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Review

Applications of Absorbent Polymers for Sustainable Plant Protection and Crop Yield

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Abstract: Natural strategies for protecting the environment as well as plant, animal and human health is considered one of the main goals of developed countries. Recently, the use of absorbent polymers and hydrogel in agriculture has demonstrated several benefits for soil amendments, saving water content, reducing the consumption of soil nutrients, minimizing the negative impacts of dehydration and moisture stress in crops and controlling several phytopathogens. The seed-coating technology for establishing the crops is a recent common practice used for improving seed protection and enhancing plant growth. Coating materials include absorbent polymers and hydrogels based on growth regulators, pesticides, fertilizers and antagonist microorganisms. The current review has highlighted the importance of different types of superabsorbent polymers and hydrogels in an integrated strategy to protect seeds, plants and soil in a balanced manner to preserve the ecosystem.

Keywords: biological control; sustainable production; phytopathogens; hydrogel; environmental protection

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1. Introduction

Recently, due to the growing world population, there is a necessity for increasing crop production [1]. Traditional agriculture in different countries, especially the developing ones, depends on mineral fertilizers and chemical/synthetic pesticides, which have several side effects on human, animal and plant health [2]. Hence, there is a need to introduce innovative strategies, such as crop rotation, new plant varieties and vertical increase of crop/land productivity, for raising crop yield without the use of pesticides and other conventional chemical substances.

In the same context, the increase of global population leads to the search for innovative solutions to increase crop production through vertical farming approaches as well as maximizing the crop/land productivity in order to provide a greater crop yield per square meter of land [3]. However, the erosion of surrounding areas, global warming, increase in urbanization and desertification phenomenon lead to the loss of agricultural lands [4,5]. For these reasons, there has become an urgent necessity to find innovative ways to increase agricultural production, as well as to protect plants and soil from diseases that may affect crops and reduce the productivity of the land in a related and parallel way.

In a similar way, it is worth noting the urgent importance of introducing appropriate agricultural management that would reduce water consumption by improving the soil's ability to retain water, increase the efficiency of the use of agrochemicals and effectively control several phytopathogens [6]. The use of absorbent polymers, especially the superabsorbent ones, has several benefits, such as conservation of water, lowering surface runoff, avoiding soil erosion and improving the performance of different soil fertilizers [7]. The protection of seeds and their main biochemical properties can positively enhance plant performance and make them more resistant towards more unfavorable surrounding conditions, such as climatic changes and severe phytopathogens. For those reasons, the seed-coating technique is one of the most interesting and recent strategies for achieving the above goals by using natural agents, such as fertilizers, hydrophilic substances, growth regulators, plant essential oils, microorganisms and biopesticides in different adhesive substances like absorbent polymers and hydrogels [8].

2. Superabsorbent Polymers

Superabsorbent polymers (SAPs) can also be identified as absorbent polymers, absorbent gels, water gels or hydrogels [9]. They are synthetic macromolecular materials having a water-hyper accumulation capacity of up to 100% of their own weights through osmosis property [9]. In addition, SAPs are used mainly to improve soil properties, and they are composed generally of sugar-like hygroscopic materials, which transform into a transparent gel when added to water [9].

2.1. Soil Amendments

The application of suitable soil conditioners to enhance soil properties has become a progressively common solution [10]. SAPs are characterized by hydrophilic, three-dimensional and crosslinked functional polymers [6,11,12], which enable them to hyper-accumulate the excess volumes of water in the soil a hundred times their own weight [13–15].

The application of absorbent polymers in agriculture is very important because they can absorb water and make it available to plants over time [16]. Recently, SAPs have been used in agriculture as soil additives for their amendments in order to save water loss and nutrients in the soil and minimize the negative impact of dehydration and moisture stress in crops [17,18].

Particularly, there are several advantages of using SAPs in the soil, such as (i) it can absorb and keep the water hundreds of times more than its own weight and become similar to long-lasting gels [15]; (ii) it can also protect the soil from runoff reduction; (iii) it can further improve the performance of different soil fertilizers [7] and (iv) finally it can enhance the activities of soil microorganisms [18,19].

