EFFECTS OF POLY-Γ-GLUTAMIC ACID SUPER ABSORBENT POLYMER ON SOIL MICROENVIRONMENT AND GROWTH OF WINTER WHEAT

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Abstract. Poly-γ-glutamic acid super absorbent polymer (γ-PGA SAP) is a novel type of SAP synthesized by γ-PGA. To study the effect of γ-PGA SAP on the growth of winter wheat and the microenvironment of the soil root zone, five levels of γ-PGA SAP addition (0, 40 kg/hm^2, 80 kg/hm^2, 120 kg/hm^2, 160 kg/hm^2) and three different irrigation levels (270 mm, 229.5 mm, and 189 mm) were set in the field. The average soil water content of each treatment increased gradually with increasing γ-PGA SAP addition. The number of soil microorganisms and the activities of soil enzymes increased with increasing γ-PGA SAP addition. The wheat yields without γ-PGA SAP addition were 5873.08 kg/hm^2 (270 mm), 5081.65 kg/hm^2 (229.5 mm) and 4181.41 kg/hm^2 (189 mm) in three different irrigation levels, respectively. Wheat yield increased with increasing γ-PGA SAP addition. The yield of winter wheat increased by 9.00% (270 mm), 17.94% (229.5 mm) and 26.31% (189 mm) respectively compared with the control group when the γ-PGA SAP addition was 160kg/hm^2. However, the increasing rate of wheat yield decreased when the γ-PGA SAP addition was more than 80 kg/hm^2.
Keywords: *γ-PGA, water retention agent, field crop, root zone environment, water use efficiency*

Introduction

Poly-γ-glutamic acid (γ-PGA) is a kind of polypeptide polymer found in Natto, which a traditional Japanese food (Shih and Van, 2001). It differs from proteins formed by α-amino and γ-carboxyl groups between D-glutamic acid and L-glutamic monomers (Kang et al., 2005). The relative molecular weight of γ-PGA ranges from 700 kD to 2000 kD. It has a straight chain structure and can be degraded into short peptide γ-PGA and glutamic acid monomers, which are environmentally friendly (Xu et al., 2013). There are a large number of active free carboxyl groups on the side chain of its molecular structure, making it easy to modify (Lin et al., 2006). In recent years, with a decrease in production costs, the use of γ-PGA in agriculture has increased. Its excellent biodegradability and renewable characteristics have also attracted much attention in the synthesis of super absorbent polymers (SAPs) using γ-PGA (Abrisham et al., 2018). The γ-PGA SAP inherit the good biodegradability of γ-PGA and contains a large number of free carboxyl groups

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in its molecular structure, which is also the basis for its ability to absorb a large amount of water (Tarui et al., 2005). Being a glutamic acid monomer, γ-PGA can be decomposed into soil nitrogen fertilizer, used as fertilizer synergist (Ma et al., 2022). It can also be used as sanitary products, and then it can be transformed into fertilizer that can be used by crops through a series of fertilizer conversion treatments (Xiong et al., 2005).

Poly-γ-glutamic acid super absorbent polymer (γ-PGA SAP) is a new type of super absorbent polymer synthesized by γ-PGA and a cross-linking agent (Ma and Wen, 2020). It contains a large number of hydrophilic groups and has a unique three-dimensional network space structure, which can absorb even thousands of times of its own water, and it will not overflow water under high pressure or temperature conditions (Wang et al., 2002). It is widely used in the processing and preservation of medical and sanitary products, additives for civil engineering materials, and water conservation in agriculture and forestry (Omidian et al., 2005). According to the different sources of raw materials for preparing SAP, SAP is mainly divided into three categories: synthetic, starch, and cellulose (Zohuriaan-Mehr and Kabiri, 2008). In the degradable super absorbent polymer on the market, starch-based SAPs, cellulose-based SAPs, and protein-based SAPs have certain degradability, and the degradation of the structure of acrylate SAP synthesized by monomers such as acrylic acid copolymerized with macromolecules is poor (Xie et al., 2019). With the improvement of people's awareness of environmental protection, the development and application of polymer materials that can be degraded by the environment have been gradually attracted the attention of researchers (Zohuriaan-Mehr et al., 2010). Only SAP synthesized by γ-PGA and poly-aspartic acid can be completely degraded (Tolmachev et al., 2020). At present, only γ-PGA can be synthesized by microbial fermentation, making full use of renewable resources, such as soybean dregs, feces and so on. At present, poly-aspartic acid is mainly synthesized by chemical polymerization. However, the molecular weight of poly-aspartic acid synthesized by peptide polymerization is lower than that of γ-PGA, and its water absorption rate and reuse performance are also lower than that of γ-PGA SAP (Huang and Kong, 2013).

After absorbing water, SAP can preserve soil water in the hydrogel network structure formed by itself, forming a micro reservoir with water regulation function in the soil (Bai et al., 2010). Li found that γ-PGA SAP could effectively inhibit soil moisture evaporation, maintain soil water, and increase soil water holding capacity (Li et al., 2005). Similarly, Zhang applied the synthesized γ-PGA SAP to the soil and found that its water absorption rate of soil water was 30-40 times, which had obvious effects of drought resistance and seedling promotion and could significantly improve the germination rate of crops (Ma et al., 2022). γ-PGA SAP, similar to other types of SAPs on the market, could improves soil water holding capacity. However, there are few studies on the new types of γ-PGA SAP in crops, and the application of acrylic SAP is more studied (Song et al., 2017). In the range of 50%-80% field water capacity, seedling mixing with SAP could increase the emergence rate of wheat seeds, significantly increase the number of productive tiller of wheat, and ultimately increase the yield of wheat by 4.49%-6.09%, indicating that SAP

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can play a role in water-saving irrigation and yield increase (Moghadam et al., 2011). Song showed that the application of SAP significantly increased the ammonium nitrogen content at jointing stage and harvest stage, significantly decreased the nitrate nitrogen content in deep soil at harvest stage and improved the partial productivity of nitrogen fertilizer (Song et al., 2019). Dhiman Jaskaran applied 15 kg/hm^2 of SAP in potato fields, which increased potato yield by 16%, and increased the utilization efficiency of phosphorus fertilizer and urea by 27.06% and 18.72%, respectively (Dhiman et al., 2021). The study also found that the application of SAP in the soil can increase nitrogen fertilizer productivity.

At present, the research on γ-PGA SAP is limited to the theoretical level of soil water retention and infiltration (Guo et al., 2021), and the application effect of γ-PGA SAP in crop planting is unknown. Therefore, in order to have a comprehensive understanding of the application of γ-PGA SAP in agricultural production, this paper discuss the effects of γ-PGA SAP on the yield of winter wheat and soil properties under different water conditions.

Material and methods

Experiment design and measurement index

The experiment was carried out at the Xiwenzhuang Township Irrigation Experiment Station, Taiyuan City, Shanxi Province from October 15, 2021, to June 20, 2022. The precipitation during this period is shown in *Fig. 1*. The experiment area belongs to warm temperate continental climate, with an average annual rainfall of 430 mm. The annual average evaporation in this area is 1812 mm, and the annual average temperature and annual average sunshine hours are 9.5 °C and 2676 mm respectively. The soil type is clay loam. The basic values of soil nutrients are shown in *Table 1*.

