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Hydrogel as innovative technology for moisture conservation in the Potohar Plateau of Pakistan

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Abstract

The Potohar Plateau of Pakistan is highly vulnerable to the stressors of climate including high rates of evapotranspiration, irregular rainfall patterns, frequent droughts, and poor physical structure of the soil. These factors combined with each other create unpredictable crop yields, and inaccessibility of soil moisture and degradation of the land, which are significant impediments to food security and livelihood of farmers. Under these circumstances, innovative soil moisture conservation solutions are urgently required for enhancing crop resilience, and water-use efficiency. This review provides a comprehensive analysis of the hydrogel technology in conserving moisture in agriculture. Their useful agricultural applications are explained in detail, and include soil amendment, seed coating and integration of drip irrigation systems. Field research has provided empirical support that the use of hydrogel can be used to increase crop yields up to 20-30% and drastically reduce the rate of irrigation and the amount of water used. Also, despite these benefits, there are barriers to adoption, such as high initial costs, lack of awareness among farmers, and environmental concerns, related to the permanence of synthetic hydrogels in soil ecosystems. The development and use of biodegradable hydrogel alternatives that are manufactured using natural polymers such as starch, chitosan and cellulose is highlighted as critical in enhancing environmental sustainability. The evaluation reveals that a multi-faceted approach is required to have a successful implementation in the Potohar Plateau. These involve specific subsidies, the bulk purchase of items in order to reduce costs, education programs of farmers, and the integration of hydrogels with other sustainable practices like mulching and conservation tillage. By addressing these challenges, the hydrogel technology can form the basis of developing climate resilience, water-efficient, and profitable agricultural systems in the water-prone areas of Pakistan, and this offers a viable long-term solution to fully intensify water-based rainfed agriculture in Pakistan.

Keywords: Agricultural sustainability, Crop improvement, Hydrogel, Moisture conservation, Potohar Plateau

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Introduction

The sustainable development of agriculture in semi-arid regions, including the Potohar Plateau in Pakistan, faces serious challenges because of soil degradation and water scarcity. Effective water management is essential in ensuring agricultural sustainability because these regions often experience high levels of freshwater shortages (Mishra, 2023). The largest consumer of freshwater is agriculture (around 70% of total water resources) despite the fact that the available amount of water is limited (Chen et al., 2018). The conventional irrigation and soil management practices are often inadequate in such circumstances. To overcome these challenges, innovative approaches to enhance the efficiency of water use and resilience of crops against water shortage are needed (Ali et al., 2020). New technologies including hydrogel should be developed and adopted to maintain soil moisture and enhance plant growth in water-scarce environments.

One of the most promising technologies has become hydrogels, particularly in the arid land area. These hydrophilic polymers may absorb huge amounts of water relative to their weight, slowly releasing it to keep soil moist during dry seasons (Patra et al., 2022; Ali et al., 2024). The drought stress can be alleviated through this process, soil structure can be improved and the growth of crops, particularly in arid and semi-arid areas, can be improved.

Hydrogels are extensively researched for application in agricultural practices, and several studies have shown that the gel can be used to improve drought resistance in plants (Patra et al., 2022; Ali et al., 2024; Nordin et al., 2024). According to literature (Albalasmeh et al., 2021), as they yield high, hydrogel is getting more applications in agriculture in arid and semi-arid areas. Plants cultivated in hydrogel-treated soils seem to grow quicker, amass more biomass, and yield more than those cultivated in untreated soils (Chang et al., 2021). They are particularly applicable in locations where rainfall is often unpredictable, since the use of the hydrogel would help in keeping the soil moist all the time and lessening the effects of the dry spells (Manimaran & Aswitha, 2024). Moreover, hydrogels enhance the physical properties of the soil by enhancing porosity and reducing bulk density, which promotes the development of roots and uptake of nutrients (Saha et al., 2020). The paper presents a complete evaluation of hydrogel, its preparation, types, usage, advantages, and limitations in application in the agriculture soil moisture conservation, and specifically on the situations in the Potohar Plateau.

