Experimental Assessment of the Use of a Novel Superabsorbent polymer (SAP) for the Optimization ofWater Consumption in Agricultural Irrigation Process

Abstract: In this work, an innovative cellulose-based superabsorbent polymer (SAP) was experimentally assessed as an environmentally friendly alternative to acrylate-based SAPs, for the optimization of water consumption in agriculture. The cellulose-based SAP was synthesized and tested for its swelling capability in different aqueous media. The effectiveness of the SAP in agricultural applications was then evaluated by analyzing its performance after several absorption/desorption cycles, over a period of approximately 80 days, upon addition to different types of soil, i.e., white and red soil, for the cultivation of two varieties of plants typical of the Mediterranean area (tomatoes and chicory). The results confirmed that SAP-amended soil can store a considerable amount of water and can release it gradually to the plant roots when needed. The adoption of the proposed SAP in cultivations could thus represent a promising solution for the rationalization of water resources, especially in desert areas.
Keywords: agriculture; hydrogel; irrigation optimization; superabsorbent polymer; water management
Water 2014, 6 2057

1. Introduction

The optimization of the use of water resources is strategic for the long-term competitiveness of the agricultural industry. Indeed, water shortage has become a serious issue, especially in those areas (such as some areas of the Mediterranean Basin) that are exposed to the progressive desertification. On the other hand, in coastal areas, saltwater intrusion (i.e., the movement of saline water into freshwater aquifers [1]), may lead to an increase of the salinity of water, thus making it unusable for irrigation.
Water management is considered one of the major challenges of the near future [2]; in fact, by 2030, water demand is expected to be 50% higher than today, and withdrawals could exceed natural renewal by over 60%, resulting in water scarcity [3].
In such a context, it is apparent the importance to develop innovative agricultural systems and to

promote technologies that could optimize the exploitation of water resources; nonetheless, it is crucial to guarantee that the appropriate amount of water is timely and efficiently delivered to the plants.
As reported in the related literature, a number of solutions to this problem are being considered [4].
For example, prediction models for irrigation are constantly being developed for facing the needs for short- and long-term water resource management [5]. Moreover, Ines et al. [6] combined remote sensing-simulation modeling and genetic algorithm optimization to explore water management options in irrigated agriculture. Indeed, the severity of the subject has motivated constant interest in individuating effective technological and management solutions for water irrigation optimization [7–10].
Another approach to the optimization of water consumption is the use of superabsorbent polymers (SAPs) [11]. SAPs can absorb and retain extremely large amounts of a liquid (water or an organic liquid) relative to their own mass [12].
In agricultural applications, SAP granules are mixed with the soil in given amounts. After watering, the granules absorb the water by swelling, and then release it slowly through a diffusive mechanism, as the soil gets dry. In this way, irrigated water is not lost through drainage or evaporation while being efficiently supplied to the plant roots when needed. Furthermore, SAP granules increase their size upon swelling, thus enhacing soil porosity and providing a better oxygenation to the roots. A further advantage of SAPs in agriculture is that they can be loaded with nutritional substances and phytopharmaceuticals, which are then gradually released to the plants.

Therefore, employing SAP in cultivations would help not only in minimizing water consumption, but also in rationalizing the use of phytopharmaceuticals, especially in the following agricultural systems:

(A) Protected cultivations: these cultivations are characterized by great intensity and high specialization of the soil, which ultimately leads to the deterioration of the essential nutrients of the soil, to the accumulation of telluric pathogens and to secondary salinization due to the excessive use of fertilizers and/or brackish water. In this context, not only would the adoption of SAP rationalize the amount of used water, but it would also allow modulating (in time) the supply of nutrients, thus avoiding the accumulation of toxic substances in the soil;
(B) Soilless cultivations: in soilless cultivations, plants are grown using mineral nutrient solutions in water, without soil [13]. In open soilless systems, there is a massive waste of water and nutrients, which is responsible for an increase in running costs and in contamination of ground and surface

water [14]. The adoption of the SAP to ration the delivery of nutrients to the plants would improve the overall environmental sustainability of these systems. Also for closed systems (in which water recirculates), the use of SAP may help hindering water retention of the plants;
(C) Open-field cultivations: in agriculture, chemically synthesized fertilizers are commonly supplied in larger quantity than actually needed by the plants. Nitrate accumulation in the soil, especially in dry areas, is a typical result of such an excessive use of fertilizers, with negative repercussions on the environment as well as on the product quality, with nitrates being absorbed by the plants and fruit. The presence of nitrates decreases the nutritional quality of the product (especially for leaf vegetables), and increases the risk of developing cancers [15]. The use of certain SAP formulations could allow reducing the amount of fertilizers used and/or limiting nitrate accumulation in the soil.

Pioneering experiments carried out by a Japanese company in the Egyptian desert, in the early 1990s, demonstrated the potential of synthetic SAPs for water management in agricultural applications [16]. Similarly, Woodhouse and Johnson [17] used synthetic SAPs as soil conditioners to aid plant establishment and growth in drought-prone growing media. The most efficient and most widely employed SAPs are based on polyacrylates, i.e., non renewable materials derived from petroleum industry that are reported to degrade at rates less than 10% per year, via delamination, shear-induced chain scission and photosensitive chain scission [18]. Because of their very low degradation rate, acrylic SAPs are regarded as potential pollutants for the soil. Moreover, there are also some concerns regarding the release of toxic molecules during their slow degradation. As a result, in the last decade, the increasing interest in environmental issues has led manufacturers and researchers to focus on the development of alternative, environmentally friendly SAPs. Examples of investigated biopolymers for the synthesis of SAPs include cellulose derivatives [19] and starch [20], which can be degraded by soil microbes [19,21]. In this work, an innovative SAP, obtained through chemical crosslinking of cellulose derivatives, was synthesized, based on the results of previous studies [22–30], and its water retaining capability was assessed with a specific focus on agricultural applications. The goal of this work was to characterize, from an operative point of view, the beneficial effect of the use of the novel SAP in combination with different types of soils, for the cultivation of plants typical of the Mediterranean area. To this purpose, preliminary experiments were carried out to evaluate the absorption capacity of the SAP. Successively, for assessing the efficiency of the SAP after several water absorption/desorption cycles in the soil, the SAP was tested (in different concentrations and at different depths in the soil) for the cultivation of plants inside pots. Finally, the SAP was employed in conditions that mimicked open-field cultivations, in order to analyze its effect on the growth of plants.

