Alleviation of Water-Deficit Stress on Seed Germination of Barley and Fenugreek in a Sandy Soil Using Superabsorbent Polymer

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Abstract: Water deficit is one of the major limiting factors of seed crop germination and productivity. Consequently, superabsorbent polymers (SAPs) are among several technologies that enhance water use efficiency, leading to worthy seed germination. The objective of this study was to investigate the potential effect of three rates of SAPs (0.0%, 0.5%, and 1.0% w/w) on the seedling emergence of barley and fenugreek sown in a sandy soil using three replicates in a randomized complete block design. Outdoor pot experiments were conducted in Aswan Province, Egypt. The differences in the final germination percentages (FGPs) were not significant for both seeds, while the application of SAPs enhanced the seedling germination index (GI) with significant differences for both crop seeds. The application of SAP at 0.5% gave the highest GI for barley (2.47 day⁻¹) and fenugreek (2.66 day⁻¹) seeds. The sigmoidal function effectively described the cumulative germination percentage rates for both seeds as a function of time under the SAP levels with R² greater than 0.992. The maximum rates were 69.4 and 64.6 day⁻¹ for barley and fenugreek seeds at SAP 0.5%, respectively. The corresponding rates for 0.0% SAP were 11 and 12 day⁻¹. The water germination efficiencies (WGE) were 27.76 and 30.04 cm⁻¹ for 0.0% and 0.5% SAP for barley, while they were 23.07 and 29.9 cm⁻¹ for fenugreek.

Accordingly, SAPs could represent a promising solution for increasing moisture conservation for seed germination in a sand soil. For strategic management, barley is recommended for growth over fenugreek in a semidried soil.

Keywords: barley and fenugreek; germination index; cumulative germination; sigmoidal function; sand soil; superabsorbent polymer; WGE

1. Introduction

Egypt is a developing country, which mainly depends upon agriculture as a main source of foods [1]. Despite the tremendous progress in the development of this sector, in recent decades, extreme population growth has become the main obstacle toward achieving the objectives of sustainable agriculture development [2] compared with other factors such as the conservation of soil, water, and animal and plant genetic resources, in addition to organic agriculture, integrated agricultural production, agroforestry production, and crop–livestock–forest integration. In other words, the global population growth, which is expected to double from 2020 to 2050, may be the main motive for creating innovative approaches to improve land productivity and maximize crop production through increasing the soil’s ability to retain water [3,4] and, furthermore, following crop rotation as one of the systems of agricultural intensification and the cultivation of new varieties of plants,
especially those that are tolerant of water-deficit stress conditions [5]. One suggested solution is the application of superabsorbent polymers (SAPs) such as absorbent polymers, absorbent gels, water gels, or hydrogels [6], which can be identified as three-dimensional, hydrophilic, and cross-linked functional materials, characterized by a high ability to absorb large volumes of water, even up to 1000 times relative to their dry weight [7–9]. Many studies have highlighted the use of SAPs in several disciplines including medicine, civil engineering, industry, soil science, and agriculture [10–14]. In agriculture, the application of SAPs is not a new concept as they have been applied since the 1950s [15]. They have gained considerable attention in recent decades due to their significant role in improving some physical, chemical, and hydrological properties of soils [16]. These materials can absorb large quantities of water, making it available to the plant over time [17], enhancing the plant’s ability to overcome drought stress [18,19], and increasing the time between irrigation periods [9]. Many studies have been conducted to evaluate the pivotal effect of applying SAPs. For instance, they can retain large quantities of water relative to their own weight, thereby increasing the plant’s available water and consequently enhancing plant growth [20–22]. Plants can absorb about 95% of the water retained within the SAPs [23]. Additionally, recent studies have indicated that SAPs can also play a substantial role in enhancing the activities of soil microorganisms [24]. Moreover, SAPs can protect the soil surface from runoff, and they can act as a reservoir, holding nutrients in fertilizers [25]. Furthermore, SAPs have been applied as a seed coating to enhance their germination parameters [26]. Several studies have highlighted the improved influence of hydrogels on soil physical characteristics including permeability, bulk density, texture, structure, and some hydraulic properties such as water infiltration rate, evaporation, and water-holding capacity [3,27]. Moreover, in previous studies [28], authors stated that hydrogels may result in saturation of the water volumetric content in arid and semiarid soil.