Barakat et al. [20] reported that the problems associated with conventional irrigation techniques could be avoided by the application of some polymers. There are several recent studies, which reported the importance of using some SAPs in order to help in absorbing and retaining water. Consequently, SAPs can prevent/reduce water loss by percolation and act as a water reservoir in the root zone [6,15,21].

There are some other basic points concerning the importance of using SAPs for improving the performance of soil fertilizers and also to enhance the activities of soil microorganisms. The application of SAPs can alter the physicochemical properties of soil as well as improving the fertilizer-retaining capacity [22,23]. Other studies have focused on the potential effect of SAPs in saving soil water content, conserving fertilizers and reducing their losses [22,24]. At the same time, the use of SAPs plays an essential role in enhancing soil microbial community [25,26].

A recent study was conducted by Yin et al. [27] to investigate the biological effect of an innovative SAP, poly-γ-glutamic acid, for maize growth and enhancing beneficial soil microorganisms. In that study, the utilization of this biological polymer proved that it could improve soil saving water, increase maize seedling growth and enhance the relative abundance of plant growth-promoting bacteria, such as *Bacillus*, *Pseudomonas* and *Burkholderia* [27].

2.2. Plant Growth

The application of some absorbent polymers has significantly increased the yield of *Citrus limon* by improving the water holding capacity of the soil, which maintains the soil moisture for a longer period, thus enhancing the microbial activity of the soil and preventing fruit loss [28].

Similarly, Pieve et al. [29] studied the effect of polymers on plant growth of coffee plants in the open field and found that the application of polymer solution at the time of new planting can reduce the mortality of coffee plants. The coating with highly absorbent polymers can potentially improve the water availability for the early growth of seeds under dry conditions and, therefore, prevent associated delays in the emergence and reduce crop standing [30–32].

Several studies have also been conducted to evaluate the application of different doses of SAPs to help soil remediation and plant growth and concluded that the use of SAPs, especially in the soil surface of (0–20 cm), has explicated promising effects on soil temperature and increasing photosynthetic rate and crop yield [23,33].

2.3. Challenges of Absorbent Polymers

In addition to the beneficial uses of SAPs in soil amendments, there are some other changes in soil physical properties, such as soil porosity, bulk density and structure [34]. The use of SAPs is often restricted by the water application rate; hence their performance may not properly be determined [6].

There are some disadvantages, especially for the synthetic SAPs; they are not biodegradable substances being nonrenewable materials and possibly toxic [35–38].

Several studies have reported the effect of commercially available SAPs on seed and plant growth where they do not decompose in the environment and their raw materials are nonrenewable [39]. Therefore, the excess use of these polymers in agriculture, either for seed-coating or soil amendments, can lead to a great risk for plant health, soil fertility and environmental pollution [39,40].

3. Hydrogel

A hydrogel is a network of crosslinked hydrophilic polymer chains. Generally, the use of hydrogels in the medical field can absorb body fluids and exchange the substances with the external environment [41]. On the other hand, hydrogels can be used successfully as a carrier in drugs for treating wounds [42]. The use of hydrogels in the agriculture field has several advantages, such as decreasing the requirement for irrigation and increasing the shelf life of containers [43].

Hydrogels can be classified into two main groups according to their physicochemical properties. The first group is a reversible hydrogel, in which the polymer chains are linked by electrostatic forces, hydrogen bonds and hydrophobic interactions [44]. It is characterized by its instability, and it can easily be converted into a polymer mixture by heating, such as gelatin and agar. The second group is chemical-stable hydrogels in which the polymer chains are linked by stable covalent bonds and include starch and vinyl monomers, such as acrylic acid, acrylamide, acrylonitrile and polyvinyl alcohol [44].

In agriculture, the common type of hydrogel is potassium polyacrylate or sodium polyacrylate. Hydrogels could have a promising use, particularly in agriculture, due to their easy decomposition in soil and their renewability compared to other commercial superabsorbent polymers [45]. Hydrogels showed promising results as a soil amendment or for seed-coating. Many studies reported that the use of hydrogels as a soil amendment could improve water and fertilizer retention in soil, improve soil aeration, reduce evapotranspiration, improve seedling emergence and prolong water availability for plants [46–48].