2. Materials and Methods

In order to test the suitability of the cellulose-based SAP for use in agricultural applications, the following experiments were carried out:

(i) Characterization of the absorption capacity of the SAP in both distilled and tap water;

(ii) Evaluation of the effect of the SAP when placed in different types of soil and at different depths, through experiments performed in plant pots; and

(iii) Evaluation of the effect of the SAP in conditions that resembled open-field cultivations.

2.1. Synthesis of Cellulose-Based SAP

For the synthesis of the SAP, cellulose derivatives meeting food and pharmaceutical standards were used. In particular, Carboxymethylcellulose sodium salt (CMCNa) and hydroxyethylcellulose (HEC) were the precursors adopted for the hydrogel synthesis. The detailed description of the synthesis process of the used SAP, which is based on the results obtained in previous works [23–30], can be found in [22]. The final powder size distribution of the SAP was in the range 0.1–1 mm. Cytotoxicity tests performed in previous studies showed that the SAP does not exhibit any toxicity [31].

2.2. Preliminary Characterization of the Absorption Capacity of the SAP

For the intended application, it is important to study and characterize the absorption characteristics of the material in water and in saline solutions with different ionic strenghts, thus simulating the actual conditions in which the SAP is used (namely, in contact with nutrients, fertilizers, and soil).

A preliminary experiment was conducted to assess the absorption capacity per gram of the used SAP. To this purpose, two samples of SAP weighing approximately 1 g were added with 100 g of water (W_{add}) each. After 24 h, during which the SAP had reached water saturation, each sample was passed through a membrane filter. This allowed to separate the excess water (i.e., the water that had not been absorbed), whose weight ($W_{not-abs}$) was measured through a precision electronic balance. The weight of the water absorbed by the SAP (W_{abs}) was then evaluated as W_{add}-$W_{not-abs}$.

A second experiment was performed to evaluate the effect of the environmental electrical conductivity on the swelling properties of the SAP. Indeed, due to the polyelectrolyte nature of CMCNa, the absorption capacity of the SAP strongly depends on the dissolved salts that are present in the solvent: the higher the amount of salts, the lower the absorption capacity. This aspect is crucial for agriculture-related applications. Generally, the electrical conductivity of dry soils is almost negligible. However, the value of electrical conductivity increases with the water content in the soil, due to the progressive dissolution of salts. Furthermore, it is necessary to take into account the electrical conductivity of water itself and of fertilizers that are typically used in agriculture [32]. In this work, comparative absorption tests were carried out by mixing 4 g of SAP with both distilled and tap water. The electrical conductivity of tap water was 1000 _S/cm, as measured through a conductivity meter (model HI 9811-5). Every 24 h for seven days, the excess water was removed from the samples and weighed, as described above. This allowed to assess not only the initial amount of water absorbed by each sample, but also the decrease of water-saturation (s_{SAP}) in time.

3. Experimental Results

3.1. Absorption Capacity of the SAP

The swelling tests in distilled water showed that the cellulose-based SAP can absorb water up to 74 times its own weight (Table 2). This value, which is comparable with those reported for other biopolymer- [19] and acrylic-based [33] SAPs , is clearly appealing for the intended application.

Table 2. Summarized results of the experiment for assessing the absorption capacity of the SAP.

Sample	SAP (g)	W_{add}(g)	$W_{not-abs}$ (g)	W_{abs} (g)
#1	1.01	100.04	25.40	74.64
#2	1.00	100.06	25.30	74.76

The second swelling experiment performed in this study focused on the effect of environmental electrical conductivity on the absorption capacity of the SAP as well as on the subsequent water loss kinetics from the hydrogel. In particular, a comparison was made between a sample of SAP saturated with tap water and another sample saturated with distilled water. Starting from the water-saturated condition, the desaturation of the SAP was then monitored for seven days by weighing the amount of water that was released daily. While the absorption of the SAP in distilled water was about 74 g water/g SAP, as reported above, the absorption in tap water was about 40 g water/g SAP, which fits in the range of the typical absorption capabilities of SAPs in saline media (30–60 g water/g SAP) [32]. Furthermore, as shown in Figure 3, in the first 4 days the desaturation behavior was similar for the two samples, independently of the type of water used. However, starting from the 5th day of observation, the percentage of water released by the SAP saturated with tap water was lower than that released by the SAP saturated with distilled water. This may be an indicator of the fact that, although the SAP absorbs a lower amount of water when it is in an electrically conductive-solvent (such as tap water), its water retaining capability is higher, likely due to the presence of fixed electrostatic charges on the polymer network which contribute favourably to the overall interaction between the solvent and the SAP. This finding thus further suggests the potential of the SAP for agricultural applications.

Figure 3. Water desaturation of the two samples of SAP mixed with distilled water and with tap water, in the seven-day observation period.

1 2 3 4 5 6 7
80.0
82.5
85.0
87.5
90.0
92.5
95.0
97.5
100.0

xSAP (%)
day of observation
tap water
distilled water