Experiment design

The area of the experiment is 2 m×3 m. There was no need for irrigation before sowing due to the soil water content is suitable for wheat growth, and it only need to plough the soil and apply base fertilizer. The amount of irrigation and fertilization during the experiment was carried out according to the local irrigation and fertilization system. Wheat was seeded on October 15 by row seeding (furrow seeding). The row spacing was 0.2 m, each row was 3 m, the sowing depth was 3 cm, and the sowing rate was 225 kg/hm^2. The wheat variety was Jinmai 1001. The 1000-grain weight of the wheat variety used is 36.27 g.

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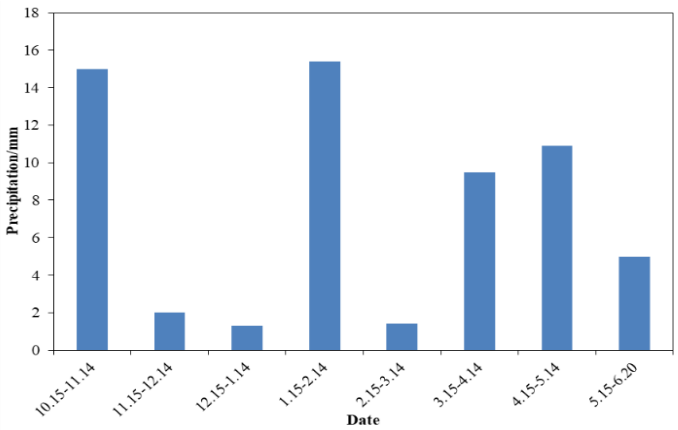

Figure 1. *Precipitation amount*

Table 1. *Soil basic nutrients*

Indicators	Total N (g/kg)	Total P (g/kg)	Organic matter (g/kg)
Value	0.54	0.73	29.93

The wheat experiment was set up 15 treatments (5 level of γ-PGA SAP and 3 level of irrigation) with each repeated three times. The experiment treatments are shown in *Table 2*.

Table 2. *The desigh of experiment*

Serial number	Treatment	Additive agent	Addition amount	Irrigation (mm)
1	CKW270	no	0	270
2	PS40W270	γ-PGA SAP	40 kg/hm^2	270
3	PS80W270	γ-PGA SAP	80 kg/hm^2	270
4	PS120W270	γ-PGA SAP	120 kg/hm^2	270
5	PS160W270	γ-PGA SAP	160 kg/hm^2	270
6	CKW229.5	no	0	229.5
7	PS40W229.5	γ-PGA SAP	40 kg/hm^2	229.5
8	PS80W229.5	γ-PGA SAP	80 kg/hm^2	229.5
9	PS120W229.5	γ-PGA SAP	120 kg/hm^2	229.5
10	PS160W229.5	γ-PGA SAP	160 kg/hm^2	229.5
11	CKW189	no	0	189
12	PS40W189	γ-PGA SAP	40 kg/hm^2	189
13	PS80W189	γ-PGA SAP	80 kg/hm^2	189
14	PS120W189	γ-PGA SAP	120 kg/hm^2	189
15	PS160W189	γ-PGA SAP	160 kg/hm^2	189

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The type of SAP used in this experiment is the γ-PGA SAP prepared by our laboratory, and the preparation method of SAP is shown in the paper (Guo et al., 2022). The γ-PGA SAP was mixed with seeds and fine sand (1:3 γ-PGA SAP: fine sand) for strip sowing. The three irrigations in this experiment were 270 mm (100% of the local conventional irrigation), 229.5 mm (85% of the local conventional irrigation) and 189 mm (70% of the local conventional irrigation). The irrigation was carried out on April 5, April 25 and May 15, and the amount of irrigation was 90 mm, 76.5 mm and 63 mm, respectively (Shen et al., 2020). In the experiment, 750 kg/hm^2 compound fertilizer (N, P, K≥15%) was directly applied as the base fertilizer, and 225 kg/hm^2 urea was applied during the jointing stage, which was equivalent to the recommended amount of local field.

Collection of soil samples and determination of indexes

The standard growth period of wheat was observed when more than 50% of wheat reached the standards of seedling stage, regeneration stage, heading stage, filling stage and maturity stage (*Table 3*) (Miller et al., 2003).

Table 3. *Division of growth stages (BBCH) of winter wheat in this experiment*

Stage	Seeding-tillering (00-10)	Tillering-overwintering (11-30)	Overwintering-regreening (31-32)	Regreening-jointing (33-39)	Jointing-heading (40-55)	Heading-filling (56-75)	Filling-maturity (66-99)
Date	Oct 15 - Nov 25	Nov 26 - Dec 4	Dec 5 - Mar 21	Mar 22 - Apr 21	Apr 22- May 10	May 11 - May 28	May 29- Jun 29

The soil samples in this experiment were collected at the November 10, February 20, April 1, April 30, May 20 and June 25 of the critical growth period of wheat. In each repeat experiment of every treatment, soil samples need to be taken for testing or analysis. The soil samples were divided into two parts, one part was used to determine the soil water content and another part was used to determine the soil available nutrients. The soil samples were divided into 0-10 cm, 10-20 cm, 20-30 cm, 30-40 cm, 40-60 cm, 60-80 cm, and 80-100 cm soil layers for collecting, and the average soil water content and average available nutrients of soil layer were the soil water content and nutrient value of the treatment in this growth period. In addition, the wheat root soil of 3~8 cm layer was used to determine the number of soil microorganisms and soil enzyme activity. These soil samples were stored in refrigerator at 4 °C and measured in time.

The soil water content was determined by the drying method. The soil samples were placed in an aluminum box and the mass was measured in time. The mass was measured after drying in an oven at 105 °C for 8 h. Soil nitrate nitrogen was determined by UV spectrophotometer at dual wavelengths of 220 nm and 275 nm, while soil ammonium

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nitrogen was determined by indophenol blue colorimetric method by UV spectrophotometer at 625 nm.

Each soil sample is tested three times for the quantity of microorganisms, and the average value is considered to be the quantity of microorganisms present in that soil sample. The number of soil bacteria, fungi and actinomycetes were determined by dilution plate counting method. The bacteria were cultured by beef extract peptone medium, the actinomycetes were cultured by modified Gaoshi No.1 medium, and the fungi were cultured by Martin medium. Each soil samples were repeated three times. Determination of soil enzyme activity: soil urease activity was measured by indophenol blue colorimetric method, soil alkaline phosphatase activity was measured by diphenyl phosphate colorimetry, and the soil sucrase activity was measured by 3, 5-dinitrosalicylic acid method.

Determination of wheat yield

Each treatment randomly selects three areas of 0.5 square meters to count the productive tillers of wheat and takes the average, which is then converted into the productive tillers per square meter. The yield of each treatment was measured by threshing after harvest, and the 1000-grain weight of each treatment was measured.