3.1. Hydrogel Applications

There are several conditions that may hinder plant growth and crop yields, such as low water retention capability, high transpiration rate, soil moisture leaching and attack by phytopathogens. Hence, the use of hydrogels in agriculture may have the following benefits: improving soil quality, preserving water, resisting biotic and abiotic drought stress, reducing irrigation frequency and water consumption, decreasing seedling mortality in nurseries and minimizing the overuse of fertilizers and pesticides in fields [46]. Hydrogels have a wide area of applications ranging from agriculture, forestry, industrial planting, municipal gardening, drought management and water conservation [47]. Finally, hydrogels have a positive effect of reducing soil erosion by surface runoffs and fertilizer/pesticide leaching into groundwater [48].

There are few studies, which have reported the biological and agricultural applications of hydrogels. A recent study was conducted by Kalhapure et al. [49] on a new absorbent polymer called "Pusa Hydrogel", developed by the Indian Agricultural Research Institute (New Delhi, India), in order to meet the requirements of increasing productivity. This new hydrogel polymer was prepared based on potassium polyacrylate and showed maximum absorbency at 50 °C, especially in semi-arid and arid soils. This study also concluded that Pusa Hydrogel was able to absorb water up to 400 times its dry weight and could reduce the leaching of herbicides and fertilizers into the soil and improved the physical properties of soil. Regarding plant growth, Pusa Hydrogel was also able to improve seed germination, seedling emergence, root growth and reduce irrigation and fertilization requirements of crops. On the other hand, this new hydrogel did not exhibit any undesirable effects on crops and soil [49].

3.1.1. Soil Amendment

Although research studies on the agricultural and biological benefits of hydrogel applications in seed-coating and soil amendments are scarce, some interesting studies reported the use of many soil amendments based hydrogels to improve the soil retention of water and fertilizers as well as to increase soil aeration and reduce the higher evapotranspiration rate [46]. The use of hydrogels directly influences soil permeability, density, structure, texture, evaporation and infiltration rates of water [46], as well as helps in increasing the water holding capacity of soil by more than 50 % according to the specific dosages [6,46]. In addition, the soil bulk density may be reduced by a hydrogel ratio ranging between 5–10%. On the other hand, the use of hydrogels may lead to a saturation of water volumetric content in the soil, according to the used amount, especially in arid and semi-arid regions [48,50]. It can also improve the water and chlorophyll content of the leaf in the arid region [51].

Regarding seedling growth, the soil supplemented with hydrogels can improve seedling emergence and prolong water availability [46,48]. On the other side, the swollen hydrogel particles can also modify the soil structure due to the modification in the size of retention pores and decrease the large drainage pores. Hence, the swollen hydrogel can significantly reduce the soil saturation hydraulic conductivity [6,50,52]. The use of deeply formed wet hydrogel may be efficient, especially in clogging rainwater for building water reservoirs in soil [53].

Abdallah et al. [54] reported that the amendment of the sandy soil with 0.3% of fine-grained hydrogel has significantly reduced saturated hydraulic conductivity and increased the available water capacity compared to the large-grained hydrogel. The same authors have also concluded that the seedling growth under drought stress was more pronounced for the small-grained hydrogel because of the water stored in the large particles, which became less available for plant roots [54].

3.1.2. Reduction of Drought Stress

The drought stress due to the low water content in soil may lead to the production of oxygen radicals and lipid peroxidation [55]. The latter effect may lead to some negative impacts on the plant morphology, such as stunted height, decreased leaf area and leaf damage. Therefore, the use of hydrogels can provide better growth and yield even in unfavorable climatic conditions [53,56].