Hydrogel preparation methods

Hydrogels are versatile materials produced by a combination of different chemical and physical cross-linking methods, which are tailored to specific applications, swelling behaviour and biodegradability:

i. Physical cross-linking

The basis of this technique is non-covalent bonds such as hydrogen bonds, ionic interactions or crystalline structures. The resulting physical hydrogels are reversible and biodegradable, but often they lack good mechanical and thermal stability (Angaria et al., 2024).

ii. Chemical cross-linking

Chemical cross-linking is done using covalent bonds formed by cross-linkers or initiators, to produce hydrogels of exceptional stability and longevity. Popular approaches to customize the capability of the hydrogels to retain water and swell include graft and free radical polymerization (Acciaretti et al., 2022). The topic of recent developments is green synthesis methods that utilize natural, renewable resources such as cellulose, starch, chitosan, and alginate. In order to improve the hydrogels' mechanical, nutrient-retention, and absorbency, all of which are crucial for agriculture in water-scarce environment, nanomaterials or functional additives are added during the synthesis process.

Critical materials in the manufacturing of Hydrogel

Hydrogels are obtained both as a result of natural and manmade polymers. Natural polymers are more biodegradable and environmentally friendly, compared with synthetic polymers, like polyacrylamide, which are more mechanically strong and slow to disintegrate. Three essential ingredients are usually used in the preparation process: cross-linkers, initiators, and monomers. In arid regions such as the Potohar Plateau, they may be sourced commercially or as agro-industrial wastes, as a way of promoting sustainable manufacturing practices that reduce the necessity of using artificial fertilizers and irrigation. The successful production of hydrogels is determined by the harmonious relationship between these elements.

i. Monomers

These basic building blocks are the monomers that form the hydrogel network upon polymerization. Examples of common monomers used due to their hydrophilic and water-absorbing properties include acrylamide, acrylic acid, methacrylic acid, and vinyl-based compounds. Because of their biodegradability and environmental benefits, natural monomers such as cellulose derivatives, chitosan, and starch are becoming more and more popular (Ahmed, 2015).

ii. Initiators

They are in charge of the production of free radicals to initiate the polymerization process. Common initiators include benzoyl peroxide (BPO), potassium persulfate (KPS), and ammonium persulfate (APS) that influence the network structure and polymerization rates when activated by heat or ultraviolet light (Mansuri et al., 2025).

iii. Cross-linkers

Cross-linkers are substances that form a network between polymer chains, which give hydrogels their network properties of cross-linking. The widely applied N, N'-methylenebisacrylamide (MBA) improves water retention, elasticity and mechanical strength. Pore size, swelling dynamics, and degradation rate are all impacted by cross-linker concentration (Magami et al., 2015). To make hydrogels customized to suit some agricultural applications, such as conservation of moisture in soils and delivery of nutrients to the arid regions, the balance of these ingredients should be precise.

Types of hydrogels

Hydrogels are able to absorb and retain up to 500 times their own weight in water. They are created in a way that they release this water gradually, which ensures that plants have a steady supply of hydration during dry spells (Wang et al., 2023). Their resources are highly versatile and are appreciated in the agricultural sector because of their superb ability to absorb and retain water. To select the most appropriate hydrogel to use in a given agricultural environment, a simple knowledge of the classification of hydrogel based on their origin, mode of crosslinking and the manner in which they interact with water in the surrounding environment. Because there are various types of hydrogels with different advantages and disadvantages, it is essential to learn the different types of hydrogels so that one can be better equipped to use the most suitable type of hydrogel in a particular agricultural situation (Skrzypczak et al., 2020).

Origin based

Based on their origin, hydrogel can be characterized as natural, synthetic as well as hybrid. Natural hydrogels consisting of biopolymers such as cellulose, chitosan, and starch, are biodegradable and are usually environmentally benign, which reduces their mechanical strength (Ribero et al., 2024; Zhao et al., 2022). On the other hand, Ali et al. (2024) and Anuar et al. (2025) reported that synthetic hydrogels, such as those made of polyacrylamide and polyvinyl alcohol, offer better water retention and increased durability; however, their buildup in soil raises environmental issues The long term environmental effects of most synthetic hydrogel is an emerging concern due to the resistant nature of synthetic hydrogel to degradation, despite their demonstrated utility in helping agriculture in hostile conditions such as drought and high salt. This has led to continued studies that will develop biodegradable hydrogel materials with similar performance. Combining the advantages of synthetic and natural polymers, hybrid hydrogels offer better functionality and still have some level of biodegradability (Rana et al., 2024). Saha et al. (2020) described that they are very useful in precision agriculture for various crops as well as soils without harming the environmental conditions. Combining synthetic and biodegradable hydrogels will be promising in the economical farming practices.

Nature of Cross-linking

The nature of crosslinking of the polymer network determines the mechanical strength of the gel and its capacity to hold water under different environmental conditions. Hydrogels can be categorized into two groups depending on the characteristics of cross-linking: physical (reversible) and chemical (irreversible).

