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Hydrogel: A Promising Technology for Optimization of Nutrients and Water in Agricultural and Forest Ecosystems

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Abstract

Hydrogel has a great potential to increase water and nutrient use efficiency, mitigate the vulnerability of plants prone to drought, improve the physical and chemical properties of soils, and increase the productivity of plants, particularly in arid and semi-arid areas of the globe. Furthermore, since the application of hydrogel prevents several environmental and economic difficulties, it is an important technology, particularly for some regions of the globe, where the water resources are scarce and expensive. However, despite its importance in agricultural and forest sectors, this promising technology is not even introduced in some tropical countries. Therefore, we strongly recommend conducting further researches on this crucial technology across wider region is very useful in order to verify its effects on various plant species and soil conditions.

Keywords: Hydrogel; Mitigation of drought; Nutrient use efficiency; Physical and chemical properties of soil; Productivity of plants; Water use efficiency

Introduction

It is predicted that by 2050, over 70% of the freshwater of the globe would be used for agriculture purpose in order to feed the nine billion individuals of the planet, which in turn increases the freshwater withdrawal by 15% [1]. Furthermore, semi-arid and arid regions, where the demand of the irrigation water is high but scarce, are increasingly vulnerable to water crisis and severe recurrent drought as a result of climate change [2,3]. Nowadays, it is estimated that 28% of the globe are too dry and less suitable for plant cultivation [4], and hence the water deficiency could retard the plant growth by dropping enzyme activities [5]. Moreover, the adverse physic-chemical properties of soil such as low cation exchange capacity (CEC), low water retention and low infiltration have a negative impact on plant productivity [6]. In order to ensure high survival and growth of the newly planted seedlings and to make them more economically successful and contribute their role in sustainable development, thus water-saving agricultural and forestry management practices are crucial in semi-arid and arid areas [7]. These require innovative technologies such as "moisture retention reagents" (for example, hydrogel), which could improve the plant's survival and growth difficulties through improving the water and nutrient use efficiency of plants [39,3] [8,9].

According to [10] and [11], the hydrogel is a hydrophilic compound, soil amending or water-absorbing polymer, capable of absorbing water approximately around 100 to 300 times of its weight [5]. The hydrogel is known to be 'physical' or 'reversible', when the linkages among the molecular entanglements are ionic and/or hydrogen bonding [11]. Commercially hydrogel is available in three forms: Agrosorb, Raindrop, and Stockosorb [12]. Hydrogel has a technical feature such as photo stability, odorless, colorless, pH neutral after swelling with water, re-wetting competency, highest absorption capacity, highly biodegradable and non-toxic, cheap price, and robust in the swelling environment [10,11].

Nowadays, the hydrogel has attracted several researchers due to its application and fascinating properties [8]. However, while there have been several studies in somewhere else, other researchers are highly interested on the potential application of hydrogel in fostering agriculture and forest to tap this technology particularly in tropical areas where soil fertility and the availability of water are the major constraints. Therefore, our primary objectives of the review were:

a) to identify and summarize the major benefits and drawback of hydrogel application in agricultural and forest productions,

b) to extract information that could help provoke and steer the future research, and

c) to better verify the use of hydrogel as a means to increase the water and nutrient use efficiency.

The information in this review paper is very crucial to improve the water and nutrient usage in agricultural and forest productions, particularly where the water scarcity and soil fertility are common problems.

Importance of Hydrogel in Agricultural and Forest Productions

A hydrogel is designed to absorb and retain water and nutrients by swelling quickly, and release nutrients and water to plants in a uniform manner, particularly when the surrounding of the root zone of the plants starts to dry up [12]. During the release of water, hydrogel creates free pore volumes in the soil for water infiltration, air and root growth [13,14]. Because hydrogel exhibits high permeability to water-soluble metabolites, oxygen, and nutrients, and has a capacity to imbibe large amounts of water, it enhances plant survival and growth, particularly in sandy soils [15,16].

Effect of hydrogel on the physical and chemical properties of soil

The application of hydrogel on sandy soil increases the porosity of sandy soils by occupying the large soil pores [17]; this implies that sandy soil has less porosity compared to the fine-textured soils such as clay and loam. Moreover, the high-level of hydrogel increases the total porosity (TP) and reduces the bulk density of the sandy soil from1.47g/cm^2 to 1.34g/cm^2 [18]. [19] also revealed that the application of hydrogel improves the water holding capacity of the sandy soils compared to the loam or silt clay soils in the degraded forest ecosystem.

