before sowing and after harvesting of crop during the experimental duration (2018-19).

Before sowing										
Treatments	0-6 cm					6-12 cm				
	pH-	EC (dS m^{-1})	P_2O_5 (mg Kg^{-1})	K_2O (mg Kg^{-1})	O.M %	pH-	EC (dS m^{-1})	P_2O_5 (mg kg^{-1})	K_2O (mg Kg^{-1})	O.M %
Control	7.79	0.98	2.45	51.26	0.62	7.72	0.97	2.92	59.26	0.62
Hydrogel (Seed drill)	7.77	0.93	2.59	62.98	0.65	7.76	0.96	3.10	73.44	0.71
Hydrogel (Broadcast)	7.76	0.95	2.51	67.49	0.69	7.91	0.93	3.23	74.19	0.68
After harvesting										
Treatments	pH-	EC (dS m^{-1})	P_2O_5 (mg Kg^{-1})	K_2O (mg Kg^{-1})	O.M %	pH-	EC (dS m^{-1})	P_2O_5 (mg Kg^{-1})	K_2O (mg Kg^{-1})	O.M
Control	7.78	0.91	2.57	57.00	0.66	7.69	0.92	2.87	63.67	0.69
Hydrogel (Seed drill)	7.7	0.89	3.10	72.33	0.71	7.75	0.95	3.30	82.00	0.73
Hydrogel (Broadcast)	7.76	0.88	3.27	76.67	0.70	7.81	0.92	3.43	85.00	0.72

Table 3: Physicochemical characteristics before sowing and after harvesting of crop during the experimental duration (2019-20)

Before sowing										
Treatments	**0-6 cm**					**6-12 cm**				
	pH-	EC (dS m^{-1})	P_2O_5 (mg Kg^{-1})	K_2O (mg Kg^{-1})	O.M %	pH-	EC (dS m^{-1})	P_2O_5 (mg Kg^{-1})	K_2O (mg Kg^{-1})	O.M %
Control	7.78	0.91	2.57	57.00	0.66	7.69	0.92	2.87	63.67	0.69
Hydrogel (Seed drill)	7.70	0.89	3.10	72.33	0.71	7.75	0.95	3.30	82.00	0.73
Hydrogel (Broadcast)	7.76	0.88	3.27	76.67	0.70	7.81	0.92	3.43	85.00	0.72
After harvesting										
Treatments	**0-6 cm**					**6-12 cm**				
	pH-	EC (dS m^{-1})	P_2O_5 (mg Kg^{-1})	K_2O (mgKg^{-1})	O.M %	pH-	EC (dS m^{-1})	P_2O_5 (mg kg^{-1})	K_2O (mg Kg^{-1})	O.M %
Control	7.77	0.90	2.70	53.33	0.64	7.69	0.54	2.70	66.67	0.66
Hydrogel (Seed drill)	7.75	0.84	3.03	70.00	0.77	7.78	0.41	3.23	73.33	0.79
Hydrogel (Broadcast)	7.75	0.77	3.23	63.33	0.68	7.81	0.43	3.43	75.00	0.70

Table 4: Physicochemical characteristics before sowing and after harvesting of crop during the experimental duration (2020-21).

Before sowing										
Treatments	**0-6 cm**					**6-12 cm**				
	pH-	EC (dS m^{-})	P_2O_5 (mg Kg^{-1})	K_2O (mg Kg^{-1})	O.M %	pH-	EC (dS m^{-})	P_2O_5 (mg Kg^{-1})	K_2O (mg Kg^{-1})	O.M %
Control	7.77	0.9	2.70	53.33	0.64	7.69	0.54	2.7	66.67	0.66
Hydrogel (Seed drill)	7.75	0.84	3.03	70.00	0.77	7.78	0.41	3.23	73.33	0.79
Hydrogel (Broadcast)	7.75	0.77	3.23	63.33	0.68	7.81	0.43	3.43	75.00	0.70
After harvesting										
Treatments	**0-6 cm**					**6-12 cm**				
	pH-	EC (dS m^{-})	P_2O_5 (mg Kg^{-1})	K_2O (mg Kg^{-1})	O.M %	pH-	EC (dS m^{-})	P_2O_5 (mg Kg^{-1})	K_2O (mg Kg^{-1})	O.M %
Control	7.74	0.89	2.77	56.67	0.68	7.66	0.67	2.97	63.33	0.68
Hydrogel (Seed drill)	7.68	0.82	3.17	60.00	0.70	7.77	0.85	3.37	70.00	0.74
Hydrogel (Broadcast)	7.69	0.80	3.60	65.00	0.74	7.72	0.9	3.60	75.00	0.75

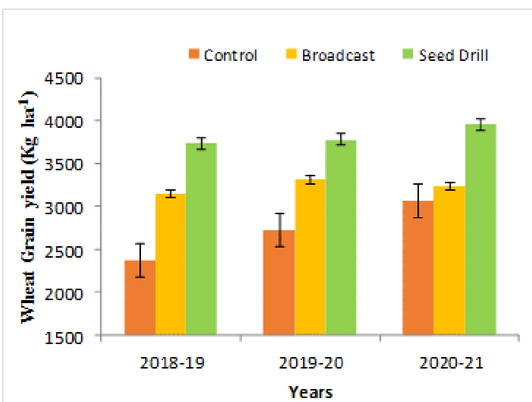

Fig. 3. Effect of hydrogel application on wheat grain yield (2018-19 to 2020-21).