Bearce and McCollum [57,58] found that hydrogel decreased the requirement for frequent watering and increased the shelf life of container-grown plants. Several research studies have reported the useful benefits of hydrogels in horticulture and reported that its addition could increase the water holding capacity [57] and improve the water storage properties of porous soils, which delay the wilting periods [56]. Macphail et al. [43] reported the importance of using different rates of "Viterra 2 Hydrogel" on enhancing turfgrass and bluegrass survival under drought conditions in greenhouse experiments. The results showed that the application of Viterra 2 Hydrogel either in the greenhouse growing media or the field had increased the establishment of turfgrass and bluegrass and their survival under drought conditions. Furthermore, the germination rate of bluegrass seeds has decreased with all tested concentrations.

Tomášková et al. [59] evaluated the effect of hydrogel treatments with sawdust, organic fertilizer, compost, wheat straw, subsoil and subsoil with a cobble cover on the survival, growth, and physiological traits of 20 tree species and observed that all treatments have significantly improved the performance of drought-sensitive species. The same authors also concluded that the addition of hydrogel during planting is considered an effective way to preserve the tree species in the region with high temperatures and facing drought problems [59].

3.1.3. Enhancement of Fertilizer Availability

Some recent studies have suggested the use of hydrogels to reduce the use of synthetic fertilizers without negatively affecting crop yield and nutritional value. This advantage of hydrogels might be more useful, especially in the case of sustainable agriculture in arid and semi-arid regions. Hydrogels can also be formulated with potassium and nitrogen ions as fertilizer components. In particular, chemicals trapped in a polymer network cannot be immediately washed out by the water but gradually released into the soil and then absorbed by plants.

Konzen et al. [60] studied the combined effect of hydrogel with different types of fertilizers based on traditional NPK, superphosphate and potassium chloride on *Mimosa scabrella* seedlings and observed that their growth was promoted due to the increase in water retention and nutrient absorption.

3.2. Biodegradability of Hydrogels

Generally, hydrogel polymers are very sensitive and can be easily absorbed into plant tissues [39]. On the other hand, hydrogels can be easily degraded when exposed to natural UV rays. In particular, polyacrylate becomes much more sensitive to aerobic and anaerobic soil microorganisms and easily degraded into the water, carbon dioxide and nitrogen compounds [61].

The mineralization of hydrogels can also happen through biological decomposition, such as fungi. In particular, the biological degradation of different kinds of polymers in the soil reaches a high degree of effectiveness, especially under conditions that help to maximize solubility [9]. For example, the biodegradation of acrylate-based hydrogels in municipal compost was reached up a rate from 1 to 9% per year under aerobic conditions similar to the decomposition of organic matter in forest areas [44].

3.3. Importance of Hydrogel for Plant Performance

The current review has covered some hydrogel uses for improving plant performance as follows:

3.3.1. Seed Germination

There is no collateral effect on seed germination due to hydrogel treatment [43,45]. Ismail et al. [62] reported that the superabsorbent hydrogel, composed of acrylamide and acrylic acid on starch using polyethylene glycol (PEG), showed a positive effect on the germination of corn seeds and growth of young plants compared to that of the seeds without the hydrogel [45]. On the other hand, hydrogel-treated plants exhibited a satisfactory effect for both fresh and dry weights of leaves and roots [63].

Elshafie et al. [45] have studied the biological activity of hydrogel supplemented with some natural substances and/or antagonizing microorganisms on the seed germination of *Phaseolus vulgaris* and concluded that the hydrogel formulations based oregano essential oil and *Burkholderia gladioli* bacteria showed the highest significant seed germination.

3.3.2. Plant Growth

Macphail et al. [43] studied the effect of hydrogels at different concentrations on turfgrass and Baron Kentucky bluegrass. They observed that the seedling growth was not negatively affected at concentrations ranging between 0–50 kg/100 m^2. Furthermore, Akhter et al. [16] reported that the applications of hydrogels improved plant growth of several species by increasing water retention, especially in sandy soils [16]. However, Konzen et al. [60] reported that the use of hydrogels could also promote plant height, collar diameter and fresh biomass of *M. scabrella* seedlings under greenhouse conditions.

