Innovations

Advancing Drought Stress Mitigation in Agriculture: The Role of Crop-Based Hydrogels in Enhancing Resilience and Productivity

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Abstract
Water stress is the main thing keeping plants from growing, developing, and producing. When there isn't enough water, the stomata close, making it tough for plants to make food and get the nutrients they need. Drought management is very important for reliable crop production. This review concentrated on using crop-based hydrogels for easing drought effects. Crop-based hydrogels made from starch, cellulose and proteins are safer for ecosystems when compared to petroleum-based ones. Just compare how they can hold water and decompose which is why we may use the gels to control soil moisture conditions and reduce irrigation. It is also noted that they do uplift soil structure to enhance root performance and nutrient uptake efficiency thus making most water use by plants. In a word, these crop-based hydrogels do not only increase water and nutrient use efficiency, but also support microbial life in soil as well. Such positive results could be even more evident when biochar or nanoparticles were added to these hydrogels. As such, it is clear that they will make life a bit easier especially in arid and semi-arid regions where water is scarce. To end with they were noted doing great job of raising water-use efficiency whilst reducing dependence on plastic materials used in agriculture today thus paving the way for sustainable intensification.

Key words: *Hydrogels, Drought, Irrigation, Biochar, Nanoparticles*

Introduction

Drought stress is probably one of the most severe abiotic stresses affecting world crop production that has negative impacts on plant physiology, growth and yield. Research carried out in the last ten years wakes people up to the fact that drought stress cause such factors as breakdown of photosynthesis, assimilation of nutrients, and growth retardation (Farooq et al. 2012; Chaves et al. 2016). These impacts are so pronounced where water is scarce as is the case for most of the arid and semi-arid areas of the developing world. However, due to escalating climate change, drought incidences are more frequent and longer in duration, pressure on the agricultural systems (Lesk et al. 2016). In fact, the necessity for proper drought combating measures has arisen to a certain degree of utmost urgency, owing to their overwhelming impact on the sustenance of the world's food supply, and hunger minimization with regard to crop yield warning.

Efficiency of water usage has become one of the most important principles of efficient agricultural activity in regions with a short rainy season. Measures like drips irrigation, rain water management, and soil conditioners are for example some of the most practices to boost up of water use effectiveness (Kirkham, 2014). However, the above-recommended conventional methods do not satisfy the water demand of the crops during one or the other dry periods occasionally experienced in most regions of the world. To this end, the focus of current research has been directed towards the use of new materials and methods that prolong water in the soil and minimize the use of irrigation. Of them, hydrogels have received considerable interest due to their ability to manage water uptake and water supply based on the needs of the plant, which promises a smart control of use of water in agriculture (Ahmed 2015, Guilherme et al. 2015).

Amongst these, starch, cellulose and plant protein based hydrogels have gigantic potential to reduce drought stress. These crop based hydrogels are eco-friendly, economical and can be used in wide range of soils and cropping systems (Sadeghi et al. 2017). New research has shown that they help to increase field capacity, increase amount of water available to the root zone, and better plant performance under water constraints (Wu et al. 2019; Liu et al. 2023). Also, their function in decreasing the numbers of irrigations, and increasing the productivity in water utilization makes them a great tool in mitigating water deficiency in agriculture.

The objective of this review is to establish to which extent crop based hydrogels can be utilized to address the impacts of drought stress on crop production. That is, it investigates the processes through which such materials enhance soil characteristics and protect plants from stress during water-deficit conditions. Additionally, the review also presents latest developments in hydrogel science as well as their appraisal in the field level and problems observed while using hydrogels. Thus, this paper aims at giving the up-to-date conclusion about the use of crop-based hydrogels in the practice of sustainable agricultural and their possible contribution to a radical change in water management under climate change conditions based on the findings of recent researches.

2. Drought Stress: Challenges in Agriculture

Drought stress remains a major constrain in crop production since it influences the crop's physiology, growth, and yield. This environmental stressor reduces the access of water in the plant, which is important in its metabolic activities. In its phytophysiological effect, water deficit causes stomata to close in an effort to conserve water and thus limit CO2 uptake and photo synthetic capacity (Farooq et al. 2012). As a result, growth rate and the biomass are decreased because photosynthesis is directly related with growth and biomass. Drought stress can affect male sterility, alter the patterns of endogenous hormones, and affect intracellular nutrient transport because drought induces the formation of ROS, which are oxides and hydrogen peroxide molecules (Ahmad et al. 2010).