On the basis of their chemical and physical properties, a hydrogel can be classified into two main groups. The first group constitutes reversible hydrogels, where polymer chains are associated with electrostatic forces and hydrogen bonds [29]. The same authors indicated that this group is characterized by its instability and can be converted by heating a polymer mixture such as gelatin and agar. The second group constitutes polymer chains related to stable bonds such as acrylic acid, acrylamide, acrylonitrile, and polyvinyl alcohol. Potassium polyacrylate and sodium polyacrylate are common types of hydrogels applied in the agriculture sector. In this regard, several SAP products are available, and their application rate is variable depending on the polymer material type, climatic and environmental conditions, and soil physicochemical properties [8]. Broadly speaking, hydrogels are the best commercial superabsorbent polymers owing to their easy decomposition in the soil [30]. Recent works have mentioned that the application of fine-grained hydrogel at 3% on sandy soil appreciably reduced the saturated hydraulic conductivity and improved the available water capacity compared with large-grained hydrogel [31]. Concerning the method of application, the direct introduction of SAPs or polyacrylamide (PAM) into the soil is the simplest [32]. SAPs can also be introduced into the soil via mixing, injection, or hydro-sowing with seeds [33].

Few studies have reported the impact of SAPs on seed germination. In [34], the authors mentioned that starch composed of hydrogel, acrylic acid, and acrylamide showed a significant influence on seed corn germination. Furthermore, the author in [30] concluded that the germination of Phaseolus vulgaris treated with hydrogel supplemented with natural substances was markedly improved compared with the untreated plant. Several studies have highlighted that the enhancing effect of SAP on early germination could be due to its high ability to increase the water-holding capacity, consequently maintaining the moisture level in the root zone and improving the microbial activities [35,36]. According to the cited literature, there is no information about the effect of superabsorbent polymers (SAPs) on the seed germination of both barley and fenugreek crops. Thus, the objective of the present study was to investigate their seed germination under a high application rate of SAPs in sand soil.
2. Materials and Methods

Prior to the initiation of the experiment, unaged (2 years old) barley (*Hordeum vulgare* L.) and fenugreek (*Trigonella foenum-graecum* L.) seeds used in the present study were screened for germination capability. In [37], it has been stated that 1-year-old air-dried barley seeds generally retain 92.6 ± 0.7% germination capability after storage at room temperature. In the report [38], the germination of fenugreek seeds was not significantly influenced by seed age.

Two outdoor pots experiments were conducted at the Faculty of Agriculture Farm, Aswan Governorate, Egypt, in the 2022 season to determine the effect of superabsorbent polymer (SAP) on the germination of barley (*Hordeum vulgare* L.) and fenugreek seeds (*Trigonell foenum-graecum*). The experiments were laid out using three levels of SAP, known as sodium polyacrylate (0%, 0.5%, and 1.0% w/w base), with three replicates for each level. Different amounts of SAP were mixed with air-dried sand soil to attain the stated levels of SAP. A total of 3.0 kg of SAP–soil mixture was packed into plastic pots (diameter ≈ 19.5 cm, height ≈ 18.5 cm). The mixture was filled in the pot to a depth of 6 cm. The study was carried out on 3 December 2022. The recommended fertilizer doses of NPK for each crop were dissolved in 600 mL of tap water. The pots were initially irrigated using the 600 mL solution, which gave a moisture content of 20% mass base. The NPK dose for barley was 3, 3, and 1 g fertilizer kg⁻¹ soil using mono-superphosphate, K sulfate, and urea, respectively. The corresponding doses for fenugreek were 2, 5, and 1 g fertilizer kg⁻¹. To avoid heating stress on the seeds, the uncovered pots were buried using a soil pin, while the soil surface inside the pots was almost identical to the soil surface of the open field. Additionally, to maintain adequate soil moisture for seed imbibition of water, some tap water was periodically added to each pot (Table 1) according to [39,40], until achieving final seed germination.

