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Research article

Investigation of the effect of superabsorbent polymer application on soil moisture and plant growth

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Abstract

As climate change continues to affect the environment, drought management has become more critical in agri-food production. Farmers are now looking for alternative drought management methods that are easy to apply. In this sense, superabsorbent polymers (SAPs) were proposed as an alternative soil conditioning and drought management tool within this study. To test the efficiency of a developed SAP in terms of soil conditioning and plant growth promotion with different soil types and extreme drought conditions, long-term soil and greenhouse experiments were carried out in at least 4 replicates. The plant growth was monitored by 4 different growth indicators using wheat as a model plant. Plant growth indicators demonstrated that shoot dry matter, spike length, and grain yield were enhanced up to 24%, and 11.6% using different amounts of SAP at varying drought conditions. The study set forth and exemplary of superabsorbent polymer use in agriculture and useful in dose adjustment and understanding the drought-dose relationship in these types of polymers.

Keywords: *Drought stress; irrigation; superabsorbent polymer; sustainable agriculture*

1. Introduction

Agriculture uses 70% of all the water used globally, and this ratio exceeds 90% in underdeveloped countries (Mateo-Sagasta et al., 2017). Achieving high yields in agriculture requires sufficient promotion of plant growth and an effective fight against pests at the same time, which can be attained by a delicate interplay of water, fertilizers, and pesticides (Sharma et al., 2024). Water is certainly the most important factor in this equation (Dalezios et al., 2017; Monteleone et al., 2019), but it does not necessarily mean it has to be applied in such high quantities to achieve acceptable yields. These main agricultural inputs should be delivered to plants in optimum quantities, and excessive or restricted application of one of them can affect the activity of others (Magen, 2008), which is especially the case with water. If water is delivered in very large quantities in a short period, for instance during heavy rainfall, fertilizers and pesticides dissolved in soil leach at an accelerated rate and rapidly reach lower levels of the soil, rendering them inaccessible by the plants (Moradi et al., 2024). Conversely, if there is a long dry spell, fertilizers and pesticides applied in solid form cannot dissolve in the soil, and thus cannot be taken up by the plants' roots (Blancon et al., 2024). Therefore, the sustained delivery of water is crucial for crop health (Morison et al., 2008),

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not only because it constantly provides plants with water and eliminates drought stress, but also because it enables necessary nutrients and pesticides to be delivered to them in a more controlled fashion for longer times and limits their leaching (Tanaskovik et al., 2019) and loss to the environment (Feng et al., 2020).

Today, one of the main issues related to agricultural practices is that most of them use a lot of water in inefficient ways (Woyessa, 2024). For example, flood irrigation is one of the oldest methods, which is still widely used. This method causes waterlogging and erosion (Yadav et al., 2013), with adverse effects on many crops and soil (Bett et al., 2017; Cox et al., 2018), along with inefficient water use. Modern, more efficient irrigation methods are termed micro-irrigation systems (Rolbiecki and Rolbiecki, 2004), which deliver water slowly and directly to where it is most needed - the roots of the plants. These systems can be categorized into sprinkler, drip, spray, subsurface, and bubbler irrigation. Each system has its advantages and drawbacks and can be used for different crop types and in different fields. For instance, sprinkler and spray irrigation is being used in large farms, whereas drip irrigation systems can be implemented in smaller farms and greenhouses, and bubbler irrigation is mostly used for watering fruit trees (Mabuza and Ndoro, 2023).

To achieve adequate plant growth with minimum resources, water should be applied where it is needed, regularly and in small quantities. This can be accomplished with micro-irrigation systems. However, in farms where these systems are not implemented, either due to economic or technical feasibility and especially for lands where dry farming practices are employed, superabsorbent polymers (SAP) can be used to regulate water delivery to plants (Satriani et al., 2018). SAP is applied in granular form, together with the seeds, under the soil. Since SAPs' mechanisms of work depend on osmotic pressure difference (Ganji et al., 2010), upon irrigation or rainfalls, SAPs swell, and hold the water in their structure until their surroundings are drier than themselves. This allows SAPs to release the water to plants when they need it the most (Elshafie and Camele, 2021). Also, during heavy rainfalls, since SAPs will compete with plant roots in terms of water absorption and keep some of the water in their structure, they will alleviate the negative effects of too much water (Bhagat et al., 2016). This way, SAPs will transform into a water reservoir for plants. The use of SAPs in agriculture allows farmers to irrigate their farms less frequently with less water. Also, their use lowers yield losses in lands where dry farming is applied since it delivers water more efficiently to plants and allows for plant root areas to stay wet for long periods.