In this study, the relationship between soil, water and plant in times of water stress is complex. Hence there is importance of texture, structure and organic matter of the soil as it determines water and availability of water to plant (Hillel, 1998). The effects of drought stress include; water deficit or low water potential of the soil and low root conductance for hydraulic flow in plants. In their attempts to overcome these limitations plants react by increasing root growth and using hydraulic redistribution to improve water uptake especially from the deeper layers in the soil (Comas et al. 2013). However, such adaptations are frequently inadequate to support greater development under such substantial pressure challenges.

Essentially, plants respond differently to drought stress, with a categories of drought escapees, avoiders and tolerant plants. Drought escape is that of getting the life cycle done prior to the onset of drought stress, an example is presented by short cycle cultivars (Blum, 2011). Some tensions that are usually hindered include water scarcity by maintaining root-shoot ratios besides efficient closure of stroma. On the other hand, drought tolerance occurs at molecular level through osmotic adjustment with solutes such as proline and trehalose together with antioxidative defense systems to reduce damages by ROS (Gupta et al. 2016).

Present approaches to minimize drought stress in agriculture involve either genetic, agronomic, and technological measures. The use of conventional breeding as well as molecular breeding methods, including marker-assisted selection to produce improved drought-tolerant crop varieties is encouraging (Kadam et al. 2019). Other cultural practices, such as mulching, conservation tillage, and appropriate irrigation management within a given production environment, improves water retention and water use efficiency. Furthermore, scientific breakthroughs in crop and soil management for instance precision agriculture and remote sensing with timely data for enhancing control of detrimental effects of drought (Chandel et al. 2021).

3. Crop-Based Hydrogels: An Overview

Hydrogels are formed by the polymerization of water-soluble monomers or other water-swollen polymers, and Water-swollen gel. Hydrogels are cross-linking, water-swellable, three-dimensional polymeric networks that are capable of desirable and reversible absorption and retention of large quantities of water or biological fluids at equilibrium without dissolution or phase separation of the polymer. These materials show great solute swelling behaviour and can be differentiated into natural, synthetic and semi-synthetic depending on their origin and content (Peppas et al ., 2000). Hydrogels possess characteristics such as porosity, elasticity and biodegradability, which has attracted application of hydrogels in variety of uses particularly in agriculture. Another essential aspect is their ability to retain water used in preserving the moisture content of the soils in areas that experience low rainfall (Sannino et al. 2009). Furthermore, hydrogels are sensitive to pH change, sensitive to temperature variation and can be designed for the slow and controlled release of nutrients or agrochemicals (Hennink & van Nostrum, 2002).

3.1 Effects of Crop Based Hydrogels on Sustainable Agriculture

Biopolymer hydrogels linked to crop based like, starch, cellulose and lignin are environmental friendly and replace wholly or partially synthetic hydrogels. The materials used are biodegradable, non-toxic, and eco-friendly which conforms with green chemistry (Rana et al. 2021). In as much as efficiency of application of flood based aquaculture and hydroponic system it solves point in agriculture such as water rationing and land degradation whereby it increases water use ratio while at the same time improving the texture of the ground. Also, such hydrogels based on crops may work as carriers for fertilizers, and pesticides, thereby minimizing their impact on the environment (Sujith et al. 2020). The raw material of the products also being renewable enhances the effort put in place to minimize use of petroleum products hence cutting out greenhouse gas emissions (Mohamed et al. 2018).

3.2 Properties of Crop-Based Hydrogels

Crop based hydrogels are different from synthetic ones due to the following reasons Crop based hydrogels are environmentally friendly . The have high water absorbent characteristics and this may differ according to the kind and the method of preparation of the biopolymer (Buchholz & Graham 1998). For further strength and durability when used in the soil their structure is strengthened through cross linking (Gómez-Melgar et al. 2021). These hydrogels are also biodegradable and therefore do not pose serious hazard to the survival of plants and soil microorganisms. Conversely, crop-based hydrogels reveal great responsiveness to external stimuli; that is, temperature, pH, making it possible to use them depending on the agricultural conditions needed (Tiwari et al. 2022). The addition of functional additives such as biochars or nanoscale materials can add more advantage and applications in smart agriculture.