[20] also revealed that hydrogel helps the formation of soil aggregates, and thereby decrease the bulk densities of soil, and improves the available water, water retention, soil moisture, aeration, texture, and compactness of the soil. In agreement with this, [21] also showed that hydrogel improves the physical conditions of soils such as soil infiltration rate, permeability, porosity, the microbial/ biological activities in the soil and air accessibility in the root zone of plants (in turn enhances the root growth), seed germination and seedling emergence rate. Additionally, [22] also showed that the application of hydrogel increased significantly the available soil N, P_2O_5 and K_2O.

Effect of hydrogel on the nutrient use efficiency of plants

Hydrogel increases the nutrient use efficiency of plants through reduction of the leaching of nutrients, particularly the micro-nutrients from the soil [23]. Furthermore, Hydrogels with synthetic fertilizers will release nutrients very slowly within a very long period of time, and this allows some rapidly available nutrients such as ammonium phosphate, ammonium nitrate and potassium chloride to be available to plants very slowly [14] (Table 1).

Table 1: Summary of Major Benefits of Hydrogel in terms of Nutrient Cycling.

Effects	Mechanisms
(a) Enhance nutrient retention	Hydrogel releases solute [9].
	Hydrogel delays the dissolution of fertilizers [9].
	Hydrogel serves as nutrient reserve, particularly in slow release of fertilizers [9].
(b) Increase the availability of nutrients	Hydrogel absorbs nutrients (for example, soluble fertilizers), and release in proper time for plants [43] [14].
	Hydrogel increases nutrient uptake [14].
(c) Reduce nutrients/ fertilizer leaching	It interacts with fertilizers and reduces leaching [23].
	Reduces soil erosion and runoff [9,23].

Effect of hydrogel on water use efficiency (WUE) of plants

Hydrogel increases the water consumption efficiency of the plants and reduces the runoff and erosion from agricultural and forest ecosystems, which in turn increases the availability of water in the soil [9]. Furthermore, it increases the resilience of plants to water stress during the long period of drought [9]. Hydrogel also assists some specific plants to reduce evapotranspiration. For example, [24] revealed that the application of 0.4% hydrogel to sandy soil reduces the evapotranspiration of some tree species such as *Azadrachtaindica, Terminalia superb, Pinuscaribaea, Maesopsiseminii, Grevillearobusta and Eucalyptus grandis*. [18] also reported that application of hydrogel at 0.2% level decreases the evapotranspiration rate and increases the water use efficiency, which in turn reduces the number of irrigations per season and the water quantity per irrigation.

Since hydrogel serves as an additional water reservoir for the soil-plant-air system [37] [4], it improves irrigation effectiveness and/or water use efficiency, and thereby enhances water productivity, especially in the drought-affected areas [4,18] also reported that compared to soils without hydrogel, soils that are amended with hydrogel moistened a bit longer after irrigation because hydrogel assists the irrigation water to be stored and released under the mechanism that controlled by evaporation and plant root absorption. In agreement with this, [25] reported

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that hydrogel increases the water use efficiency of plants and the water consumption by the plant roots, which in turn contributes to increase in biomass and the plant dry matter. However, [26] in contrast reported that hydrogel has no effect on the daily water consumption (DWC) of plants.