SAPs are lightly crosslinked polymers that are synthesized with natural, synthetic, or a combination of both sources. Since SAPs have a 3D hydrophilic polymer network with a low crosslinking density, they can absorb a significant amount of water while maintaining their physical structure without any intact (Singh et al., 2021).

Natural SAPs are generally made with saccharide (Qureshi et al., 2020), chitosan (Sanchez-Salvador et al., 2021), and cellulose (Zinge and Kandasubramanian, 2020) while synthetic SAP sources are generally based on ionic monomers (Mignon et al., 2019). The unique swelling and water-retaining properties of SAPs are due to the comprising hydrophilic groups such as carboxyl, amine, hydroxyl, amide, and sulfonic groups (Qureshi et al., 2020). SAPs have already been using in hygiene products (Bachra et al., 2020), biomaterials (Rahimi et al., 2020), medicine, and wastewater treatment (Maji and Maiti, 2021). Nevertheless, the use of SAPs in agriculture is a topic, rising in importance day by day, due to the increase in drought and loss of arable lands (Rizwan et al., 2021).

Nanocomposite materials can demonstrate unusual property combinations for various applications (Ahmed et al., 2023; Ariturk et al., 2024). The nanocomposite SAPs used in agriculture include natural polymers combined with inorganic fillers (Sethi et al., 2023; Wypij et al., 2023). For instance, a copolymer of starch-polyvinyl alcohol combined with zeolite derivative clinoptilolite demonstrated higher water absorption capacity than the pure hydrogel, both at neutral pH and in a saline solution (Olad et al., 2018). The SAP nanocomposite structures may also include chemically modified inorganic fillers (Fu et al., 2022).

In a study on SAP nanocomposite preparation, ball-milled and chemically modified natural char nanofiller was incorporated into starch-g-poly (acrylic acid-co-acrylamide) copolymer and compared to neat hydrogel copolymer (Motamedi et al., 2020). Among them, chemically modified filler containing SAPs demonstrated two-fold water absorbency and three-fold water retention due to the coexistence of both chemical and physical crosslinking between chemically modified filler and the SAP structures.

Depending on the morphology and surface properties, inorganic fillers may also be used as the active agent or the carrier materials for agrochemicals (Seven et al., 2019; Perera et al., 2023). A Nano-titanium dioxide-containing polyacrylamide-based SAP demonstrated enhanced thermal and biological traits, plant growth regulation, and antibacterial activity arising from the chemical structure and function of the nanofiller (Shirsath et al., 2020). The current study describes the preparation and performance evaluation of a nanocomposite SAP in terms of its water retention capacity and its effect on plant growth under drought stress. The water retention capacities of prepared SAP nanocomposites were tested using different soil samples, while the dose-response relationship was demonstrated via greenhouse trials on a set of 64 pots. The effects of a set of SAP nanocomposites in varying doses on plant height, spike height, biomass accumulation, grain weight, and grain yield were investigated via long-term greenhouse trials. Results demonstrate that the SAP nanocomposites enhance water retention capacities of all soil types, particularly of sandy soil samples. In addition, the grain yields and biomass accumulations were observed to enhance by 3-14% and 8-19%, depending on the SAP doses applied.