Reversible physical hydrogels

These gels are caused to develop by non-covalent interactions such as hydrophobic association, ionic forces or hydrogen bond. This hydrogel can be reversed when exposed to environmental stimuli like pH or temperature (Bustamante-Torres, 2021). Such responsiveness is applicable to the controlled-release use, where the environmental factors may trigger the flow of nutrients or water. Nevertheless, generally speaking, compared to chemical hydrogels, physical networks tend to be weaker in mechanical properties and less stable over time, which limits their use in the situations that require an extended performance (Abdelghafar et al., 2024).

Chemical (Irreversible) hydrogels

Chemical hydrogels are robust, stable networks that are marked by long-lasting covalent bonds between polymer chains. High mechanical strength is provided by this crosslinking, which also enables the gel to retain its structure and functionality in the face of severe stressors such high temperatures or salt (Patra et al., 2022). They are thus preferred when there is long-term agricultural usage such as soil conditioning where stability of performance over a number of growing seasons is of paramount importance (Azeem et al., 2014). Although, unlike physical gels, they are not generally that sensitive to the environmental signals, their remarkable water binding properties and long-term supporting properties are key advantages in highly demanding agricultural conditions. Finally, there exists a basic trade-off between chemical and physical hydrogel design: chemical hydrogel can be depended on to provide long-lasting performance in continuous operation, whereas physical hydrogel can be relied upon to provide intelligent, stimuli-responsive behaviour.

Classification based on environmental stimuli response

Stimuli-responsive hydrogels, sometimes known as "intelligent" or "smart" materials, are capable of changing in response to the changes in their surrounding environment, such as changes in pH, temperature, light, or the presence of certain biomolecules.

Biomolecule-sensitive hydrogels

These hydrogels are engineered to detect and respond to specific biological molecule- glucose or proteins- allowing them to be used in biosensors and precision drug delivery systems (Liu and Chen, 2024).

Temperature-sensitive hydrogels

They can be used in controlled drug release and tissue engineering applications because of the reversible phase transition of these materials in response to change in temperature (Kaith et al., 2021).

pH-sensitive hydrogels

Hydrogels that are pH-sensitive swell or deswell in response to the pH of the surroundings, which is particularly beneficial to introduce drugs into specific body regions with different pH levels, such as the gastrointestinal tract (Ganguly et al., 2024).

Electro-sensitive hydrogels

These hydrogels can react to electrical stimuli by changing their volume or shape, making them useful in the development of actuators, sensors, and biomedical devices (Kaliaraj et al., 2023).

Light-sensitive hydrogels

These hydrogels can be precisely, spatiotemporally controlled in terms of drug release and other therapeutic interventions when exposed to light (Chang et al., 2021).

Application of hydrogels in agriculture

For getting maximum return in soil moisture conservation, there is need to proper application of superabsorbent polymer (SAP) hydrogels which depend on certain factors such as selection and their dosage, different application method and rate. This is detailed below:

Selection and dosage

The absorption capacity and flow rate of different type of hydrogels and whether they are specifically chosen to be used in agriculture depends on the type of hydrogel used but generally ranges between 0.5 and 5 grams per kilogram of soil.

Methods of application and rate

Dry application

Adding dry granules of hydrogel to the topsoil in large amounts, which is appropriate in large plots of land.

Pre-soaked application

Hydrogels are soaked until fully expanded before mixing, therefore offer immediate water retention but is more labor intensive.

Individual planting

Adding small amounts of dry or pre-soaked hydrogel into planting holes.

Recommended dosage summary

Patra et al. (2022) described that the application rate of hydrogel to agriculture depends on the type and texture of soils. For instance, when applied to clay soil the application rate is 2.5 kg ha^{-1} at 15-20 cm depth and in sandy soil it is 5 kg ha^{-1} at 10 cm depth. Various research studies showing hydrogel doses recommendations are presented in Table 1. Furthermore, some of the application methods of hydrogels are presented in Fig. 1.