Statistical analysis

In this paper, all data were subjected to one-way analysis of variance (ANOVA), and significant differences among different treatments were analyzed using Duncan's test. All analyses were performed in SPSS statistical software (version 20.0).

Results and analysis

Effect of γ-PGA SAP on soil water content

The response of different contents of γ-PGA SAP to soil water content at different growth stages of winter wheat under three different irrigations were showed in *Fig. 2*. The suitable soil water range for winter wheat growth is generally 13% to 22%, with 13% as the minimum water requirement and 18% as the most suitable water content range for loamy soil. During the planting process, too much or too little water will have adverse effects on wheat growth. It can be seen from the trend of soil water content change in the figure that with the advancement of winter wheat growth period, soil water content decreased firstly, then increased to a certain extent and then decreased, which was mainly related to the irrigation cycle. In the early jointing stage, the soil water content increased with the increase of γ-PGA SAP addition in the soil when the irrigation was not distinguished, but no significant difference among the different treatments. In the treatment with less irrigation, the soil water content of each treatment was lower than that of the treatment with more irrigation.

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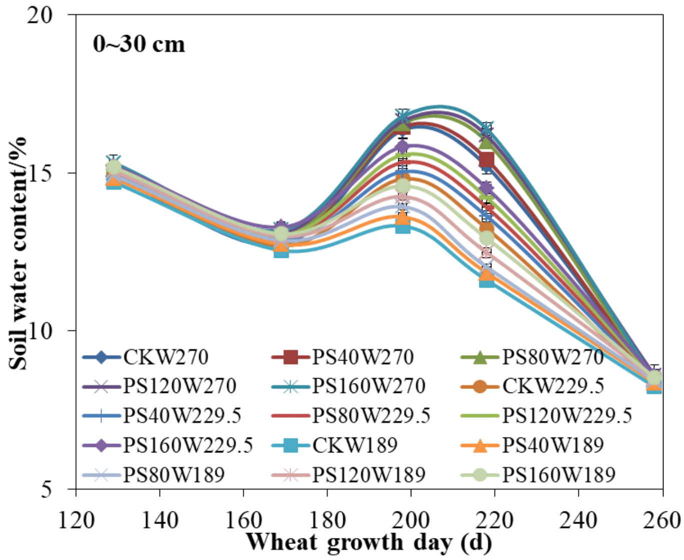
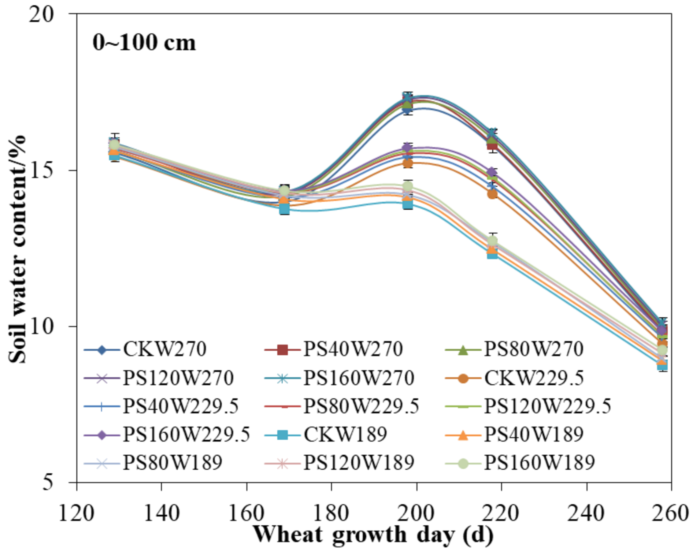


(a) Average soil moisture content in 0-30 cm soil layer during growth period



(b) Average soil moisture content in 0-100 cm soil layer during growth period

Figure 2. *Effects of γ-PGA SAP for soil water content. Notes: The soil water content in the figure is the soil mass water content*

The average soil water content in the 0-30 cm soil layer during the growth period of W270 treatment showed a gradual increase with the addition of γ-PGA SAP to the soil. Compared to CK, the increase was 0.80% (PS40W270), 1.75% (PS80W270), 2.78% (PS120W270), and 3.77% (PS160W270). Similarly, the average soil water content in the 0-30cm soil layer during the growth period of W229.5 treatment increased by 1.51% (PS40W229.5), 2.80% (PS80W229.5), 3.72% (PS120W229.5), and 5.28% (PS160W229.5) compared to CK. The average soil water content in the 0-30cm soil layer during the growth period of W189 treatment increased by 1.59% (PS40W189), 2.85% (PS80W189), 4.68% (PS120W189), and 6.39% (PS160W189) compared to CK. But

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there was no significant difference in soil water content between the same applications of γ-PGA SAP addition in the soil. In contrast, the average soil water content in the 0-30 cm soil layer during the growth period of W229.5 treatment was lower than that of W270 treatment, with a decrease of 5.25%, 4.58%, 4.30%, 4.36%, and 3.88% across the different levels of γ-PGA SAP addition. Similarly, the average soil water content in the 0-30cm soil layer during the growth period of W189 treatment was lower than that of W270 treatment, with a decrease of 15.24%, 14.66%, 13.75%, 14.23%, and 13.61% across the different levels of γ-PGA SAP addition. The soil water content of 0~30 cm soil layer increased more than that of CK group at the treatment with more reduced irrigation, which may be that SAP can effectively play its water retention performance under low water conditions (Yu et al., 2017) and the γ-PGA SAP is a type of SAP that has a similar function. With the advance of growth period, the difference of soil water content between γ-PGA SAP treatment and CK group gradually decreased.

The average soil water content of the 0-100 cm soil layer in the growth period of W270 treatment increased with the increase of γ-PGA SAP content by 1.22% (PS40W270), 1.10% (PS80W270), 1.94% (PS120W270) and 2.39% (PS160W270) compared with CK. The average soil water content of the 0-100 cm soil layer in the growth period of W229.5 treatment increased by 1.52% (PS40W229.5), 2.49% (PS80W229.5), 2.76% (PS120W229.5) and 3.55% (PS160W229.5) compared with CK, respectively. At the same time, the average soil water content of the 0-100cm soil layer in the growth period of W189 treatment increased by 1.49% (PS40W189), 2.46% (PS80W189), 3.04% (PS120W189) and 3.75% (PS160W189) compared with CK, respectively. The average soil water content in the growth period of W229.5 treatment decreased by 5.30%, 5.02%, 4.00%, 4.55% and 4.23% compared with that of W270 treatment in the 0-100 cm soil layer, respectively. And the average soil water content in the growth period of W189 treatment decreased by 10.86%, 10.63%, 9.66%, 9.91% and 9.67% compared with that of W270 treatment in the 0-100 cm soil layer, respectively.