2. Materials and methods

Monomers acrylamide (AM, ≥99% HPLC) and 2-acrylamido-2-methylpropane-1-sulfonic acid (AMPS, ≥99%) were purchased from Sigma Aldrich. Acrylic acid (AA, analytical grade) was obtained from Alfa Aesar. Monomers were used as received, without any purification. Vinyltrimethoxysilane (VMTS, 98%) and ammonium persulfate (APS, ≥99%) were purchased from Sigma Aldrich. Sodium hydroxide solution 10 mol/L and ethanol (EtOH, absolute-99.9%) were obtained from Merck and used without further purification. Halloysite nanotubes (HNT) were kindly supplied by ESAN Inc. Distilled water was used for the preparation of all solutions.

2.1. Synthesis of superabsorbent nanocomposite polymer (SAP)

Synthesis of the superabsorbent nanocomposite SAP (WO2021167577) was performed using a previously developed method (Menceloglu et al., 2022), carried out via free-radical polymerization in distilled water. Nanocomposite random copolymer was synthesized by acrylic acid (AA), acrylamide (AM), and 2-acrylamido-2-methylpropane-1-sulfonic acid (AMPS) monomers in the presence of ammonium persulfate (APS) as a free radical initiator and VTMS as a crosslinking agent.

Initially, an amount of AM and AMPS were dissolved in distilled water and AcOH was added to the monomer solution. The pH of monomer solution was adjusted to 7 with 12 M sodium hydroxide before the reaction began. HNT, 1% of total monomer amount, was added to the neutralized monomer solution. After HNT was well dispersed in mixture, monomer solution was transferred to a three necked flask. The reactor was purged with nitrogen for 15 minutes to obtain an inert environment. As an *in-situ* crosslinking agent (Jaber et al., 2012), VTMS was added to the reaction mixture and continued to purge with nitrogen. After dissolving an amount of APS in water was added to the reaction environment. The reflux and heating were started. Nitrogen flow was closed after removing oxygen and air in the environment. The polymerization was carried out at 78°C in an oil bath for 2 hours. The reaction was maintained for 2 hours to complete the reaction and to increase the polymerization efficiency.

At the end of the reaction, the polymer solution was precipitated in ethanol to obtain powder super absorbent polymer. The precipitated polymer was dried at 70°C for 20 hours to remove solvent residues.

2.2. Wheat planting and harvesting

Wheat cultivation trials were carried out in a greenhouse under natural daylight conditions at Sabanci University (Khampuang et al., 2023). Three drought conditions were selected for the experiment, including extreme water shortage (40% of the field capacity), moderate water shortage (60% of the field capacity), and sufficient soil moisture (80% of the field capacity).

Plastic pots were filled with a fertilized medium loamy soil amended with three concentrations (0.0, 0.1, 1, and 2 g/kg) of SAP set including a negative control, and the experiments on each group were carried out with four repetitions. Wheat cultivars were placed at a Venlo-type greenhouse at Sabanci University, Istanbul. During the cultivation, temperature was kept constant (25 ± 2°C during daytime and 18 ± 2°C at night). The cultivars were sown in an order that is 4 m with length and 10 cm inter-row spacing and 10 cm pot spacing distances. Wheat seeds of cultivar "Tekfen 1016" were planted into the pots filled with fertilized soil by the following basal treatment: 100 mg of P in the form of KH_2PO_4, 25 mg of S in the form of K_2SO_4, 2.5 mg of Fe in the form of Fe-EDTA, 2 mg of Zn in the form of $ZnSO_4.7H_2O$, and 200 mg of N in the form of $Ca(NO_3)_2.4H_2O$. Tap water was added to reach the target moisture content (40, 60, or 80% of the field capacity) for adjusting soil moisture. All samples were irrigated daily for the first three weeks to provide the plant growth without water stress in the first stage. Irrigation was carried out by weighing each pot, calculating the amount of water lost, and bringing it back to 80% field capacity. At the end of the third week, the irrigation frequency was reduced to three days (equivalent to 1/3 of the normal watering) to examine water release, and the amount of irrigation was reduced to 40, 60, or 80% of field capacity, respectively.

Wheat were harvested after 120 days by cutting plants at the soil surface. Whole plants were placed in a paper bag for each pot and dried to analyze dry biomass. Before harvesting, the grains were collected to calculate grain yield.