![Table 1. The amount of applied water and its time of application for both seed species during germination.](image)

<table>
<thead>
<tr>
<th>SAP (0.0%)</th>
<th>SAP (0.5%)</th>
<th>SAP (1.0%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>* TFG ** AW TBG AW * TFG ** AW TBG AW * TFG ** AW TBG AW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>day cm</td>
<td>day cm</td>
<td>day cm</td>
</tr>
<tr>
<td>0 2.01 0 2.01 0 2.01</td>
<td>0 2.01 0 2.01 0 2.01</td>
<td>0 2.01 0 2.01</td>
</tr>
<tr>
<td>7 0.68 7 0.68 7 0.58</td>
<td>6 0.58 7 0.68 6 0.58</td>
<td>→ →  → →  → →  → →</td>
</tr>
<tr>
<td>10 0.71 10 0.71 8 0.24</td>
<td>→ →  → →  → →  → →  → →</td>
<td>→ →  → →  → →  → →</td>
</tr>
<tr>
<td>14 0.22 15 0.27 → →  → →  → →  → →  → →  → →</td>
<td>→ →  → →  → →  → →  → →</td>
<td></td>
</tr>
</tbody>
</table>

* * TFG and TBG indicate the time of fenugreek and barley germination, respectively, ** AW and AW represent the amount of added water for fenugreek and barley, respectively, and SAP = superabsorbent polymer.

The Romanenko’s model used is as follows:

\[
ET = 0.0018(25 + Ta) \times (100 - hm)
\]

where ET is the evaporation rate from water (mm/month), Ta is the air temperature in C, and hm is relative humidity (%).

2.1. Experimental Soils

2.1.1. Soil Characteristics

A sand soil (Typic Torriorthent) at a depth of 0–30 cm was collected from the experimental fields of the Faculty of Agriculture Farm, Aswan Government (latitude 24°05′20″ N and longitude 032°53′59″ E), Egypt. Aswan’s climate is characterized by dry and hot summers and cool–wet winters. Climatic data are presented as averages in Table 2.
Table 2. Climatic data of Aswan district, Egypt.

<table>
<thead>
<tr>
<th>Month</th>
<th>ANT (°C)</th>
<th>ADT (%)</th>
<th>ARH (%)</th>
<th>AWS (m s⁻¹)</th>
<th>AP (mm·day⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>November</td>
<td>9.07</td>
<td>30.54</td>
<td>40.63</td>
<td>2.96</td>
<td>0.00</td>
</tr>
<tr>
<td>December</td>
<td>6.18</td>
<td>27.93</td>
<td>42.97</td>
<td>2.67</td>
<td>0.00</td>
</tr>
<tr>
<td>January</td>
<td>3.13</td>
<td>27.25</td>
<td>44.78</td>
<td>3.01</td>
<td>0.00</td>
</tr>
<tr>
<td>February</td>
<td>2.57</td>
<td>28.33</td>
<td>39.47</td>
<td>3.36</td>
<td>0.00</td>
</tr>
</tbody>
</table>

ANT = average night temperature, ADT = average day temperature, ARH = average relative humidity, AWS = average wind speed, AP = average precipitation. Source: https://power.larc.nasa.gov/index.php (accessed on 22 August 2022).

The soil samples collected were air-dried, crushed, and sieved (2 mm) before analysis. Subsamples of the air-dried soil were used to evaluate some chemical and physical parameters. All chemical properties were subsequently measured in a soil paste. The soil reactivity (soil pH) and electrical conductivity (ECe), as well as the contents of soluble Ca²⁺, Mg²⁺, CO₃²⁻, HCO₃⁻, Cl⁻, Na⁺, and K⁺, were measured in soil paste as described by [41]. Using the hydrometer method according to [42], the particle size distribution was determined. In addition, the soil particle distribution was used to calculate some moisture constants (Table 3), as described by [43]. The water capacity of SAP was measured as described by [18]. The main properties of the soil and SAP are shown in Table 3.