Filho et al. [64] evaluated the most suitable dose of hydrogel to establish seedlings of *Enterolobium contortisilliquum* under two levels of luminosity 50% and 100% and 10 doses of hydrogel ranging between 0–6 g/L. They observed that the two tested doses 2 and 3 g/L showed the best development of seedlings even under full sun and shaded environments, respectively. In agreement, Bernardi et al. [65] reported that the application of 6 g/L of hydrogels in substrates of *Corymbia citriodora* was able to increase plant height and stem diameter by 23%. In contrast, Sarvas et al. [66] reported that the 7 g/L of hydrogel per *Pinus sylvestris* has led to plant mortality.

3.3.3. Avoiding Desiccation

Elegba and Rennie [67] studied the addition of rhizobia in a solution of legume seeds to improve inoculation. In contrast, the desiccation due to the use of non-appropriate seed-coating materials can cause poor survival of rhizobia on legume seeds. This could be due to the death of inoculated bacteria on the dried surface of seeds, especially once the individual bacterial cells are exposed to low relative humidity [19]. On the other hand, there are several studies indicating the improvements of using the suspended medium and binding agents in growth media for seedlings to increase the tolerance of rhizobia to low water content and eventual desiccation due to low moisture content [19,68].

4. Seed-Coating

Seed-coating is considered one of the most common recent practices for covering seeds using external materials to protect them from external factors, salinity, water shortage and possible pathogens and successively enhance plant establishment [69–71].

For those reasons, seed-coating is one of the most promising technologies to enhance germination and establishment, especially in unfavorable conditions. The annual value of the application of this technology, either for private or scientific fields, exceeds US$1 billion [71].

On the other hand, seed-coating is one of the most economical strategies, which can deliver viable organisms in the development of successful biological control products against several plant pathogens [72,73]. Many beneficial microorganisms have been encapsulated in several formulations based on sodium alginates or hydrogels for biological control and enhancement of biodegradation [68,74–76].

Seed-coating represents the first defense line against various external climatic and pathogenic factors and may also adjust its metabolism in response to unfavorable environmental conditions [8]. Seed-coating can be carried out in two forms, including melt and split coats. The melt coat can be dissolved by gradually becoming wet around the seed [6], whereas the split one can retain its shape when wet and passes moisture through the pill by capillary action [6]. This technology may also help in seed germination with less water consumption [77,78]. It should be taken into consideration that coating should not have any adverse effects on germination pattern or seed health and should not induce secondary dormancy of seeds [78].

Although an early study has reported that the seed-coating was carried out only to modify the shape and size of the seed [79], it can also include polymer technology, microbial inoculation, growth regulators, systemic and contact pesticide treatments and micro- and macronutrient applications. Many recent studies reported that the coating materials could be used effectively for carrying nutrients [80,81], biocontrol agents, such as beneficial microorganisms and mycorrhizal fungi [79,82], improving plant growth [79], and transporting agrochemicals, such as bactericides, fungicides and insecticides [83]. The addition of a variety of nutrients, microbes, bio-pesticides on the formulation of seed-coating has several benefits without any negative collateral effects on the surrounding environment compared to different traditional applications [7,84].

In particular, hydrogel seed-coating has been found to improve seed aeration of *Caragana korshinskii* family Fabaceae, significantly enhance seed germination and reduce drought symptoms under stress conditions [85,86]. Pathak and Ambrose [39] studied the effect of a biodegradable hydrogel as a seed-coating on the early growth of corn seed and concluded that the coated seeds showed a significantly higher rate of emergence than uncoated seeds at a water supply of 77% field capacity.

Isabel et al. [87] studied the encapsulation of *Pseudomonas fluorescens* using chitosan and sodium alginate as a carrier material for standardization. They observed significant differences in some biometric parameters between the control plants and encapsulated treated ones [87]. In particular, the encapsulated culture successfully improved the plant growth, yield and nutrient content of the soil. Isabel et al. [87] also reported that the encapsulation of bio-agents helps to improve and promote higher yield and productivity of the crops.