2.3. Determination of morphometric characters

Shoot height measurements were performed on the 6th week of the experiment. The shoot heights were recorded from the ground level to the leaf base of the highest fully expanded leaves. Shoot dry weights were recorded by weight measurements of the individual wheat samples (3 samples from each replicate pot) collected from pots in the 6th week of the greenhouse experiment. Prior to weight measurements, wheat samples were removed from pots, washed with d-water, and dried at 70°C. For spike length measurements, the spikes were collected at the full maturation stage of the harvest. 5 spikes were collected from each replicate pot, cut from the spike ends, and their lengths were measured and averaged. Grain weights were determined at the end of the harvest, from the cumulative weights of each replicate pot of the corresponding SAP dose.

2.4. Elemental analysis

For elemental analysis, grain samples were ground to a fine powder in an agate vibrating cup mill (Pulverisette 9; Fritsch GmbH; Germany), and each sample was digested using a closed-vessel microwave system (MarsExpress; CEM Corp., Matthews, NC, USA) with 2 ml of 30% H_2O_2 and 5 ml of 65% HNO_3. Digested samples were diluted to 20 mL with ultra-deionized water and filtered by quantitative filter papers. Elemental analysis was performed with inductively coupled plasma optical emission spectrometry (ICP-OES; Vista-Pro Axial; Varian Pty Ltd, Mulgrave, Australia) to determine grain concentrations as described (Acar et al., 2023), and whether the SAP has a negative effect on nutrient uptake or not.

3. Results and discussion

3.1. Effect of SAPs on plant growth and grain production

There are several parameters to determine plant growth, including the change in its height, dry weight, and grain production. Hence, the shoot dry weight, shoot height, spike length, and total grain weight of wheat plants planted in soil were investigated concerning SAP dose.

The first indicator investigated to demonstrate the effect of SAP on plant growth is the shoot height, obtained by the average heights of the plants grown in all replicate pots. Here, no significant difference was observed in shoot height at any drought conditions or doses compared to the control plants ($p>0.05$). However, an increasing trend was observed with increased SAP dose within 80% irrigation regime suggesting that in the shoot height differences would be more pronounced when higher doses of SAP are applied (Fig. 1, 2).

The second parameter investigated is the shoot dry matter of productivity. As demonstrated in Fig. 3, shoot dry matter production linearly increases with increased doses of SAP at every drought regime. This increase was linear with respect to

SAP dose. 18.2% (p=0.0256) and 24.0% (p=0.0344) increase were observed in the plants treated with 0.1 g and 1 g SAP in low drought conditions (3 days; 80% irrigation), respectively. This shows that SAP application can increase shoot biomass production by up to 24% depending on the dose in low drought conditions. In the application of 2 g SAP, the effect cannot be seen completely due to the experimental errors, but it was observed that up to a 25% increase would be expected due to the increased trend line. When the irrigation was reduced to 60%, we observed an average increase of 12.5%, 16.8%, and 11.9% with respect to increased SAP dose (0.1, 1, and 2 g, respectively) against controls. Even when the irrigation was reduced further to 40%, SAP still promoted shoot dry matter enhanced by 8.9%, 8.8%, and 8.7% (0.1, 1, and 2 g, respectively) against control.

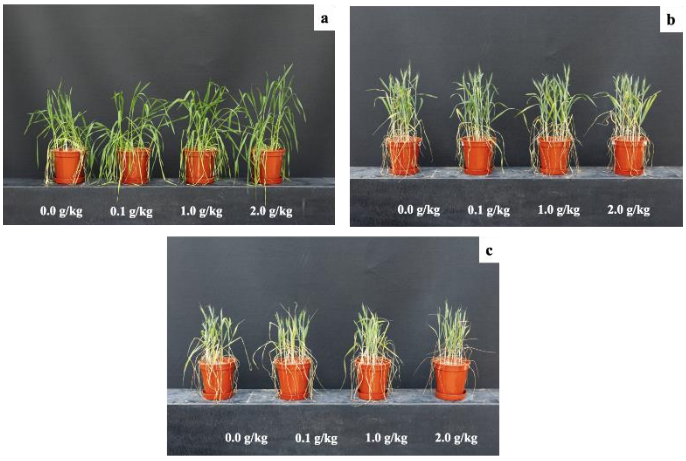

Fig. 1. Snapshots of the selected pots from greenhouse trials datasets. 80% (a), 60% (b), and 40% (c) of the field capacities, with an irrigation frequency of three days. Snapshots were gathered on the 30th day of the experiment.