Table 3. Some chemical and physical properties of the tested soil and SAP.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>----</td>
<td>7.73</td>
</tr>
<tr>
<td>EC</td>
<td>dS·m⁻¹</td>
<td>1.097</td>
</tr>
<tr>
<td>Total CaCO₃</td>
<td>%</td>
<td>2.63</td>
</tr>
<tr>
<td>Sand</td>
<td>%</td>
<td>93.2</td>
</tr>
<tr>
<td>Silt</td>
<td>%</td>
<td>2.5</td>
</tr>
<tr>
<td>Clay</td>
<td>%</td>
<td>4.3</td>
</tr>
<tr>
<td>Texture</td>
<td>----</td>
<td>Sand</td>
</tr>
<tr>
<td>SC</td>
<td>m³/m³</td>
<td>0.35</td>
</tr>
<tr>
<td>FC</td>
<td>m³/m³</td>
<td>0.12</td>
</tr>
<tr>
<td>WP</td>
<td>m³/m³</td>
<td>0.05</td>
</tr>
<tr>
<td>Ca²⁺</td>
<td>meqL⁻¹</td>
<td>6.00</td>
</tr>
<tr>
<td>Mg²⁺</td>
<td>meqL⁻¹</td>
<td>2.33</td>
</tr>
<tr>
<td>K⁺</td>
<td>meqL⁻¹</td>
<td>0.86</td>
</tr>
<tr>
<td>Na⁺</td>
<td>meqL⁻¹</td>
<td>1.78</td>
</tr>
<tr>
<td>CO₃²⁻</td>
<td>meqL⁻¹</td>
<td>0.00</td>
</tr>
<tr>
<td>HCO₃⁻</td>
<td>meqL⁻¹</td>
<td>3.33</td>
</tr>
<tr>
<td>Cl⁻</td>
<td>meqL⁻¹</td>
<td>3.00</td>
</tr>
<tr>
<td>SO₄⁻</td>
<td>meqL⁻¹</td>
<td>4.64</td>
</tr>
<tr>
<td>Saturation capacity of SAP</td>
<td>g water/g SAP</td>
<td>231.5</td>
</tr>
</tbody>
</table>

pH = soil reactive, EC = electrical conductivity, SC, FC, and WP indicate saturation capacity, field capacity, and wilting point, respectively.

2.1.2. Seed Germination

Initially, the sand soil was moistened as shown in Table 1, using NPK solution. Ten seeds from each crop were sown in each pot at a 2 cm depth on 3 December 2022. A fungicide was used to sterilize the soil. Shoot emergence was monitored daily. The below-described germination parameters were calculated.

Final Germination Percentage (FGP)

According to AOSA [44], the final germination percentage (FGP) was calculated by dividing the final number of germinated seeds sown in each pot by the total number of sown seeds, multiplied by 100 as follows:
FGP % = \frac{N_f}{N_i} \times 100, \quad (1)

where \( N_f \) and \( N_i \) are the final germinated seeds and initial seeds, respectively.

Germination Index (GI)

As described by AOSA [44], the GI (germination index) was calculated as follows:

\[
GI = \frac{\text{number of germinated seeds in the first count/days of first count}}{\text{days of first count}} + \ldots + \frac{\text{number of germinated seeds in the final count/days of final count}}{\text{days of final count}}. \quad (2)
\]

However, in calculating the germination index (GI), maximum weight is given to the seeds germinated on the first day, with less given to those germinated later. The lowest weight was given to seeds germinated on the 16th day. Therefore, the GI emphasizes both the percentage of germination and its speed [45]. A higher GI value denotes a higher percentage and rate of germination.

Germination Characterization

Germination or emergence percentage data were subjected to nonlinear regression analysis. Germination percentages (GP, %) at different times were fitted to a functional three-parameter logistic model [46]. The fitting sigmoidal function was as follows:

\[
GP(x) = a \frac{1 + \exp\left(-\frac{x-x_0}{b}\right)}{1 + \exp\left(-\frac{x-x_0}{b}\right)}, \quad (3)
\]

where GP is the germination percentage (%) at time \( x \) (day), and \( a, b, \) and \( x_0 \) are fitting constants. The first derivative of the equation indicates the slope of the sigmoidal function. The following equation was used for calculating the slope (the germination rate was as a function of time):

\[
\frac{\partial GP}{\partial x} = \frac{a}{b} \left(\frac{\exp\left(-\frac{(x-x_0)}{b}\right)}{1 + \exp\left(-\frac{(x-x_0)}{b}\right)}\right)^2 \quad (4)
\]

The Water Germination Efficiency (WGE)

The WGE is a newly suggested means for evaluating the SAP impact on boosting germination. This term can be calculated from the final germination percentage (FGP %) and total amount of water (cm) used to give the final germination (Table 1) as follows:

\[
\text{WGE} = \frac{\text{FGP} \text{ (%)}}{\text{amount of water (cm)}} \quad (5)
\]

2.2. Statistical Analysis

Data of the final emergence percentage, germination index, germination percentage as a function of time, and germination rate were statistically analyzed using Equations (1)–(4), respectively. The analysis of variance (ANOVA) of some parameters was calculated using the Co-Stat computer package (version 6.45). Least significant differences (LSDs) between the means were obtained as described in [47].