From the comparison of the average soil water content of the 0-30 cm soil layer and the 0-100 cm soil layer, it can be seen that the average soil water content of the 0-100 cm soil layer is slightly higher than that of the 0-30 cm soil layer without distinguishing different irrigation, which was due to the soil water content in the wheat soil surface layer was more easily affected by atmospheric environment and crop water consumption. The difference of soil water content between different γ-PGA SAP addition in the soil in 0-100 cm layer was smaller than that in 0-30 cm layer after distinguishing different irrigation, due to cultivated soil (0-30 cm) is easily affected by the external environment and various types of additives in the soil (Liang et al., 2019).

Effect of γ-PGA SAP on soil nitrate nitrogen content

The response of different contents of γ-PGA SAP addition in the soil to soil nitrate content changes at different growth stages of winter wheat under three different irrigation water conditions were showed in *Fig. 3*. As can be seen from the figure, soil nitrate

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nitrogen content in different treatments showed a trend of decreased firstly, then increased to a certain extent and then decreased, which was mainly related to the fertilization cycle. With the advancement of growth period, the difference in soil nitrate nitrogen content among different treatments gradually decreased, which was due to the absorption of nitrate nitrogen in soil by wheat roots after stopping urea application at the middle and late stages of wheat growth. The addition of γ-PGA SAP to the soil resulted in an increase in the average soil nitrate nitrogen during the growth period of W270, W229.5, and W189 treatments, with varying percentages ranging from 0.05% to 7.37% compared to the control group. However, there was no significant difference in soil nitrate nitrogen content between the control group and the treatment with γ-PGA SAP addition in the soil, without reducing the numerical comparison. The results indicated that the application of γ-PGA SAP had little effect on soil nitrate nitrogen content. However, there is no significant difference in the nitrate nitrogen content between W229.5 and W270, and the nitrate nitrogen content in W189 and W270 also showcases no significant variation.

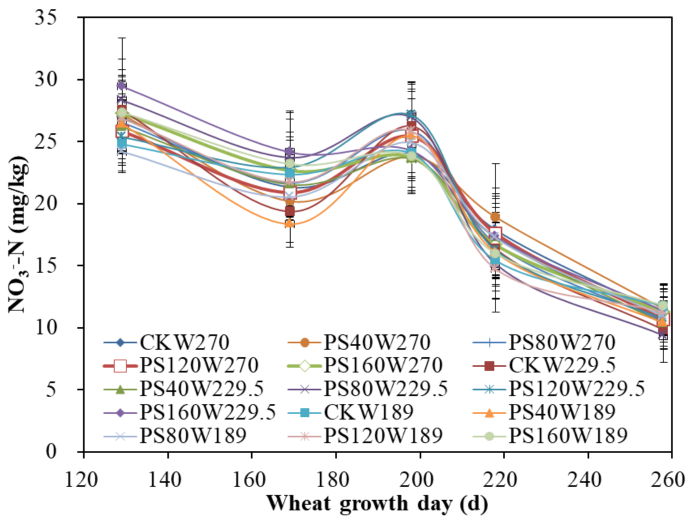

Figure 3. *Effects of γ-PGA SAP for soil nitrate nitrogen content*

Effect of γ-PGA SAP on soil ammonium nitrogen content

The response of different γ-PGA SAP addition in the soil and different irrigation to the change of soil ammonium nitrogen content at different growth stages of winter wheat was showed in *Fig. 4*. It can be seen from the figure that the change of soil ammonium nitrogen in the whole growth period showed a decreasing trend, but the content of ammonium nitrogen in the soil was lower than that of nitrate nitrogen in the soil. The average soil ammonium nitrogen in the growth period of W270 treatment increased with the increase of γ-PGA SAP addition in the soil by 8.80% (PS40W270), 15.47% (PS80W270), 22.89% (PS120W270) and 29.40% (PS160W270) compared with CK. The average soil ammonium nitrogen in the growth period of W229.5 treatment increased

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with the increase of γ-PGA SAP addition in the soil by 9.84% (PS40W229.5), 17.44% (PS80W229.5), 29.40% (PS120W229.5) and 32.87% (PS160W229.5) compared with CK. The average soil ammonium nitrogen in the growth period of W189 treatment increased with the increase of γ-PGA SAP addition in the soil by 9.98% (PS40W189), 19.96% (PS80W189), 30.18% (PS120W189) and 42.35% (PS160W189) compared with CK. The soil ammonium nitrogen content increased with the increase of γ-PGA SAP addition in the soil compared with the control group, indicating that γ-PGA SAP addition in the soil could increase soil ammonium nitrogen content. In addition, the average soil ammonium nitrogen content varied with the increase of γ-PGA SAP in the soil. Compared to W270 treatment, this content increased by -0.79%, 0.15%, 0.90%, 2.04%, and 1.87% for the W229.5 treatment while it increased by 2.79%, 3.91%, 6.79%, 8.89%, and 13.08% for the W189 treatment.

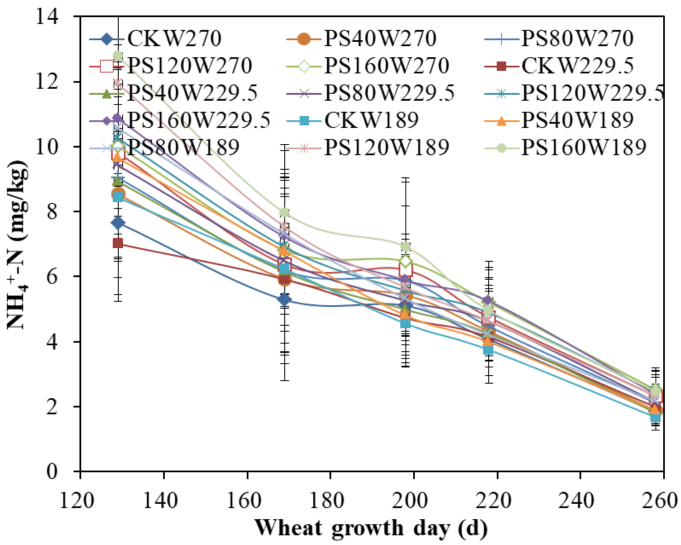

Figure 4. *Effects of γ-PGA SAP for soil ammonium nitrogen content*

Effect of γ-PGA SAP on soil microorganism

Table 4 shows the changes of soil microbial numbers (bacteria, actinomycetes and fungi) at the end of winter wheat growth with different γ-PGA SAP addition in the soil under different irrigation conditions.

The addition of γ-PGA SAP to the soil increases soil bacteria, soil actinomycetes and soil fungus at the end of growth stage, with a greater increase seen in treatments with higher γ-PGA SAP additions. However, less irrigation results in lower soil bacteria, soil actinomycetes and soil fungus counts in winter wheat rhizosphere soil at the end of the growth period. Increasing γ-PGA SAP additions in lower irrigation treatments also leads to increased soil bacteria, soil actinomycetes and soil fungus compared to higher irrigation treatments. The number of bacteria, actinomycetes and fungi at the end of growth stage

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under different γ-PGA SAP addition and irrigation were analyzed by significant interaction analysis (*Table 4*). It is found that the change of irrigation has a significant impact on the number of bacteria and actinomycetes but has no significant impact on the number of fungi. However, the change of γ-PGA SAP addition in the soil has a very significant effect on the number of bacteria, actinomycetes, and fungi. Under the interaction analysis of irrigation and γ-PGA SAP, there was no significant effect on the number of bacteria but had a significant effect on the number of actinomycetes and fungi.