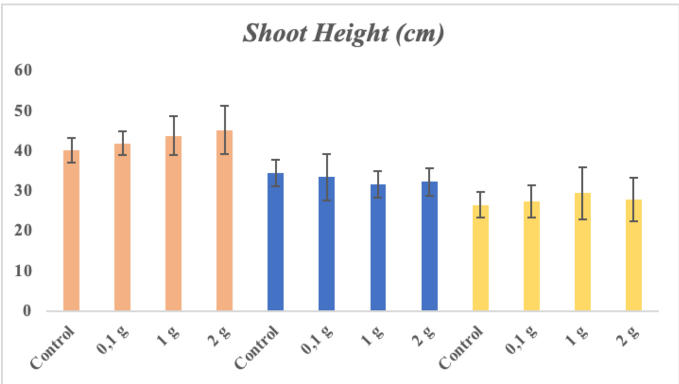

Fig. 2. Shoot height of plants grown under different SAP concentrations and irrigation with 80% (yellow), 60% (blue) and 40% (orange) of the field capacities.

The spike length and spikelet number were not statistically different between the cultivars SAP doses within the 80% irrigation regime (Fig. 4). However, a significant increase (11.56%) was observed in the spike length of 2 g SAP treated plants in moderate drought conditions (irrigation up to 60% of the soil capacity) (p=0.0021). The increase indicated that SAP is advantageous at higher doses within the moderate drought regime.

The total grain weight was calculated from the average of the grain weights obtained from each pot within the dose sets. As demonstrated in Fig. 5, an increase was observed at certain doses of SAP, and it was dose-dependent. While a 3.3% increase

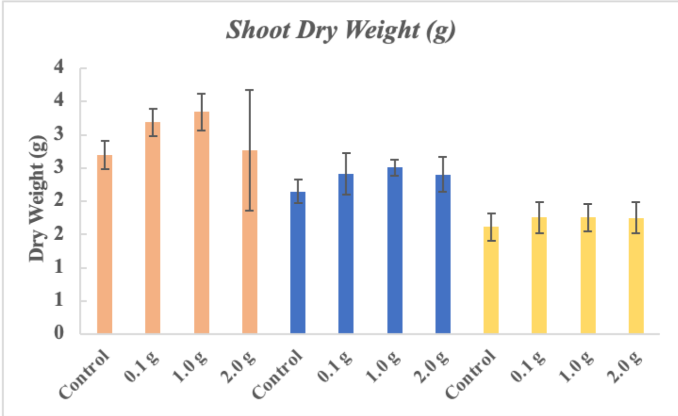

Fig. 3. Shoot biomass production of plants grown under different SAP concentrations and irrigation with 80% (yellow), 60% (blue), and 40% (orange) of the field capacities.

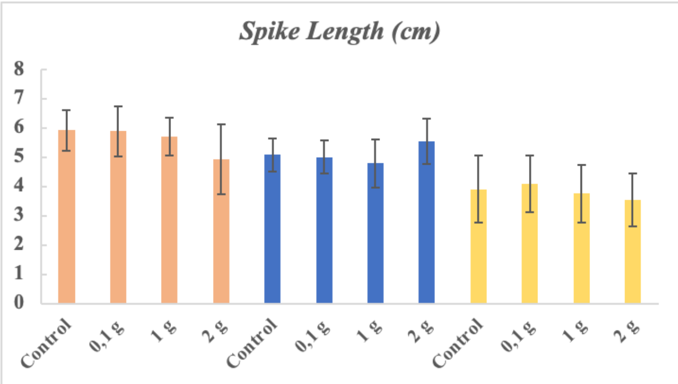

Fig. 4. Spike length of plants grown under different SAP concentrations and irrigation with 80% (yellow), 60% (blue) and 40% (orange) of the field capacities.