3.3 Comparison Between Crop Derived Hydrogels with Those Derived from Synthetic Materials

Other synthetic hydrogels, as polyacrylamide hydrogels, have increased water absorption ratios and excellent stability, however, questions concerning their degradation into the environment and possible biotoxicity are still problematic (Akhtar et al. 2016). Conversely, the crop based hydrogels are biodegradable and prepared from renewable resource, and disintegrate in the soil without any toxic effect (Ahmed, 2015). Nevertheless, in most cases synthetic hydrogels appear to have better mechanical properties and higher functional cycles which can be desirable under some circumstances. Crop based hydrogels perform well in the fields where environment friendly remedies are desired and more so in the context of sustainable agriculture. Lower production cost and use of agricultural waste as raw material also makes crop based hydrogels more desirable (Guilherme et al. 2015).

3.4 A comparative analysis of crop based hydrogels against synthetic hydrogels

Crop-based hydrogels have even more benefits than synthetic hydrogels that have been discussed above. This they do not pose the risk of long-term accumulation in the environment and detriment to the bio-system; they are biodegradable (Berger et al. 2001). They also demonstrate good soil compatibility wherein they enhance microbial and nutrient turn over (Khadem et al. 2021). Also, the crop-based hydrogels are synthesized with low-cost, abundant agricultural waste products which will be affordable to small holding farmers (Xie et al. 2020). Their production is consistent with the circular economy concept since waste is converted to new valuable products. In addition, the hydrogels derived from crops exhibit versatility in functionality and can be used to create intelligent hydrogels suitable to prevailing agro-climatic conditions (Reddy & Yang, 2011).

4. Types of Crop-Based Hydrogels

4.1 Starch-Based Hydrogels

Starch based hydrogels are from renewable resources like corn, cassava, and potato and most of them are plenty available globally. These hydrogels are thus distinguished by their high biodegradation Graduate, low cost, and high water absorption. The gel-forming properties of the amylose and amylopectin components of starch make both of them extremely valuable in the agricultural industry (Zhang et al. 2018). With an apex on citric acid, crosslinking starches strengthens their structural configuration and the ability to swell (Patel et al. 2019). These hydrogels can also be altered chemically or enzymatically for enhancement of its mechanical strength and nutrient carrying capacity [Jiang, Ahmad, Yamin & Tong, 2020]. Its use includes the areas of soil treatment, the utilization of controlled release fertilizers and methods of combating drought (Wang et al. 2016). Nevertheless, they exhibit lower mechanical properties than synthetic hydrogels; therefore, studies on the processing and composition of the composites are required.

4.2 Cellulose-Based Hydrogels

Cellulose based hydrogels can be prepared from agricultural residues, cotton and wood pulp. Hydrogels derived from cellulose possess big water absorption capacity and good mechanical features because of the presence of hydroxyl groups of cellulose (Liu et al. 2019). Due to their eco-friendly and fully degradable characteristics they serve as alternatives to more conventional approaches to sustainable farming (Chen et al. 2020). Carboxymethyl or hydroxyethyl modification improves their swelling ability in water and the release of nutrients (Zhao et al. 2021). Furthermore, cellulose nanocrystals are also added to enhance mechanical properties and likely water retention in the soil (Das et al. 2020). These hydrogels are incorporated with several applications in soil conditioners and as carriers of agro chemicals in precision farming.

4.3 Protein-Based Hydrogels

Protein-based hydrogels from soy protein, wheat gluten and other crop residues are seeing a rising trend because of their high water absorption and nutrient release capabilities. These hydrogels possess particular gelling behaviour due to the presence of protein cross-linking via disulphide bonds as well as ionic interactions (Hassan et al. 2019). Due to their biodegradation and non-toxicity, they can be used in environmentally friendly agriculture (Chen et al. 2021). The recent development involves the use of the bioactive peptides that enhance plant germination and pest control (Luo et al. 2020). However, mechanical properties of the protein-based hydrogels put forward the requirements for reinforcement with additives or composites in field application (Nguyen et al. 2020).

4.4 Composite Hydrogels

Composite hydrogels are prepared using crop based polymers enriched with additives like clay biochar or nanoparticles to increase its mechanical strength and water retention capacity. They use the compounded synergy of organic and inorganic parts, and the performance of these composite hydrogels is higher than that we find in monolithic hydrogels (Yang et al. 2017). For example, composite containing clay has better aeration and better nutrients recharge compared to soil; nanoparticle also enhances the controlled release of agrochemicals (Bhattacharya et al. 2020). Composite hydrogels also have improved thermal stability and longer degradation rates thus can be sued for long term agricultural use (Ahmed et al.