Table 4. *The number and community index of microorganisms in root zone of different treatment*

Treatment	Bacteria (×10^9 cfu)	Actinomycetes (×10^7 cfu)	Fungi (×10^5 cfu)	Shannon index	Simpson index
CKW270	0.45±0.24efg	0.14±0.08ef	0.41±0.43g	0.0219	0.0064
PS40W270	0.67±0.30def	0.31±0.21def	1.43±0.72efg	0.0314	0.0096
PS180W270	0.91±0.12bcd	0.74±0.28bc	4.51±1.11bc	0.0511	0.0170
PS120W270	1.33±0.32b	1.05±0.30b	5.72±1.76ab	0.0495	0.0164
PS160W270	1.82±0.40a	1.47±0.51a	6.85±1.91a	0.0500	0.0166
CKW229.5	0.23±0.12fg	0.041±0.03f	0.18±0.19g	0.0139	0.0037
PS40W229.5	0.37±0.18fg	0.13±0.08ef	0.81±0.49fg	0.0256	0.0075
PS80W229.5	0.53±0.23defg	0.30±0.17ef	2.42±1.14def	0.0391	0.0122
PS120W229.5	0.84±0.27cde	0.49±0.10cde	3.11±0.98cde	0.0390	0.0123
PS160W229.5	1.14±0.32bc	0.59±0.17cd	3.83±1.34cd	0.0353	0.0109
CKW189	0.11±0.08g	0.01±0.01f	0.08±0.07g	0.0093	0.0023
PS40W189	0.29±0.19fg	0.07±0.04f	0.53±0.29g	0.0195	0.0054
PS80W189	0.38±0.21fg	0.13±0.05ef	1.18±0.35fg	0.0260	0.0076
PS120W189	0.52±0.19defg	0.18±0.08ef	1.46±0.30efg	0.0257	0.0075
PS160W189	0.65±0.22def	0.22±0.06ef	1.84±0.34efg	0.0254	0.0074
PS	**	**	**		
W	**	**	**		
PS×W	ns	**	**		

Note: Means with different lowercase letters in the same column represent significant differences at $P<0.05$. ** indicates highly significant correlation ($P < 0.01$), and ns indicates not significant

Both the Shannon index and the Simpson index are indicators of biodiversity. In this experiment, the microbial species determined by all treatments were bacteria, actinomycetes and fungi. Therefore, the higher value of Shannon index and Simpson index, the more uniform classification of microbial species. As can be seen from the table, the Shannon index and Simpson index increased with the increase of γ-PGA SAP addition in the soil, indicating that increasing γ-PGA SAP addition in the soil could promote the uniformity of microbial community. This may be due to the low proportion of fungi in the experimental treatments, and the application of γ-PGA SAP in the soil can

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significantly promote the increase of the number of fungi, thereby promoting the uniformity of the microbial community. Under the same application rate, the effect of different irrigation rates on Shannon’s index and Simpson's index was not obvious.

Effect of γ-PGA SAP on soil enzyme activities

The changes of soil enzyme activities (urease, phosphatase and sucrase) at the late growth stage of winter wheat with different amounts of γ-PGA SAP under different irrigation conditions was showed in *Table 5*. The soil enzyme activity increased with the increase of γ-PGA SAP addition in the soil under the condition of the same irrigation; the decreasing of irrigation will also reduce the soil enzyme activity in the case of the same γ-PGA SAP addition in the soil. The changes of various enzyme activities are analyzed in detail below.

Tabel 5. *Soil enzyme activities in root zone of different treatments at maturity stage*

Treatment	Urease activity	Phosphatase activity	Sucrase activity
CKW270	0.1247±0.0393gh	1.4325±0.4638efg	2.7483±1.2121fghi
PS40W270	0.1524±0.0413fgh	1.8364±0.3825de	5.4191±0.5541cdefg
PS180W270	0.2217±0.0409def	2.4489±0.4269bcd	7.5752±1.9384bcd
PS120W270	0.3289±0.0612abc	2.9873±0.4625ab	9.4216±1.9017ab
PS160W270	0.3974±0.0726a	3.5476±0.5391a	11.6665±3.2539a
CKW229.5	0.0932±0.0454gh	1.0313±0.3667fg	1.8942±1.0139hi
PS40W229.5	0.1253±0.0456gh	1.5451±0.2847ef	4.0920±1.4159efgh
PS80W229.5	0.1823±0.0353efg	1.9992±0.4009cde	6.1941±2.0151cde
PS120W229.5	0.2745±0.0422bcd	2.4463±0.4626bcd	8.0632±0.9490bc
PS160W229.5	0.3362±0.0474ab	2.9831±0.3735ab	9.2415±1.9319ab
CKW189	0.0769±0.0278h	0.7491±0.2970g	0.9831±0.2621i
PS40W189	0.1154±0.0276gh	1.3234±0.3904efg	2.4672±0.8541ghi
PS80W189	0.1652±0.0326efgh	1.6723±0.2668def	3.8512±1.4288efghi
PS120W189	0.2474±0.0521cde	1.9351±0.3350cde	4.9467±1.4620defgh
PS160W189	0.3191±0.0719abc	2.6542±0.6083bc	5.6832±1.8176cdef
PS	**	**	**
W	**	**	**
PS×W	ns	ns	ns

Note: Means with different lowercase letters in the same column represent significant differences at P<0.05. ** indicates highly significant correlation (P < 0.01), and ns indicates not significant

The addition of γ-PGA SAP increased soil urease activity, soil alkaline phosphatase activity and soil sucrase activity under the same irrigation. The increase in γ-PGA SAP content in the soil resulted in increased soil urease activity, soil alkaline phosphatase activity and soil sucrase activity in W270, W229.5, and W189 treatments compared to CK. The decrease in irrigation also led to a decreasing trend in soil urease activity, soil alkaline phosphatase activity and soil sucrase activity in winter wheat rhizosphere soil at

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the end of the growth period. The soil urease activity, soil alkaline phosphatase activity and soil sucrase activity of W229.5 and W189 treatments increased compared to the W270 treatment with the increase of γ-PGA SAP content in the soil. Through the interactive significance analysis of soil enzyme activity (urease activity, phosphatase activity and sucrase activity) on different irrigation and different γ-PGA SAP addition in the soil at the end of growth, we found that the change of irrigation and the change of γ-PGA SAP addition in the soil had a significant effect on the enzyme activities (urease activity, phosphatase activity and sucrase activity) of wheat rhizosphere soil, but the interactive significance analysis of the irrigation and the γ-PGA SAP had no significant effect on the enzyme activity of wheat rhizosphere soil.