3. Results

The final germination percentage (FGP) and germination index (GI) for barley and fenugreek seeds as a function of SAP percentage are presented in Table 4. The FGP's for barley seeds were 97.67%, 86.67%, and 86.67% for the 0.0%, 0.5%, and 1.0% SAPs, respectively. The corresponding values for the fenugreek were 76.67%, 86.67%, and 80%. The FGP's value differed between the two plant seeds as a function of the SAP levels. However, the differences among the SAP levels in these traits were not significant. Generally, the FGP's for barley were greater than those for fenugreek. The GI index is a better parameter than FGP because the former combines the speed of germination and the final germination conditions. The GIs for the barley seeds were 0.93, 2.47, and 2.01 day\(^{-1}\) for the 0.0%, 0.5%,


and 1.0% SAPs, respectively. The corresponding GIs for the fenugreek were 1.11, 2.66, and 2.46 day\(^{-1}\). It is clear that the SAP enhanced the germination speed of seeds for both plants. The speed of germination was slightly faster for the barley seed. The differences in GI among the SAP levels were significant in comparison to the 0% SAP levels for both plant seeds. The differences in GI values between the 0.5% and 1.0% SAP levels were nonsignificant for both seeds. The addition of SAP boosted the speed of germination, as indicated by the values of GI. The times of final germination for barley seeds were 16, 6, and 6 days for the 0.0%, 0.5%, and 1.0% SAPs, respectively. The corresponding times for fenugreek seeds were 14, 8, and 7 days for complete germination.

### Table 4. The final germination percentage (FGP) and germination index (GI) for barley and fenugreek.

<table>
<thead>
<tr>
<th>Levels of SAP (%)</th>
<th>Barley</th>
<th>Fenugreek</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FGP %</td>
<td>GI (Day(^{-1}))</td>
</tr>
<tr>
<td>0.0</td>
<td>96.67</td>
<td>0.93</td>
</tr>
<tr>
<td>0.5</td>
<td>86.67</td>
<td>2.47</td>
</tr>
<tr>
<td>1.0</td>
<td>86.67</td>
<td>2.01</td>
</tr>
<tr>
<td>LSD (0.05)</td>
<td>ns</td>
<td>0.76</td>
</tr>
</tbody>
</table>

The germination characterization of barley and fenugreek seeds was described using a sigmoidal function (Equation (3)). Figure 1a presents the germination percentage of barley seeds as a function of time and SAP percentage. The observed data were described well for all levels of SAP using the sigmoidal model. The determination coefficients (\(R^2\)) were 0.986, 0.995, and 0.997 for 0.0, 0.05, and 1.0% SAP, respectively. The germination processes at 0.0% SAP extended the duration of germination by 16 days for barley seeds.

![Figure 1a: Germination percentages of barley as a function of time and SAP %](image1)

![Figure 1b: Germination percentages of fenugreek as a function of time and SAP %](image2)

**Figure 1.** Germination percentages of barley (a) and fenugreek (b) as a function of time and SAP %.
The addition of SAPs at 0.5% or 1.0% greatly reduced the period of germination to approximately one-third the value at 0.0% SAP. Similarly, Figure 1b presents the germination percentage of fenugreek as a function of time and SAP percentage. The germination data were described using Equation (3). The determination coefficients ($R^2$) were 0.992, 0.998, and 0.997 for 0.0%, 0.05%, and 1.0% SAP, respectively. The germination processes at 0.0% SAP extended the duration of germination by 14 days. For the SAP levels of 0.5% and 1.0%, the periods of germination were 8 and 7 days, respectively. It is obvious that 0.0% SAP provided the greatest FGP in barley in comparison to the other SAP levels. The SAP might release the water to the seed slowly, which reduces the FGP in SAP-treated soils. However, the FGP in barley seeds was not significant among the three SAP levels. The corresponding values for the fenugreek were 76.67%, 86.67%, and 80%. The differences among the SAP levels were not significant, as in the barley seeds as well.