2019). They can be easily adapted for use where issues like soil salinity or nutrient leaching may be a concern according to Wang et al. (2020).

5. Crop-Based Hydrogels: Synthesis and Development

5.1 Supply of Materials for Producing Hydrogels

Crop-based hydrogels are made from natural and environment-friendly polymers Starch, Cellulose, Pectin and proteins. Starch crops such as corn, potato and cassava have amylose which when used as a gelling agent, offers a powerful gel formation, (Zhou et al. 2018). Cellulose derived from agricultural residues and wood pulps serves as a universally useful backbone for hydrogel synthesis owing to availability of extensive hydroxyl functional groups. Citrus pectin and apple pomace derived pectin are used in hydrogels due to its high water surface area, biocompatibility (Patel et al. 2021). Further, proteins, including soy and wheat gluten, make the hydrogels have better nutrient-binding ability (Chen et al. 2021). These sources make the process sustainable and cut down dramatically on the use of synthetic polymers.

5.2 Methods of Hydrogel Synthesis

There are various methods in hydrogels preparation such as; physical hydrogels, chemical hydrogels, and grafted hydrogels (Gupta et al. 2020). Physical methods use hydrogen bonding and ionic interactions to generate reversible hydrogels that are eco-friendly but exhibit poor mechanical stability (Ahmed et al. 2020). Covalent cross-linking based synthesis is most commonly used for the synthesis of mechanically strong hydrogels using cross-linking agents such as glutaraldehyde or epichlorohydrin (Zhang et al. 2019). Techniques like grafting improves characteristics such as swelling capacity and thermal stability as monomers are polymerized directly onto a biomaterial (Kumar et al. 2021). More effective approaches, such as free radical polymerization and microwave synthesis enhance reaction outcomes and hydrogel properties (Li et al. 2019). These are because each method has some unique features suitable in meeting the agricultural requirements.

5.3 Uses of Cross Linking Agents and Additives

The chemical nature of cross-linking agents is especially active in controlling the mechanical properties and performance of hydrogels. Such agents as citric acid and borax develop covalent linkages resulting in improved mechanical properties and swelling characteristics (Wang et al. 2018). Different additives including nanoparticles, bio-char and clay enhance properties such as water holding capacity and nutrient supply (Liu et al. 2021). For instance, some nanocomposite hydrogels with silica or graphene oxide well heal, possess enhanced thermal stability, and undergo slow degradation (Chen et al. 2020). This improves crop-based hydrogels to adapt to a variety of agricultural climates including, drought and saline stressed regions.

5.4 Biodegradability and some of the environmental advantages of polymer materials.

Crop-based hydrogels are eco-friendly because they degrade naturally into products that can enhance soil elemental nutrition. Their application reduces the reliance on synthetic polymers thereby decreasing the amount of plastics that find their way into agricultural systems (Zhao et al. 2020). These hydrogels reduce water evaporation, lessen nutrient losses through leaching and enhance the physical properties of the growing medium (Kumar et al. 2019). Some of the biodegradable hydrogels also contribute to lowering the environmental impact of farming techniques thus creating a good melody for the sustainable development goals (Ahmed et al. 2021). Besides, due to compatibility with organic farming they can be regarded as an indispensable part of environmentally friendly farming.

6. Strategies of Drought Stress Alleviation with Crop-Based Hydrogels

Plant-incorporated hydrogels are becoming widely appreciated for the reduction of risky influences of drought stress in the coming agricultural production processes due to improved water and soil structures. One of these we have covered is their ability to absorb and retain a sizedable amount of water. These hydrogels can swell and absorb water many times their weight and create a depot that dispenses water to the roots of the plants, or surrounding soil as needed (Zhao et al. 2020). This capacity makes certain that sufficient water is available in the plants even in dry climates to spur normal photosynthesis during drought periods (Ahmed et al. 2021).

Enhanced status of moisture content control in the soil surface is another significant advantage related to crop based hydrogel system. Hydrogels lower the chances of water irrigation frequency and decrease water loss by evaporation because of its ability to retain soil moisture for a longer time. Research has also found that hydrogel-treated soil results to higher water holding capacity; thus better plant growth and crop yields (Chen et al. 2021). There is no water logging for the plant but the roots are well supplied with water due to the controlled release of water (Liu et al. 2018).