Effect of γ-PGA SAP on winter wheat yield composition

The effects of different contents of γ-PGA SAP and different irrigation on winter wheat yield indexes (spike number, number of grains per ear, 1000-grain weight, and yield) was showed in *Table 6*.

Table 6. *Composition of yield indexs of wheat under different treatment*

Treatment	Number of panicles ($\times 10^4$)	1000-grains (g)	Yield (kg/hm^2)
CKW270	432.35±13.86bcd	36.81±0.56abc	5873.08±132.96abc
PS40W270	456.17±62.79ab	36.85±0.41ab	6008.38±356.05ab
PS180W270	471.62±54.36ab	36.67±0.25abc	6177.61±481.37ab
PS120W270	494.24±49.09a	37.14±0.42a	6246.78±332.92ab
PS160W270	501.16±28.49a	36.47±0.35abc	6305.49±263.81a
CKW229.5	360.35±18.33fgh	35.69±0.74bc	5081.65±334.09de
PS40W229.5	372.16±22.27efg	35.92±0.59abc	5404.22±221.72cde
PS80W229.5	396.21±30.20cdef	36.31±0.45abc	5705.84±203.71bcd
PS120W229.5	416.74±26.23bcde	36.62±0.58abc	5852.91±126.40abc
PS160W229.5	436.92±22.27bc	36.44±0.72abc	5993.14±180.66ab
CKW189	304.44±10.5h	35.75±0.68bc	4181.41±340.44f
PS40W189	328.61±18.04gh	35.58±0.82c	4614.74±320.21ef
PS80W189	348.42±18.33fgh	36.14±1.47abc	4952.51±211.30de
PS120W189	360.77±24.03fgh	35.86±0.41abc	5154.62±332.48e
PS160W189	376.92±22.27defg	35.73±0.45bc	5281.73±286.80de
PS	**	**	**
W	**	ns	**
PS×W	ns	ns	ns

Note: Means with different lowercase letters in the same column represent significant differences at $P<0.05$. ** indicates highly significant correlation ($P < 0.01$), and ns indicates not significant

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The spike number refers to the total spike number per unit area of wheat, which can reflect the tillering and growth of wheat situation and is one of the important indicators to reflect the yield of wheat. The spike number of W270 treatment increased with the increase of γ-PGA SAP addition in the soil by 5.56% (PS40W270), 9.17% (PS80W270), 14.39% (PS120W270) and 16.00% (PS160W270) compared with CK. The spike number W229.5 treatment increased with the increase of γ-PGA SAP addition in the soil by 3.33% (PS40W229.5), 10.01% (PS80W229.5), 15.56% (PS120W229.5) and 21.11% (PS160W229.5) compared with CK. The spike number of W189 treatment increased with the increase of γ-PGA SAP addition in the soil by 7.89% (PS40W189), 14.47% (PS80W189), 18.42% (PS120W189) and 23.68% (PS160W189) compared with CK. With the increase of γ-PGA SAP addition in the soil, the spike number of W229.5 treatment decreased by 16.67%, 18.42%, 16.03%, 15.82% and 12.99% compared with W270 treatment, respectively. And the spike number of W189 treatment decreased by 29.63%, 28.07%, 26.21%, 27.15% and 24.97% compared with W270 treatment, respectively. The changes of irrigation and γ-PGA SAP addition in the soil had a significant effect on the spike number of wheat, but the interactive significant test between them had no significant effect.

The 1000 grain weight are directly related to the yield of winter wheat, and it's also the main indicators of winter wheat yield. In the interactive significance analysis of the application of irrigation and γ-PGA SAP on the 1000-grain weight of winter wheat, the change of irrigation had significant effect on 1000-grain weight of winter wheat, but the change of γ-PGA SAP addition in the soil had no significant influence on 1000-grain weight of winter wheat, and the interaction analysis of irrigation and γ-PGA SAP had no significant influence on 1000-grain weight.

With the increase of the application amount of γ-PGA SAP in the soil, the yield of winter wheat increased by 2.30%, 5.19%, 6.36% and 7.37% compared with CK in each treatment of W270, respectively. With the increase of the application of γ-PGA SAP addition in the soil, the yield of winter wheat increased by 6.35%, 12.28%, 15.18% and 17.94% compared with CK in each treatment of W229.5, respectively. With the increase of the application amount of γ-PGA SAP in the soil, the yield of winter wheat increased by 10.36%, 18.44%, 23.27% and 26.31% compared with CK in each treatment of W189, respectively. However, when the application of γ-PGA SAP was more than 80 kg/hm^2, the increase rate of wheat yield decreased.When the same amount of γ-PGA SAP was applied in the soil, the increasing rate of the yield with γ-PGA SAP addition in the soil was higher than that of CK group with the lower irrigation, and the yield of winter wheat increased with the increase of γ-PGA SAP amount in the soil. With the increase of γ-PGA SAP content in the soil, the wheat yield of W229.5 treatment decreased by 13.48%, 9.00%, 5.65%, 6.66% and 6.38% compared with W270 treatment, respectively. And the wheat yield of W189 treatment decreased by 28.80%, 22.29%, 18.11%, 17.80% and 17.49% compared with W270 treatment, respectively. Therefore, the γ-PGA SAP could better reflect its water retention under the lower water treatment, thereby reducing the

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impact of crop yield reduction due to reduced irrigation. In the interactive significance analysis of the application of irrigation and γ-PGA SAP on the yield of winter wheat, the change of irrigation and the change of γ-PGA SAP addition in the soil had significant effect on the yield of winter wheat, and the interaction analysis of irrigation and γ-PGA SAP had no significant influence on the yield of winter wheat.

Effect of γ-PGA SAP on water use efficiency (WUE) of winter wheat

By calculating the soil water use efficiency (WUE) of each treatment (*Table 7*), the WUE gradually increased with the increase of γ-PGA SAP addition in the soil under the condition of the same irrigation. When the application amount of γ-PGA SAP was above 40 kg/hm^2, the WUE of W229.5 treatment exceeded than that of control group of W270 treatment. And when the application amount of γ-PGA SAP was above 80 kg/hm^2, the WUE of W189 treatment exceeded than that of control group of W270 treatment.