The use of alginate to encapsulate meristematic tissues for producing artificial seeds has been suggested for many years [77], but the use of seeds in hydrogel formulation will have fewer risks due to the fact that seeds are more resistant than meristematic tissues. Sarrocco et al. [73] studied the seeds encapsulation in calcium alginate pellets treated with some antagonistic microorganisms for wheat, cabbage, basil and radish and concluded that the seed emergence percentages were not different from untreated ones. The obtained results of the latter research showed that the alginate seeds could regulate the consumption of nutrients without reducing seedling emergence. Hence this technique represents a new future strategy to enhance the activity of antagonistic microorganisms when applied to seeds [73]. Among the benefits correlated to the use of seed-coating technology, the current review has taken into consideration other benefits, such as avoiding desiccation and controlling the diseases.

Controlling the Diseases

There is no doubt that controlling plant pathogens is one of the most important pillars of food safety policy, particularly the protection of the seeds, the main nutrition reservoir for plant embryos [71]. Seed treatment with pesticides is mostly restricted to fungicides and insecticides, but some other developments and regulations have included the use of herbicides under some limitations [88,89]. Brockwell [90] reported that the use of lime and some other organic materials in the seed-coating technology was able to help seedling and nodulation for better survival and lower the disease infection of the root hairs.

The use of several pesticides for seed-coating treatment could be carried out by different methods, such as solution for seed treatment, water dispersible powder for slurry treatment or Emulsion of seed treatment [91,92]. The following pesticides have been commonly used for seed treatment either for contact or systemic action [93,94]. The most common insecticides are benfuracarb and carbosulfan for systemic action, whereas carbaryl, thiocarb and hydramethylnon for contact action [93,94]. Regarding fungicides, the most common types are fludioxonil, silthiopham and thiram for contact action, whereas triadimenol and tebuconazole for systemic action [93,94]. However, there are some pesticides, which could be used effectively for both systemic and contact action, such as carboxin/thiram [93,94].

In particular, the seed-coating formulations based hydrogel supplemented with oregano essential oil showed the highest significant antimicrobial activity against *Clavibacter michiganensis* and *Pseudomonas syringae* pv. *phaseolicola* [45]. On the other hand, the same study also concluded that the seeds coated with hydrogel supplemented with oregano essential oil were able to significantly inhibit the fungal disease incidence of *Fusar-*

ium oxysporum, *Rhizoctonia solani*, *Penicillium expansum* and *Aspergillus flavus* on *P. vulgaris* seeds. The latter study proved the importance of using hydrogels based on some natural substances for seed-coating technology in order to reduce the use of chemical pesticides, which can have a negative impact on the environment, animal and human health.

Ismail et al. [62] reported that many pesticides could not totally reach their intended target due to volatilization, degradation, and leaching effects, which in turn can lead to a serious problem in environmental pollution and plant, animal and human health [95]. Therefore, the use of innovative controlled release formulations based on hydrogels can resolve the abovementioned problems where the hydrogel formulation can slowly deliver the active substance of pesticides according to the purpose. Hence, it can also reduce leaching, soil degradation, pesticide volatilization and possible toxicity [96,97]. Singh et al. [98] studied the efficiency of using some hydrogel formulations with ammonium persulfate for controlling the release of thiram fungicide from the prepared hydrogels and observed that it increased with time. The same authors also concluded that the increase in the concentration of cross-linker in the polymer matrix led to the decrease of the fungicide release.

5. Conclusions

There is a global increase in new innovative strategies for plant protection for reducing the dependency on chemical and synthetic pesticides and saving living organisms as well as the environment. SAPs and hydrogels have been successfully used to protect soil and to positively enhance plant performance against several unfavorable surrounding conditions. The seed-coating technology is considered an interesting strategy for protecting seeds against several phytopathogens and improving plant growth. The current review has highlighted the importance of using SAPs and hydrogels in an integrated manner to protect seeds, plants and soil in order to achieve production efficiency and preserve the environment and the health of living organisms. In particular, SAPs have many advantages, especially as amendments and saving water and nutrients in the soil; however, they have some disadvantages being they are not biodegradable, having possible toxicity and are not renewable materials. Hence, the use of hydrogel-based natural agents, such as moisture attractive, growth regulators, plant essential oils, microorganisms and biopesticides, has explicated promising results in seed and plant protection without any obstacles to preserve the fertility of the soil, lowering water consumption and reducing nutrient loss.

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