Figure 2a shows the calculated germination rates for barley as a function of time and the SAP percentage using Equation (4). The values of the germination rates differed greatly among the three levels of SAP. All rates behaved similarly in terms of their trends over time, showing a peak followed by a decline. However, the treatments of 0.5% and 1.0% SAP gave the highest and fastest change rates at the peaks. The maximum germination rates of barley seed were 68% and 66.5% per day for both levels of 0.05% and 1.0% SAP, respectively. The maximum germination rate was 18% per day for the zero SAP level. The time to reach maximum germination rates was 11, 5, and 4 days for SAPs of 0.0%, 0.5%, and 1.0%, respectively. It is worth noting that the SAP greatly accelerated the germination process.

![Figure 2a](image-url)

**Figure 2a.** Calculated germination rate of barley as a function of time and the SAP percentage using Equation (4).

![Figure 2b](image-url)

**Figure 2b.** Calculated germination rate of fenugreek as a function of time and the SAP percentage using Equation (4).

Table 5 shows some germination parameters calculated using Equation (3) as a function of time and SAP percentage for both kinds of seeds. These parameters include time of 50% germination ($T_{50}$), maximum germination time ($T_{max}$), and WGE. The $T_{50}$ values were 11.0, 3.0, and 3.6 days for 0.0%, 0.5%, and 1.0% SAP, respectively, for barley seeds. The corresponding maximum germination times for fenugreek seeds were 16, 6, and 6 days. Generally, the greatest values for the germination parameters ($T_{50}$ and $T_{max}$) were obtained with the untreated SAP soil, while the 0.5% and 1.0% SAPs gave the lowest values. The germination parameters of fenugreek behaved similarly to those of barley, but the $T_{50}$ values were lower. Therefore, the speed of fenugreek seed germination was high in comparison to the barley seeds for all SAP levels. The results of $T_{50}$ are in agreement with the observed trends.
The germination rate of fenugreek seeds behaved similarly to that of barley seeds (Figure 2b). Actually, the differences in the values of the germination rates were greatly pronounced among the three levels of SAP, similar to the barley seeds. They showed an increase over time to a peak, followed by a decline. The 0.5% and 1.0% SAP treatments gave the highest change rates at the peaks. The germination rates of seeds were 8.45%, 63.38%, and 55.38% per day for the levels of 0.0%, 0.05%, and 1.0% SAP, respectively. The time to reach maximum germination rates was 9.5, 2.8, and 3.0 days for SAPs of 0.0%, 0.5%, and 1.0%, respectively. It is worth noting that SAP greatly boosted the germination process. It can be concluded that the SAP is a promising solution for enhancing germination and ameliorating water scarcity.

Table 5 shows some germination parameters calculated using Equation (3) as a function of time and SAP percentage for both kinds of seeds. These parameters include time of 50% germination (T\text{50}), maximum germination time (T\text{max}), and WGE. The T\text{50} values were 11.0, 3.0, and 3.6 days for 0.0%, 0.5%, and 1.0% SAP, respectively, for barley seeds. The corresponding maximum germination times for fenugreek seeds were 16, 6, and 6 days. Generally, the greatest values for the germination parameters (T\text{50} and T\text{max}) were obtained with the untreated SAP soil, while the 0.5% and 1.0% SAPs gave the lowest values. The germination parameters of fenugreek behaved similarly to those of barley, but the T\text{50} values were lower. Therefore, the speed of fenugreek seed germination was high in comparison to the barley seeds for all SAP levels. The results of T\text{50} are in agreement with the germination index shown in Table 4. The WGE represents the germination efficiency as a function of the total amount of water used to obtain the maximum germination percentages. The WGE values of barley seeds were 27.76, 30.04, and 31.49 cm\textsuperscript{-1} for the 0.0%, 0.5%, and 1.0% SAPs, respectively. The corresponding values of WGE for fenugreek were 23.07, 29.9, and 28.13 cm\textsuperscript{-1}. There were small variations in WGE between the seeds of the two plants.