The application of hydrogel via the seed drill method resulted in a 57.34%, 38.34%, and 29.04% rise in wheat grain yield compared to the control (Fig. 3). Broadcast application of hydrogel also showed significant increases, with 32.63%, 21.24%, and 16.86% higher yields than the control (Fig. 3).

The results consistently correlated with previous work, such as Shweta (2022), which indicated that hydrogel application can enhance wheat yield and water productivity. Similarly, Kumar et al. (2022) reported that hydrogel application increased wheat yields and net returns while contributing to water conservation in sandy soils under limited irrigation conditions. The improved wheat grain yield with hydrogel application may be attributed to better consistent moisture supply, especially at critical growth stages like booting, tillering, and heading, to maintain its metabolic processes, where moisture supply can severely impact yield. These factors collectively contribute to reduced water stress, enhanced nutrient uptake, improved soil structure, and increased water use efficiency, resulting in higher yields.

3.7 Straw yield

The impact of hydrogel application on wheat straw yield is illustrated in Figure 4. The results of the study showed that hydrogel application significantly enhanced wheat straw yield compared to the control. Among the hydrogel application methods, the seed drill method (T_2) yielded the highest mean straw yield (4162 kg ha^{-1}), while the control treatment (T_1) had the lowest mean straw yield (2430 kg $ha^{-1)}$. The application of hydrogel via seed drill method resulted in a 33.31%, 44.85%, and 35.34% increase in wheat straw yield compared to the control (Fig. 4). Broadcast application of hydrogel also showed significant increases, with 16.20%, 24.32%, and 13.49% higher yields than the control

(Fig. 4). The seed drill method of hydrogel application remained significantly superior to other methods and the control. The increase in wheat straw production may be attributed to improved water retention and nutrient availability in the soil, leading to higher biomass production, increased tiller formation, and enhanced photosynthetic activity. These findings are consistent with Kumar et al. (2024), who reported that hydrogel application influenced the productivity of rainfed maize and wheat. Their study supports the notion that hydrogel application can have a positive impact on crop yields.

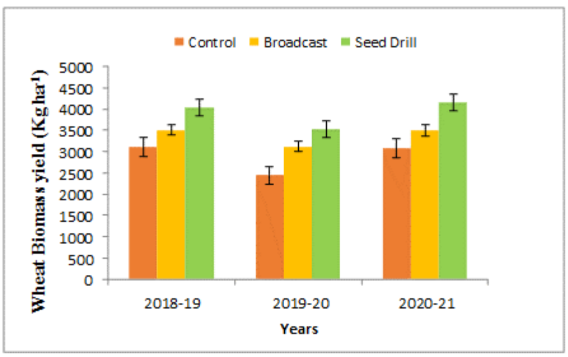

Fig. 4. Effect of hydrogel application on wheat biomass yield (2018-19 to 2020-21).

4. Conclusion

In conclusion, concerning the soil moisture conservation for dry periods to supplement a sufficient supply of moisture for consistent growth and enhanced crop yield, hydrogels performance is considered a need for arid areas. Hydrogels are water-absorbing polymers that are linked with aqueous solutions through bonding with water molecules. In agriculture, hydrogels are used for absorbing water up to 400 times their weight, which increases the water potential of soil and is released slowly in soil under low water potential conditions. The relative increase in moisture content in hydrogel applied soils results in a decrease of soil pH, EC, and an increase in nutrients like phosphorus, potassium, and organic matter due to sufficient supply of moisture to seedlings for survival of the wheat crop over a prolonged period. Therefore, in view of the above facts investigated in the study, hydrogels might have a revolutionary influence for enhancing wheat yield in arid regions of Punjab, Pakistan.

Author's Contribution

This work was carried out in collaboration between all authors. Authors Rahina Kausar, Obaid-ur-Rehman designed the study. Authors M. Imran Akram, Ayesha Malik performed the statistical analysis, Saftain Ullah Khan, Asia Munir, and M. Usman Mohsin wrote the protocol, and wrote the first draft of the manuscript. Authors Sarosh Alvi, Kouser Majeed Malik, and Natasha Kanwal managed the analyses of the study. Authors Muhammad Rashid, Sabir Hussain, and Rashid Minhas reviewed the manuscript and managed the literature searches. All authors read and approved the final manuscript.

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Conflict of Interest

The authors declare that they have no conflicts of interest.

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