Effects of hydrogel on water retention in the soil

The hydrogel is a very useful technology to retain water in arid and semi-arid areas, where there is a scarcity of water, limitation of irrigation schemes and salinity problems [9,14]. The survival and growth of plants in arid and semi-arid areas are determined critically by the plant available water (PAW) storage capacity of the soil. Thus, hydrogel could play a great role in increasing the water storage capacity of the soil [27]. For example, [28] evaluated that hydrogel increases the available water capacity of the sandy soils from 7.29% to 18.75%. [15] also revealed that the application of hydrogel in combination with N fertilizer on Mandarin (*Citrus reticulata*) could increase the water holding capacity of the soil from 28.74 to 34.63%. In line with this, [16] have reported also that soils, which were amended with low levels of the hydrogel, were able to store less water than soils with high levels of the hydrogel. The major benefits of the hydrogel in terms of soils water retention capacity includes, improving water penetration rate [29], enhancing the availability of water to plants both in quantity as well as duration, increasing the field capacity of different soils, and increasing the water reservoir near the root system [30]. For instance, [31] showed that available water content increased about 1.8-fold that of control in clay, 2.2-fold in loamy and 3.2-fold in sandy loam soil, using a hydrogel application of 8g/kg. Furthermore, [24] showed that amending sand soil with 0.4% hydrogel significantly increases the plant available water by three folds in some of the tree species such as *Azadirachta indica*, *Eucalyptus grandis*, *Eucalyptus citriodora*, *Pinus caribaea*, and *Gravillea robusta*. However, contrary to those successes with hydrogen application to moisture requiring plants, there are some negative results on the hydrogel application both infield and greenhouse trials. For example, an increased overall plant biomass and the amount of available water in European birch (*Betula pendula*) have been reported [31]. Therefore, the amount of water retention in the hydrogel amended soils depends on the types of soil and plant species [21,32] (Table 2).

Table 2: Summary of the major benefits of hydrogel in improving the physical and chemical properties of soil.

Property	Effects	Reference
Physical and chemical	Reduces the hydraulic conductivity (Ksat)	[24,26,33]
	Increase the water holding capacity (WHC)	[26,34]
	Increase the plant available water (PAW)	[24,26,35]
	Increase the porosity of the soil	[17,26]
	Reduce soil compaction	[34,35]
	Increase the water use efficiency (WUE) of plants	[26]

Effect of hydrogel on plant growth and development

Prior to Hydrogel degradation into non-toxic components, it persists a few years in the soil and assists to delay tree's wilting point and extend its survival [36,37]. [24] also revealed that hydrogel amended sandy soil with 0.2 or 0.4%, increases the survival of some tree species such as *Azadirachta indica, Eucalyptus grandis, Eucalyptus citriodora, Pinus caribaea,* and *Gravillea robusta*. In line with this, [34] also revealed that the hydrogel amended clay soil increased the survival and growth of transplanted seedlings from *Eucalyptus grandis* clones because of high interaction of hydrogel with the water. Furthermore, [34] revealed that seedlings of *Grevillea robusta,* which are grew in amended sandy soil with 0.2% and 0.4% hydrogel level survived longer under water stress conditions. [18] have also evaluated that *Conocarpus lancifolus* seedlings that were grown in the hydrogel amended soils exhibited the highest roots percentages and taller seedlings when compared to seedlings grown under untreated soil with hydrogel. The same authors revealed that hydrogel amended soils with 0.2%, increases the plant height by 49.9% and the root length by 43.9%. Consecutively, the dry weights of roots and shoots also significantly increased from 48.2 to 52.1g and from 62.9 to 66.5g, respectively. Furthermore, it has been reported that shoot-root ratio of a tree of *Conocarpus lancifolus* was significantly affected by hydrogel amendments [18]. Hence, the shoot-root ratio of this species was decreases to 1.24 in 0.2% hydrogel amended soil whereas in soil that is untreated with hydrogel increases the ratio to 1.49. In agreement with this report, [13] also concluded that as hydrogel assists to improve the root growth of plants and the movement of water in the soil-plant continuum, hydrogel also assists the emergence of new root growth, and ultimately decrease the shoot-root ratio.

In a more recent experiment, hydrogel improved plant height at maturity, number of kernels per panicle and 1000-kernel weight [38]. Similarly, the addition of hydrogel either alone or mixed with fertilizer increased the yield of maize (*Zea maize*) and Valencia orange trees [9]. Data from experiments also specified that the application of hydrogel has significantly increased the number of leaves, the root weight, and the weight of the aboveground

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biomass of cucumber seedlings, by 7.9%, 28.1%, and 17.3%, respectively [5]. Conversely, the same authors were also reported that the addition of hydrogel did not influence significantly the height growth of the above ground part of the plant and the diameter of the roots (Table 3).

Table 3: Summary of the effects of hydrogel on the growth and development of plants.