Table 7. *Water use efficiency of each treatment*

Treatment	Yield (kg/hm^2)	I (mm)	P (mm)	△W (mm)	WET (mm)	WUE (kg/(hm^2 mm))
CKW270	5873.08±132.96abc	270	60.5	112.31	442.81	13.26
PS40W270	6008.38±356.05ab	270	60.5	111.48	441.98	13.59
PS180W270	6177.61±481.37ab	270	60.5	110.51	441.01	14.01
PS120W270	6246.78±332.92ab	270	60.5	109.53	440.03	14.20
PS160W270	6305.49±263.81a	270	60.5	108.28	438.78	14.37
CKW229.5	5081.65±334.09de	229.5	60.5	117.32	407.32	12.48
PS40W229.5	5404.22±221.72cde	229.5	60.5	114.68	404.68	13.35
PS80W229.5	5705.84±203.71bcd	229.5	60.5	113.42	403.42	14.14
PS120W229.5	5852.91±126.40abc	229.5	60.5	113.98	403.98	14.49
PS160W229.5	5993.14±180.66ab	229.5	60.5	111.76	401.76	14.92
CKW189	4181.41±340.44f	189	60.5	126.91	376.41	11.11
PS40W189	4614.74±320.21ef	189	60.5	124.82	374.32	12.33
PS80W189	4952.51±211.30de	189	60.5	123.85	373.35	13.27
PS120W189	5154.62±332.48e	189	60.5	121.63	371.13	13.89
PS160W189	5281.73±286.80de	189	60.5	119.96	369.46	14.30

Note: Means with different lowercase letters in the same column represent significant differences at $P<0.05$

Discussion

In this experiment, the effects of different γ-PGA SAP addition in the soil on soil root zone microenvironment, crop yield composition and winter wheat quality under different irrigation levels were studied. It can be seen from the experiment results that the

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increment of soil water content with the increase of γ-PGA SAP content is higher than that of their respective control groups under low water conditions. The more γ-PGA SAP was applied in the soil, the soil water content was higher compared with the control group, which is similar to the results of many studies. This is because SAP expands after absorbing water in the soil to form a three-dimensional network structure and stores the water in the network structure of SAP, thereby reducing the evaporation of soil water. The water stored in SAP slowly released when the water in the surrounding environment is low (Liao et al., 2018). Therefore, the soil water content in the treatment with γ-PGA SAP addition in the soil was higher than that of the control group.

In this experiment, two different forms of nitrogen content in soil were measured. We found that the content of soil nitrate nitrogen and ammonium nitrogen increased to a certain extent with the decrease of irrigation water in this experiment, but the increasing degree of ammonium nitrogen content was not consistent with that of soil nitrate nitrogen content. This may be due to the reduced utilization of nitrate and ammonium in the soil due to the limited growth of winter wheat with the decrease of irrigation water (Ozcelik and Usta, 2008). The reason for the inconsistent change rates of soil nitrate nitrogen and ammonium nitrogen may be that the charge of nitrate nitrogen and ammonium nitrogen is related, and soil nitrate nitrogen has the same negative charge as soil (Latifah et al., 2017). Therefore, nitrate nitrogen is easily to be leached by water. The soil nitrate nitrogen was leached more by the soil water in the treatments with more irrigation, while the soil ammonium nitrogen is due to the negative charge after water absorption expansion of the SAP, which can be absorbed by γ-PGA SAP after water absorption expansion and adsorption by soil (Latifah et al., 2017).

The change of irrigation and the change of γ-PGA SAP addition in the soil have different degrees of influence on different microorganisms. The main reason is that the suitable growth environment required by bacteria, fungi and actinomycetes is not consistent. Due to the large size of fungi, the application of γ-PGA SAP can increase soil porosity, so the number of soil fungi in the treatment with more γ-PGA SAP is more than that in other treatments (Li et al., 2020). The changes of irrigation and γ-PGA SAP addition in the soil had a great influence on soil enzyme activity, which may be due to the changes of irrigation and γ-PGA SAP addition in the soil can affect the changes of soil microorganism quantity, and the microorganisms have a direct correlation with soil enzyme activities (Varaljay et al., 2022). However, sucrase activity is sensitive to the change of γ-PGA SAP content, which may be due to the strong correlation between the intensity of sucrase activity and soil porosity (Xiang et al., 2018). The application of more γ-PGA SAP under low irrigation conditions can reduce the yield reduction caused by reduced irrigation. The main reason is that under low water treatment, the SAP can better reflect its water retention function, thus reducing the impact of reduced irrigation on crop yield (Ashkiani et al., 2013).

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Conclusion

The average soil water content of each treatment increased gradually with increasing γ-PGA SAP addition in the soil, and the increase degree of the average soil water content was higher under the low water condition. The application of γ-PGA SAP in the soil could increase the content of soil ammonium nitrogen but had no significant effect on the content of soil nitrate nitrogen. The number of soil microorganisms (bacteria, actinomycetes and fungi) and the activities of soil enzymes (urease, alkaline phosphatase and sucrase) increased with increasing γ-PGA SAP addition in the soil. In the three different irrigation treatments, wheat yield increased with increasing γ-PGA SAP addition in the soil. The yield of winter wheat increased by 9.00% (270 mm), 17.94% (229.5 mm) and 26.31% (189 mm) respectively compared with the control group when the γ-PGA SAP addition in the soil was 160 kg/hm^2. However, the increasing rate of wheat yield decreased when the γ-PGA SAP addition in the soil was more than 80 kg/hm^2. The γ-PGA SAP can better reflect its water retaining effect under low water treatment, so as to reduce the impact of crop yield reduction due to reduced irrigation.

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REFERENCES

[1] Abrisham, E. S., Jafari, M., Tavili, A., Rabii, A., Chahoki, M. A. Z., Zare, S., Egan, T., Yazdanshenas, H., Ghasemian, D., Tahmoures, M. (2018): Effects of a super absorbent polymer on soil properties and plant growth for use in land reclamation. – Arid Land Research and Management 32: 407-420.

[2] Ashkiani, A., Ghooshchii, F., Tohidi-Moghadam, H. R. (2013): Effect of super absorbent polymer on growth, yield components and seed yield of wheat grown under irrigation withholding at different growth stages. – Research on Crops 14: 48-53.

[3] Bai, W., Zhang, H., Liu, B., Wu, Y., Song, J. (2010): Effects of super-absorbent polymers on the physical and chemical properties of soil following different wetting and drying cycles. – Soil Use and Management 26: 253-260.

[4] Dhiman, J., Prasher, S. O., ElSayed, E., Patel, R. M., Nzediegwu, C., Mawof, A. (2021): Effect of hydrogel-based soil amendments on yield and growth of wastewater irrigated potato and spinach grown in a sandy soil. – Environmental Technology & Innovation 23: 101730.

[5] Guo, J. Z., Shi, W. J., Li, J. K., Zhai, Z. M. (2021): Effects of poly-gamma-glutamic acid and poly-gamma-glutamic acid super absorbent polymer on the sandy loam soil hydro-physical properties. – Plos One 16: 0245365.

[6] Guo, J. Z., Shi, W. J., Wang, P. H., Hao, Q. G., Li, J. K. (2022): Performance characterization of gamma-poly (glutamic acid) super absorbent polymer and its effect on soil water availability. – Archives of Agronomy and Soil Science 68(8): 1145-1158.