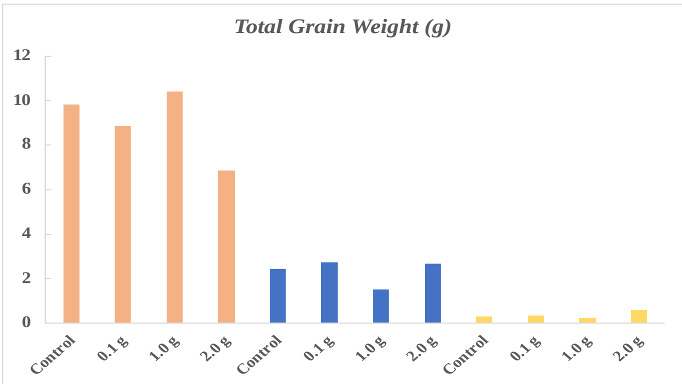

Fig. 5. Total grain weight of plants grown under different SAP concentrations and irrigation with 80% (yellow), 60% (blue), and 40% (orange) of the field capacities.

was observed in 1 g SAP treated samples in low drought conditions, 11.2% and 12.3% increases were observed in 0.1 g and 2 g SAP treated plants in moderate drought conditions, respectively. Moreover, 11.4% and 11.3% increases were observed in plants treated with 0.1 g and 2 g SAP in extreme drought conditions, respectively. However, the total grain weight was found very low in the whole set of extreme drought conditions. Thus, the results could not be reliable. The free variation of total grain weight indicated that the concentration of SAP application should be adjusted according to drought conditions of the soil. When the low and moderate drought conditions were compared, the dose of SAP application should

Table 1
The nutrient uptake study performed by ICP-OES analyses of grains collected at the end of the experiment.

Sample	Field Capacity	K	P	S	Mg	Ca	Fe	Zn	Mn	Cu	Na	Mo	B	Ni	Al
		(%)				(mg kg^{-1})									
Control	80%	0.44± 0.01	0.44± 0.01	0.20± 0.01	0.17± 0.01	497± 12	48± 3	43± 4	52± 5	7± 0	13± 0	0.68± 0.04	0.82± 0.10	4± 0	2± 0
0.1 g SAP	80%	0.43± 0.00	0.40± 0.00	0.17± 0.01	0.15± 0.00	458± 39	39± 2	35± 6	44± 2	6± 0	13± 0	0.67± 0.02	0.74± 0.05	3± 0	2± 0
1g SAP	80%	0.43± 0.01	0.41± 0.01	0.19± 0.01	0.15± 0.01	502± 13	42± 4	35± 6	45± 4	6± 0	14± 1	0.61± 0.03	0.73± 0.05	3± 0	2± 0
2g SAP	80%	0.43± 0.01	0.42± 0.02	0.20± 0.01	0.16± 0.01	529± 49	41± 4	35± 7	48± 7	7± 0	14± 1	0.64± 0.07	0.69± 0.07	3±1	2± 0
Control	60%	0.48± 0.01	0.47± 0.00	0.22± 0.00	0.18± 0.00	472± 14	58± 2	66± 6	65± 1	8± 0	12± 0	0.89± 0.04	1.18± 0.08	6± 0	2± 0
0.1 g SAP	60%	0.48± 0.00	0.46± 0.01	0.21± 0.01	0.18± 0.00	516± 9	51± 4	60± 6	61± 3	7± 0	13± 1	0.85± 0.02	1.25± 0.06	5± 0	1± 0
1g SAP	60%	0.51± 0.02	0.48± 0.00	0.22± 0.01	0.18± 0.00	513± 10	57± 4	73± 7	63± 2	8± 0	14± 0	0.99± 0.08	1.52± 0.04	5± 0	1± 0
2g SAP	60%	0.47± 0.00	0.46± 0.01	0.22± 0.01	0.18± 0.00	508± 8	50± 4	57± 7	60± 3	8± 0	14± 0	1.00± 0.04	1.24± 0.09	5± 0	1± 0
Control	40%	0.50± 0.03	0.46± 0.01	0.23± 0.01	0.18± 0.00	511± 25	54± 3	73± 7	63± 1	8± 0	9± 1	1.00	0.38± 0.20	7± 0	2± 0
0.1 g SAP	40%	0.51± 0.02	0.46± 0.01	0.23± 0.00	0.18± 0.00	499± 6	55± 7	70± 14	64± 2	8± 0	9± 1	0.99± 0.09	0.36± 0.21	6± 0	1± 0
1g SAP	40%	0.54± 0.03	0.46± 0.00	0.22± 0.01	0.18± 0.00	581± 66	53± 7	75± 11	61± 4	8± 0	14± 0	0.87± 0.17	0.92± 0.26	5± 1	4± 1
2g SAP	40%	0.50± 0.01	0.38± 0.00	0.22± 0.01	0.16± 0.00	501± 28	55± 1	21± 3	60± 0	7± 0	25± 5	0.41± 0.02	1.02± 0.05	7± 0	3±1