Effects	Mechanisms
1. Improve seed germination, seed viability, seedling emergence and root development	Since hydrogel has lower water potential compared to seed water potential, it regulates the water potential of seeds, particularly after imbibition's period [21].
	Reduce the impact of environmental stress on seed and/or plant physiology [21].
	In nursery condition, hydrogel can protect roots against desiccation and increase the root-to-soil contact after out planting, particularly when applied as a root dip [39].
2. Increase seedling survival/establishment	Improve the water holding capacity of soil [6,26,40] which in turn can increase the survival of seedlings in dry land afforestation [36,41,42].
	Reduce the evapotranspiration of some plant species [13,14].
	Increase both the leaf water and chlorophyll content [37,38].
	Prolongs the plant nutrient and water uptake by releasing the water slowly over a long period [21,36].
	Prolongs the duration of wilting point under water stress condition [14,26].
	Offer chances of replanting during water stress [21,36].
	Double application of STOCKOSORB AGRO (gel) on the pine seedlings of root system after lifting caused an about 19% higher survival rate compared to control variants [43].
	Improves the survival of tree seedlings before and after water stress [36].
3. Reduce water stress of plants	Cause improvement in plant growth by increasing water retention capacity in soils [2,44,45].
	Increase the amount of plant available water (PAW) in the root zone [3,21,26].
	Decrease osmotic moisture of soil [45].
	Decrease the adverse effect of water stress after transplantation [22,28].
	Reduce the downward movement of irrigation water and percolation [26].
	Increase irrigation intervals [34,45].
	Increase water use efficiency [20].
	Delaying the duration to wilting point in drought stress [46].
	Store water and nutrients and release them in drought stress conditions in light soils [47].
4. Enhance the plant yield both in quantity and quality	Increase the growth of plant and yield, especially under limited irrigation [3,9,24,35].
	Increase plant height at maturity, number of kernels per panicle and/or number of seed per pod [27,38].
	Decrease fruit drop ratio [5].
	Increase fruits size and weight under various severity conditions [9].
	Increases number of flowers [9].
	Improves the fruit quality [3].
	Improves the biomass production of tree seedlings before and after water stress [36].
	Significantly improve the photosynthetic performance of drought-stressed beech seedlings [19].

Other forms of hydrogel applications in agricultural and forest sector

Nowadays, hydrogel is used for numerous multi-functional technological applications in agricultural and forest sector. These include:

a) Soil conditioner: hydrogel can be used as a carrier of slow release fertilizers and can be sprayed directly to surface soil or can be mixed with soil [9,23].

b) Structural material: hydrogel can be used as a raw material for producing greenhouses and mulches [9,21].

c) Seed priming and Osmo-conditioning: hydrogel can be used for pre-sowing hydration treatments for initiating germination and embryo development [21].

d) Seed coating: hydrogel can be used as a seed coating either in combination with fungicides, herbicides, and insecticides or alone in order to protect the seeds from pathogens,

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which hinder the establishment of seedlings, particularly at the early stage [21]. Furthermore, hydrogel decreases the potential side effects of biologically active ingredients from pesticides through controlling the release of ingredients in the optimum limits over a targeted time [9,47,48].

Conclusions and Future Research Needs

Conclusion

In conclusion, hydrogel amendments improve the water holding capacity of soil, which in turn can increase the survival and growth of seedlings especially in dry lands. This technology is also very useful in rehabilitation of degraded lands and can boost crop and tree productivity. However, further investigations, which scrutinize the effects of hydrogel on various soils and plant species across several geographic regions, are needed in order to explore and use the potential benefits of the hydrogel. We also strongly suggest this important technology should be integrated in research and development projects, where land degradation sustained as a serious problem especially in dry lands to facilitate the rehabilitation efforts where needed.

Future research needs

Past researches have clearly shown that hydrogel has a great potential for water use efficiency and soil management, particularly in arid and semi-arid areas, where there are limitations of soil nutrients and moisture for plant use. However, in some tropical areas, efforts are lacking to access this promising technology in the research and development agenda. We identified a number of research needs when reviewing the application of hydrogel and its contribution to agricultural and forest development. Therefore, further researches on soil physico-chemical properties, seed germination, seedling emergence, seedling establishment, and seedlings survival of different agricultural crop and tree species are highly required. Studies on the effects of hydrogel on the growth and productivity of different plant species at different soil texture, soil moisture and pH, and hydrogel levels are also very important. Furthermore, evaluating the cost and benefit of using hydrogel in agricultural and forest productions is very crucial.

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