Hydrogels in the root zone improve root-water interaction as well as improving soil structure through aggregation. These hydrogels surround the roots and lock moisture form getting evaporated hence providing efficient uptake of water especially in areas that experience complications of drought. This results in enhancement of plant performance, nutrient assimilation and other plant health factors (Patel et al. 2020). This mechanism is useful for the crops in regions with low water retentive capacity of sand such as hydrogels which address the problem of high degree of drainage inherent in sandy soils (Kumar et al. 2021).

The decrease in the irrigation frequency is an empirical repercussion of the protraction of water supplied through hydrogels. In this way, they cut the direct demand for constant irrigation, and the energy costs linked with water pumping (Gupta et al. 2020). This characteristic makes hydrogels an ideal active component in efficient water management in agriculture especially in the arid areas where water rationing is common (Singh et al. 2019).It is also important to identify that crop based hydrogels play an important role in soil management, apart from water management. Due to their application, they enhance porosity, aeration, and structure of the soil hence enhancing root development. Better physical properties such as increased organic matter content and improved water infiltration as well as improved biological properties that lead to improved plant establishment and vigorous growth under drought conditions (Wang et al. 2018). Moreover, the hydrogels developed are biodegradable and can break down into non-harmsome components that further improve soil organic content (Ahmed et al. 2021).

7. Use of Crop Based Hydrogels in Agriculture

7.1 Soil application, such as for improving soil properties, the use of appropriate soil conditioners has enhanced for a normal use (Bhardwaj et al. 2007). Hydrogel (absorbent polymers) needs to be applied in agriculture because it is or can absorb water and deliver the water to the plants after a long time hence efficient usage of water (Akhter et al. 2012). At present, hydrogel polymers are used as soil conditioners to minimize water loss and nutrient retention in the soil and counteract the detrimental impact of dehydration and moisture stress in crops (Gokavi et al. 2018). Particularly the following benefits are seen (i) Hydrogel polymers used in the soil satisfy specifications that involve absorbing far much larger amount of water than its own weight with a durability of what could be called a gel (Thombare et al. 2018), (ii) they help to shield the soil from the flow of runoff and (iii) help to enhance fertilizer efficiency in the soil and (iv) improve the microbial growth in the The biological effects of polyglutamic acid, a new hydrogel polymer for corn growing and the enhancement consequences of useful microorganisms in the soil (Yin et al. 2018). Application of this organic polymer has demonstrated that it can improve the soil conservation water, germination of corn seeds and the density of microbial bacteria which particulalry Bacillus, Pseudomonas and Burcholderia which promotes the growth the plant (Yang et al. 2020). Reduce seepage through the creation of membranes in the soil that limit water and nutrient flow downwards, enhance the level of permeability and infiltration of a soil, aeration, and soil drainage and prevent plant injury from salt toxicity.

7.2 Greater access to fertilizer – The fertilizers held within the polymer network of hydrogel are not readily irrigated away but are gradually diffused into the soil and up taken by the plants. Work done on the various aspects of hydrogels with regard to other forms of fertilizers based on the conventional herbaceous NPK, super phosphate, potassium chloride indicated the growth improvement in Mimosa scabrella seedlings due to enhanced water and nutrient retention (Konzen et al. 2017).

7.3 Hydrogel as a Potting Medium – A light-weight potting medium is of more importance of growing plant especially under soil-less culture systems since it is easy to manage. Hence, hydrogel is seen as a relatively light-weight growing substrate and could thus be employed today for the cultivation of crops. Planting media with the best water-holding features are the most essential because water and nutrients are requirements for plant growth. Hydrogel was introduced into urban farming as a potting medium in the 1950s and has subsequently been used as a seed additive to enhance root anchorage of the seedlings, in slow-release coatings and so on (Abobatta 2018). A superabsorbent acrylamide-acrylic acid/silver nanocomposite has been found to exhibit desirable negotiable water-uptake capacity which can be useful in rain-fed agriculture (Vundavalli et al. 2015). This concurs with the assessment of melon seedling growth enhancing effects that were observed to be caused by a superabsorbent hydrogel composite (Vasconcelos et al. 2020).