be reduced from 1 g to 0.1 g to increase the grain yield in case of enhanced drought.

3.2. Nutrient uptake & bioaccumulation

The nutrient uptake and residue analysis of SAP applied wheat samples were performed by ICP-OES analyses. Elemental analysis was performed on grinded grain samples obtained from greenhouse cultivation studies. Shoot Na content was slightly increased with SAP under all drought conditions, but generally, SAP application did not make a statistically significant change in the uptake of nutrient elements, nor did it induce accumulation of heavy metals and/or non-nutrient and toxic elements (Table 1) (Taylor et al., 2003). ICP-OES measurement levels for several nutrients are in line with the literature, particularly for Zn (Cakmak et al., 2010), Fe (Dimpka et al., 2020), and for Na, K (Pasławski and Migaszewski, 2006).

4. Conclusions

The current study describes the implementation of a sub-soil water reservoir polymer into wheat cultivation, demonstrating the efficiency of SAP in drought conditions and different soil types. To carry out soil and greenhouse trials, SAP was first synthesized using a previously developed method (Menceloglu et al., 2022).

SAP was tested in greenhouse cultivation of wheat, to demonstrate the effectiveness in extreme drought conditions. To create drought stress throughout the whole dataset (including controls) the irrigation frequency was reduced to ⅓. In addition to this, irrigation amounts were further reduced to 80%, 60% and 40% of the calculated field capacity. 4 different growth indicators were monitored under the extreme drought stresses applied. The first indicator was the shoot weight, where no significant difference was observed between the control and the dataset in increasing drought levels. However, a linear trend was observed between the SAP dose and the shoot weight, suggesting that higher doses outside the dataset may promote shoot height elongation. The second growth indicator, spike length increased by 11.6% only when 2 g of SAP was applied in a moderate drought regime. The third growth indicator was the shoot dry matter, where there was a significant increase at every drought regime and every SAP dose applied. The average of 24%, 14%, and 8.8% increase indicates that SAP is very efficient in shoot dry matter enhancement. The final growth indicator, the total grain weight was perhaps the most dose-sensitive parameter investigated. Depending on the dose/drought conditions, a 3.3-12.3% increase was recorded in total grain weight.

Due to the long-term water supply capacity, SAP reacclimates soil types that are either arid and/or non-arable regions such as sandy soils. As it can retain water for extended periods (up to 40 days depending on the soil type), SAP is suitable for irregular rainfall regimes. In addition to that, no negative effect was observed in nutrient uptake of the plant. Investigating the plant growth indicators, dose adjustment of SAP is very critical to ensure the maximum benefit, and when assured, it is observed that SAP promotes plant growth.

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Conflict of interest: The authors declare that they have no conflict of interests.

Informed consent: The authors declare that this manuscript did not involve human or animal participants and informed consent was not collected.

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