[7] Huang, K., Kong, L. (2013): Preparation and Characterization of Poly(aspartic Acid) Derivatives as Biodegradable Water Treatment Agents. – Asian Journal of Chemistry 25: 10233-10237.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2103_24572475
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[8] Kang, S. E., Rhee, J. H., Park, C., Sung, M. H., Lee, I. (2005): Distribution of poly-γ-glutamate (γ-PGA) producers in Koreanfermented foods, Cheongkukjang, Doenjang, and Kochujang. – Food Science and Biotechnology 14: 704-708.
[9] Latifah, O., Ahmed, O. H., Majid, N. M. A. (2017): Enhancing nitrogen availability from urea using clinoptilolite zeolite. – Geoderma 306: 152-159.
[10] Li, H., Zhu, H., Jin, H., Hua, J., Wang, J. (2005): Preparation and Crystal Structure of Sodium Hydrogen Epoxysuccinate. – Structural Chemistry 24: 259-262.
[11] Li, F. Z., Men, S. H., Zhang, S. W., Huang, J., Puyang, X. H., Wu, Z. Q., Huang, Z. B. (2020): Responses of Low-Quality Soil Microbial Community Structure and Activities to Application of a Mixed Material of Humic Acid, Biochar, and Super Absorbent Polymer. – Journal of Microbiology and Biotechnology 30: 1310-1320.
[12] Liang, J. P., Shi, W. J., He, Z. J., Pang, L. N., Zhang, Y. C. (2019): Effects of poly-gamma-glutamic acid on water use efficiency, cotton yield, and fiber quality in the sandy soil of southern Xinjiang, China. – Agricultural Water Management 218: 48-59.
[13] Liao, R. K., Yang, P. L., Wang, Z. H., Wu, W. Y., Ren, S. M. (2018): Development of a Soil Water Movement Model for the Superabsorbent Polymer Application. – Soil Science Society of America Journal 82: 436-446.
[14] Lin, W. C., Yu, D. G., Yang, M. C. (2006): Blood compatibility of novel poly(γ-glutamic acid)/polyvinyl alcohol hydrogels. – Colloids & Surfaces B Biointerfaces 47: 43-49.
[15] Ma, X., Wen, G. (2020): Development history and synthesis of super-absorbent polymers: a review. – Journal of Polymer Research 27(6): 136.
[16] Ma, H. Z., Li, P. P., Liu, X. W., Li, C., Zhang, S. K., Wang, X. H., Tao, X. (2022): Poly-gamma-glutamic acid enhanced the drought resistance of maize by improving photosynthesis and affecting the rhizosphere microbial community. – BMC PLANT BIOLOGY 22(1): 1-15.
[17] Miller, H. R., Randolph, T. L., Peairs, F. B. (2003): Categories of resistance at four growth stages in three wheats resistant to the Russian wheat aphid (Homoptera: Aphididae). – Journal of Economic Entomology 96: 673-679.
[18] Moghadam, H. R. T., Zahedi, H., Ghooshchi, F., Lak, S. (2011): Effect of super absorbent application on destructive oxidative stress in canola (*Brassica napus* L.) cultivars under water stress conditions. – Research on Crops 12: 393-401.
[19] Omidian, H., Rocca, J. G., Park, K. (2005): Advances in superporous hydrogels. – Journal of Controlled Release 102: 3-12.
[20] Ozcelik, G., Usta, S. (2008): Effect of Different Irrigation Methods on Soil Nitrate and Ammonium Contents. – Journal of Agricultural Sciences-Tarim Bilimleri Dergisi 14(3): 267-+.
[21] Shen, Y. B., Zhang, J. F., Li, T. (2020): Effect of Shading on The Water Use Efficiency of Winter Wheat (*Triticum Aestivum* L.) In Semi-Arid and Semi-Humid Regions of China. – Applied Ecology and Environmental Research 18: 7739-7755.
[22] Shih, I. L., Van, Y. T. (2001): The production of poly-(γ-glutamic acid) from microorganisms and its various applications. – Bioresource Technology 79: 207-225.
[23] Song, W., Xin, J., Zhang, J. (2017): One-pot synthesis of soy protein (SP)-poly(acrylic acid) (PAA) superabsorbent hydrogels via facile preparation of SP macromonomer. – Industrial Crops and Products 100: 117-125.
[24] Song, J., Zhao, H. D., Zhao, G. Z., Xiang, Y., Liu, Y. Q. (2019): Novel Semi-IPN Nanocomposites with Functions of both Nutrient Slow-Release and Water Retention. 1. Microscopic Structure, Water Absorbency, and Degradation Performance. – Journal of Agricultural and Food Chemistry 67: 7587-7597.
[25] Tarui, Y., Iida, H., Ono, E., Miki, W., Hirasawa, E., Fujita, K-i., Tanaka, T., Taniguchi, M. (2005): Biosynthesis of poly-gamma-glutamic acid in plants: transient expression of poly-

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2103_24572475
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gamma-glutamate synthetase complex in tobacco leaves. – Journal of bioscience and bioengineering 100: 443-448.
[26] Tolmachev, D., Lukasheva, N., Mamistvalov, G., Karttunen, M. (2020): Influence of Calcium Binding on Conformations and Motions of Anionic Polyamino Acids. Effect of Side Chain Length. – Polymers 12(6): 1279.
[27] Varaljay, V. A., Charles, T. C., Daniel, R. (2022): Editorial: Functional Metagenomics for Enzyme Discovery. – Frontiers in Microbiology 13: 956106.
[28] Wang, H., Liu, C., Zhang, L. (2002): Water-saving agriculture in China: An overview. – Advances in Agronomy 75: 135-171.
[29] Xiang, H. M., Guo, L., Zhang, J. E., Zhao, B. L., Wei, H. (2018): In Situ Earthworm Breeding to Improve Soil Aggregation, Chemical Properties, and Enzyme Activity in Papayas. – Sustainability 10(4): 1139.
[30] Xie, Q. X., Xiong, H. P., Qin, W. Q., Wen, X. J., Sun, Z. H., Wang, C. (2019): Effect of Polyacrylamide/Attapulgite Composite on Foraging Behaviors of Formosan Subterranean Termites (Blattodea: Rhinotermitidae). – Journal of Economic Entomology 112: 290-299.
[31] Xiong, C., Chen, S., Ming, S., Yu, Z. (2005): High yield of poly-γ-glutamic acid from by solid-state fermentation using swine manure as the basis of a solid substrate. – Bioresource Technology 96: 1872-1879.
[32] Xu, Z., Wan, C., Xu, X., Feng, X., Xu, H. (2013): Effect of poly (γ-glutamic acid) on wheat productivity, nitrogen use efficiency and soil microbes. – Journal of Soil Science & Plant Nutrition 13: 744-755.
[33] Yu, J., Shi, J. G., Ma, X., Dang, P. F., Yan, Y. L., Mamedov, A. I., Shainberg, I., Levy, G. J. (2017): Superabsorbent Polymer Properties and Concentration Effects on Water Retention under Drying Conditions. – Soil Science Society of America Journal 81: 889-901.
[34] Zohuriaan-Mehr, M. J., Kabiri, K. (2008): Superabsorbent Polymer Materials: A Review, Iran. – Iranian Polymer Journal 17: 451-477.
[35] Zohuriaan-Mehr, M. J., Omidian, H., Doroudiani, S., Kabiri, K. (2010): Advances in non-hygienic applications of superabsorbent hydrogel materials. – Journal of Materials Science 45: 5711-5735.

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