7.4 Decrease in Drought stress – Drought stress in the soil due to scarcity of water results to generation of oxygen radicals which in turn increase lipid peroxidation and oxidative stress in plant. Therefore drought stress results into the following adverse impact on the plant morphology; reduced plant height, decreased size of the leaf area and damage on the leaves. Thus, the utilization of hydrogels can be efficiently focused to be saving tools for higher plant growth and crop yield in alllclimatic situations (Taylor et al. 1986). Many scholars have found that hydrogel can generate profits in cultivation experiment; in addition, it can enhance the water reserve capacity of the soil (Bearce et al. 1997) and the water storage quantity of the pores of soil, which reduces the possibility of wilting for plants (Taylor et al. 1986). Assessment of hydrogel after the planting is perceived as the method of survival of tree species in this area against high temperature and moisture stressed environments (Tomaskova et al. 2020).

7.5 Soilless agriculture is regarded as the practice of cultivating crops with a base material other than soil, such, sand, peat, rock wool, sawdust, cocopeat, compost, perlite and vermiculite. Hydrogel can be classified as an addition because it improves the structure of soils, enhances water infiltration, prevents excessive erosion and water runoff, reduces soil compaction, benefits plants when irrigation is low and extends the period before fertilizers are leached away (Abobatta et al. 2018; Vasconcelos et al. 2020). Gholamhoseini et al. (2018) proposed that different types of hydrogels could be produced for use in soilless agriculture. An integration of hydrogel in the cultivation beds for plant growth was successful in soilless vertical farming using woven, knit and non-woven structures (Salam et al. 2019). Silica based nanoparticles embedded in smart hydrogels act as agrochemical carriers in plants. It is proposed that additive manufacturing and fabrication of receptive structures would result in hydrogels that would work as soilless cultivation substrates aiding in the facilitation of plant growth (Kalossaka et al. 2021).

7.6 Efficient Irrigation - Hydrogel's potential as a soil amendment has been demonstrated to increase water retention in the soil, making it more readily available to plants for up to three times longer than untreated soil (Narjary et al. 2012). This may reduce the need for irrigation in several cases. Hydrogel has been demonstrated to improve soil quality by enhancing soil structure. Its application in irrigated cropping systems has resulted in healthy crop recovery from drought (Tm et al. 2020). Neethu et al. (2018) stated that applying hydrogel as a soil amendment has the potential to minimize the frequency of irrigation. Incorporation of hydrogel into soil has been found to improve water management significantly.

8 Methods of Application

Certains types of crop-based hydrogels can be applied by several applications such as soil mixing, seed coating, and direct application. The action of integrating hydrogels through soil mixing is carried out by mixing them with the soil before the planting in order to achieve the more even distribution of water-retentive content across the root zone (Sharma et al. 2022). Thin layering of seeds with hydrogel by seed coating has been found to increase germination and seedling vigor by planting localized water supply to remain (El-Sayed et al. 2021). Direct application of hydrogels for sowing of seeds into planting grooves or for placing them near the root target location causes the water retention to be improved thus water-use efficiency is increased (Bhardwaj et al. 2020).

8.1 Suitable Crops and Soil Types for Hydrogel Application

Crop based hydrogels are very flexible and can be helpful for variety of crops, such as cereals, vegetables, and fruits. As an example, rice and wheat cropped in sandy soils exhibit a better water retention property and yield increase with hydrogel applications (Das et al. 2021). The vegetables like lettuces and carrots, that are grown in loam soil, benefit from the use of hydrogels, which are water-absorbent compounds (Hassan et al. 2020). Besides, the berry plants are among the ones that have shown their best growth when grown in the hydrogel-amended clayey soils which allow for the reduction of soil compaction and the improvement of aeration (Iqbal et al.2019).

8.2 Integration with Other Agronomic Practices

Being crop-related hydrogels facilitate synergy with other agronomic practices which in turn can lead to their benefits being raised to maximum. The synergy of crop-based hydrogels with mulching is expected to prevent rain from direct contacting the surface and hence reduce surface evaporation and, at the same time, meliorate soil temperature regulation (Chakraborty et al. 2020). In most cases, when using hydrogels with soil, it contributes to nitrogen efficiency by holding the nutrient in the rhizosphere, thus preventing them from leaching, and the slow-release property of the material makes sure the plants have enough nutrient supply over time (Singh et al. 2022). Additionally, it is found that fungibility leads to facilitated soil fertility next to nickel application, which mitigates the loss of water in a field and contributing to a more sustainable agricultural system if hydrogel is incorporated into crop rotation (Reddy et al. 2021).