4. Discussion

There are several means to alleviate water stress during the growth stages of a plant. The authors in [48] suggested some means such as microbes, nanoparticle applications, hydrogels (SAPs), and metabolic engineering techniques to alleviate the water stress during the growth stages of a plant. These means enhance the antioxidant enzyme activity for amelioration of drought stress in plants. Table 4 presents the variations in germination percentages and germination indices for barley and fenugreek seeds using a superabsorbent polymer (SAP). Looking at Figure 1, the germination time at 0.5 and 1.0% SAP was equal for barley seeds, while the germination time at 1.0% SAP was less than its value for 0.5% SAP. The germination percentages did not differ significantly because the water availability was enough to protrude the embryo of seeds under the three levels of superabsorbent polymer (SAP). Similar findings were presented by [18]. They reported that the application of hydrogel with rates at 0.1%, 0.2%, and 0.3% (w/w) significantly increased the amount of plant-available water (PAW) for barley and wheat crops grown on sandy loam and loam soils in comparison with the untreated soils. In contrast, the seed germination of these crops was not affected by the gel amendment in both sandy loam and loam soils. In other words, the seeds’ germination is a function
of several abiotic parameters such as soil temperature, soil water contents, and type of seeds. So, any factor such as SAP leads to an increase in the available soil water content and can boost the seeds’ germination percentages. In the present study, the germination indices (GIs) differed markedly for both plant seeds, because this index combines the percentage and speed of germination. These differences in GIs can mainly be explained by soil physical and seed coat chemical properties. The soil’s physical properties include water availability, which is increased by SAP, and unsaturated hydraulic conductivity. Both properties enhance water transfer toward plant seeds, thus enhancing seed germination activity. The SAP treatment primarily provided the soil with a high rate of water, which spurred the cotyledon protrusion of seeds. For example, the GI values of barley seeds were 0.93 and 2.47 day$^{-1}$ for 0.0% and 0.5% SAP, respectively. The corresponding values for fenugreek were 1.11 and 2.66 day$^{-1}$. Therefore, the seed water uptake rate is one of the essential requirements in the germination process. In their studies, the authors in [49,50] indicated that their addition rates are controlled by three main factors: (a) seed composition, (b) water availability in the medium, and (c) seed coat water-permeable properties. In addition, germination involves the absorption and movement of large volumes of water and aquaporins (AQPs), which form water tubes in the membranes and improve intra-and intercellular water transport, thus playing a pivotal role in the germination process. The cotyledon protrudes earlier in SAP-treated than untreated soil. The reduction in the time of protrusion is due to the high soil water-holding capacity caused by the SAP.

The seed germination behavior of barley and fenugreek was also evaluated using a sigmoidal function. Thus, several parameters were calculated, such as germination rate, time of 50% germination ($T_{50}$), time of maximum germination ($T_{max}$), and water germination efficiency (WGE). All parameter values for both seed species were favorable in the SAP-treated sand soil in comparison to the untreated soil, as presented in Table 4. The differences in the germination rates of both plant seeds might be due to their imbibition rates of water [51–53]. For example, Hadas [51] revealed that the water rate uptake and the total volume absorbed rely greatly upon the seed and soil characteristics with respect to water (the water potential differences between the seed and the soil) and are controlled by the water conductivity of the soil and the soil–seed contact zone. Furthermore, water is a milieu for all metabolic processes, being a universal solvent of gases (oxygen, carbon dioxide, and ethylene) and other metabolites, as well as their transport pathway [52]. Generally, water is imbibed through the membranes of seeds to activate the process of seed germination. For example, water is transported through orthodox and recalcitrant seeds during germination mechanisms [52]. The authors stated that the embryonic axes of orthodox cells that remain viable in a dry state must absorb water to a hydration level of 60% in order to activate metabolism and begin the cell’s preparation for germination. These findings were confirmed in a very recent study conducted by [53]. The same authors stated that the germination of groundnut and pulses showed poor germination under water-deficit moisture conditions, indicating a positive correlation with soil moisture. In another investigation, the authors in [54] measured the soil water potential limits for rapid, adequate, and marginal germination of winter wheat. Laboratory data showed that germination was rapid (3–4 days) in soil at water potentials above $-1.1$ MPa but slower (4–5 days) at water potentials ranging from $-1.1$ to $-1.6$ MPa.

5. Conclusions

The water availability of SAP-treated soil enhanced the seed’s water imbibition and, thus, cotyledon protrusion. Generally, the uptake of water is controlled by the total water potential gradient through the seed components and soil, as well as the properties of seeds and soil, i.e., conductivity. According to the results of this study, SAP is a promising solution for boosting the germination of barley and fenugreek seeds under water-scarce conditions. The final germination for barley seeds was higher than for fenugreek seeds. Therefore, it can be concluded that barley is preferred as a strategic crop over fenugreek when using SAPs in sandy loam soils in a semiarid region. In a future study on the management of seed
germination, using a wide range of low SAP percentages might be helpful for minimizing the negative effects of soil surface crusting that can be caused by high SAP percentages.


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