8.3 Case Studies and Field Applications

Field applications of crop-based hydrogels have brought out their benefits in a number of agricultural settings. The use of hydrogels on maize fields in a drought-prone area in Kenya resulted in 30% more yield as compared to the control without hydrogels (Mwangi et al. 2021). In Central China, it was revealed that the use of hydrogel on paddy fields decreased water loss by 25%, while the yield stayed the same (Li et al. 2020). Consequently, coffee plantations had the most substantial benefit, they had the highest water retention and also soil health as a result of hydrogel that was incorporated, meanwhile coffee trees became more resistant to drought in Brazil (Santos et al. 2019). These examples show the elasticity of gel use and the universality of their effectiveness on different soils and climates.

9.Advantages of Crop-Based Hydrogels

Agriculture in the modern world has been given a fresh perspective through the usage of crop-based hydrogels which have been a breakthrough, offering several benefits that are in line with the standards of the environment, economy, and agronomics. These benefits are explored in detail below.

9.1 Environmental Sustainability

One of the most outstanding environmental assets of biodegradable crop-based hydrogels is their tolerance of the natural environment and their ability to degrade which in essence is their biodegradability. Whatever the case, it is not for the synthetic polymers. Gels that are renewable or come from healthily sourced materials like starch, cellulose, and proteins are the ones that become soil-friendly. The hydrogels decompose right in the soil principally from renewable sources like plant starch, cellulose, or proteins. Thus, the natural soil cycle is preserved. The utilization of crop residues as the primary source of renewable energy in the biopolymer industry gives the polymer industry major advantages for the substitution of non-renewable resources along with the contribution. Also, their better adjustment to the soil would develop organic matter and therefore the corresponding improvement of fertility in the soil is sure to follow (El-Sayed et al. 2022).

9.2 Cost-Effectiveness for Smallholder Farmers

Crop-based gels not only have advantages of cost-effectiveness but are also very lucrative to the smallholder farmers whose main source of livelihood is agriculture. It is very amazing that the major parts of the raw materials which are needed for production come from agricultural residues which always are cheap and ready to be found (Bhardwaj et al. 2021). This will slash the cost of producing and the organic materials will be a cheaper alternative for farmers who want to save on money. Water retention and less frequent irrigation are also beneficial for farmers because they do save on water and labor costs, the major factors considered by small-scale farming operations. Thereby, they should adopt green farming technologies (Patel et al. 2020).

9.3 Potential for Reducing Crop Loss During Drought Events

One of the primary tasks of crop hydrogels is their capability to safeguard against crop loss in the drought-prone season. These hydrogels can absorb and retain significant water amounts, which they later gradually release to the plant roots during the time of water scarcity (Sharma et al. 2020). This property contributes to a constant water supply, even in arid and semi-arid regions, thereby, crop resilience, and productivity are enhanced (Das et al. 2021). Research has found out that hydrogel-treated plants have a better growth, less representative symptoms of stress, and more harvests under drought conditions than those untreated crops (Mwangi et al. 2021).

10. Limitations and Challenges

Even though crop-based hydrogels present a great number of advantages apart from them, their distribution is burdened by numerous limitations and challenges that must be dealt with if we are to apply them successfully in the agriculture industry. The following issues are elaborated below.

10.1 High Initial Cost of Production and Limited Scalability

The process of manufacture crop-based hydrogels is marked by the use of sophisticated machines and the use of particular substances, which to the end, result to high initial costs. Smallholder farmers and large-scale agricultural enterprises might not want to use the technology (Ahmed, 2021). This can also be attributed to the few factories that are built to produce such materials and this leads to difficulty in meeting the demand, especially in areas where agriculture is high (Kumar, 2020).

10.2 Variable Performance Under Different Environmental Conditions

It is often the case that hydrogels produced from plants and crops, fail to perform as they are supposed to and some of the factors behind this include soil type, temperature, and moisture levels. One common example of the less effective absorption and release capacities of some of these hydrogels is when they are placed in saline or highly alkaline soils (Patel et al. 2021). As such, they may not be the best solutions since the failure of one may affect the others. In this way, they may only be good for a certain region where the soil is of a certain type and the climatic zonality is similar (Singh et al. 2022).

10.3 Potential for Microbial Degradation in the Soil

Besides the edible factor, it may also be that a downside is that crop-based hydrogels, which are degradable, may be pre-degraded in the earth. Microbial life is a bit different thing in the summer when the temperatures are high and bacteria grow on the organic material. If a short functional lifetime, due to the above-mentioned issues, is treated, then the gel materials will damage the environment and lead to less effectiveness in the long term (Gupta et al. 2021). Activities of this kind seem therefore less significant than they may appear at the sight of them which might be due to erosion or some other reason.

10.4 Farmers' Awareness and Adoption Challenges

The misunderstanding among farmers that does not familiar with the multiple uses and procedures for administering crop-based hydrogels remains to be the biggest challenge to their adoption. Moreover, the unavailability of institutions to send people out for extension services and training, which is the case mostly for developing regions, causes the problem to worsen (Reddy et al. 2022). Furthermore, farmers may be reluctant to invest in new technologies since they are not certain about their effectiveness and return on investment (Sharma et al. 2020).

11. Future Perspectives

It is predicted to be the material science revolution that will be responsible for the development of crop hydrogels of the highest quality and efficiency. Scientists are attempting to modify at molecular level such that the hydrogels develop the ability to secure water as well as prevent the loss of it even though the soil is sterile and has no nutrients. Breakthroughs in chemistry of the polymers is making the gels that are adaptive to environmental factors like temperature and water or changes in humidity, which can be even more useful in agriculture (Chandra et al. 2023). The quest for new resources that are crop-based used for the making of polymers is a stimulating field of research. Wastes from non-conventional forms of agriculture, such as oilseed crops or fruit processing byproducts, as well as aquatic plants, are all in the pipeline for bioconversion and thus becoming potential organic constituents to perform the synthesis of the already-mentioned hydrogels. Through such techniques we aim at reducing the dependence on the common sources of the materials, but at the same time the focus is on circular economy using the materials, which would otherwise be the waste products (Rao et al. 2023).

Activities that aim to add multifunctionality to hydrogels are increasing in number in the agricultural field of their involvement as carriers of inputs. The quickest-developed hydrogels are being developed to catch and release fertilizers, micronutrients, and microbes directly into the base of the plant to help it grow. The result is the use of less resource, while a further advantage is the significant reduction of pollution thanks to the sluggish decomposition of the runoff/leach chemicals into the water systems (Patil et al. 2023). Nanotechnology has become a significant helper in the other era's discoveries in hydrogels. Attachment of graphene oxide, silica nanoparticles, and carbon nanotubes in hydrogels using the nanocomposite technique showed considerable extension on the flexibility and durability of hydrogels. Technically, this new form of gel can be extremely durable. The hydrogel has advanced properties like self-healing, anti-inflammatory, making it suitable for agricultural activities (Shukla et al. 2023).

Conclusion:

Crop-based hydrogels have emerged as a logical way to effectively tackle the problems that arise as a result of drought stress and water scarcity in agriculture. In addition, these materials are also eco-friendly, as they can be biodegraded. The materials are playing a significant role in the management of water sustainably due to their high water retention, the process of breaking down the materials, and their degradability. It is great to see such huge progress made in this new sphere. These materials are practical alternatives to synthetic polymers through their potential to decrease water use in agriculture, soil quality improvement, and crop productivity. Nevertheless, the successful treatment of current issues like high production costs, variable performance, and limited scalability is very significant when it comes to the wider use of the technology. The main focus of future research should be the development of cost-effective ways to make these materials, finding new types of materials, and mixing them with new technological advancements like nanotechnology, to be made more efficient. In order to make these materials more efficient and, thus, reduce water usage, one of the multiple alternatives that should be explored is nanotechnology. Field trials and farmer education will be some positions that will be vital to the implementation of crop-based hydrogel programs. These two positions are very important in the company's reputation.

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Author Contributions
Navyashree R conceptualized the review, conducted an extensive literature analysis, and wrote the article. She examined how crop-producing hydrogels affect the reduction of drought stress and integrated the most significant discoveries from the works which studied hydrogels' effects on crop productivity and resilience. Additionally, the author made crucial changes and fine-tuned the manuscript for the publication.

Conflict of Interest
The author declares that there is no conflict of interest regarding the publication of this review paper.

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