Table 1 Hydrogel doses recommendations

Application method	Hydrogel dose	Reference
Soil application (Field crops)	0.1% - 0.5% (1-5 kg per 1000 kg of soil)	(Mandal & Naskar, 2019)
Seed coating	1-3 g per kg of seed	(Ekebafe et al., 2011)
Nursery/Seedling treatment	2-5 g per plant (root zone application)	(Kumar et al., 2021)
Tree plantation	20-50 g per pit	(Mandal & Naskar, 2019)
Drip irrigation	0.01% - 0.05% (0.1-0.5 g/liter of water)	(Kumar et al., 2021)
Soil application	0.5 % (w/w)	(Wang et al., 2025)

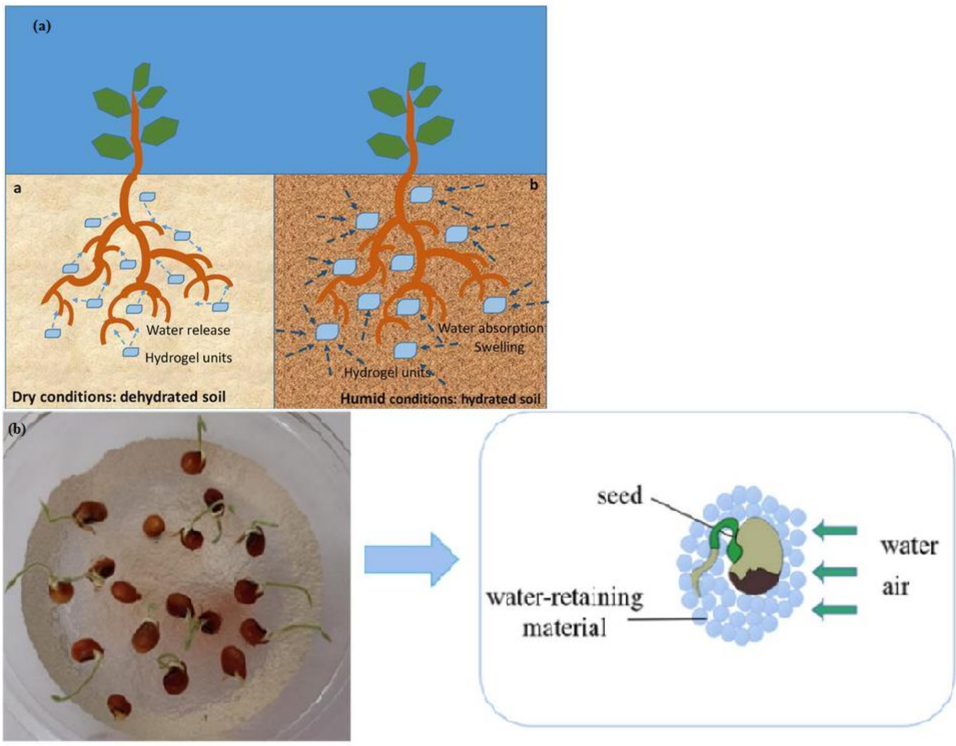

Fig. 1 Methods for applying hydrogels in agriculture (a) Soil application (Patra et al., 2022) (b) Seed coating method (Kaur et al., 2023)

Research evidence of hydrogel impact on soil water retention and crop growth

Various researches have proven that the use of hydrogel helps in increasing the water retention of the soil by 30-50%, thus increasing the growth of plants and reducing the amount of water required (Patra et al., 2022). Songara and Patel (2023) reported that the application of 2.5 and 5 kg ha^{-1} of guar-gum based hydrogels resulted in a 5.5 and 8% increase in yields. Furthermore, soil moisture content increased by 10.5% and 17% for fields treated with the hydrogel and also reduced by two- and three-times irrigation frequency. The ratios of benefits to costs were 2.7 and 2.1 to the application rate of 2.5 and 5 kg ha^{-1}, respectively. Improved soil water-holding capacity and plant growth was shown in local trials by Kausar et al. (2025) and local trials in rainfed Pakistani areas. According to Narjary and Aggarwal (2014), there was up to 40% higher soil moisture retention, which enhanced drought survival. Field tests with rainfed maize showed 25-30% increase in soil moisture and a 20-30% yield increase (Saha et al., 2018). Cea et al. (2022) is of the view that when using hydrogel in deficit irrigation, the irrigation level will be half of that without hydrogel in citrus. The use of hydrogels under rain-fed conditions minimizes soil clogging caused by raindrops in the soil (AbdAllah et al., 2021; Rix et al., 2023). Using hydrogel on silty clay loam soils for corn cultivation resulted in an increase in plant height of 26.3% (Albalasmeh et al., 2021). The heights of the corn plants that are planted in the sandy soil treated with hydrogel are double that of the corn plants that are planted in the control (untreated). The number of pods/plant (38) and the seed yield (1032 kg ha^{-1}) were increased by 22.2% and 51.1%, correspondingly, in comparison to the control (Shankarappa et al., 2020). Hamdy et al. (2020) found that when strawberry seeds were planted with hydrogel coating, they increased in their fruit firmness and water and sugar content. The effect of hydrogel on soil moisture retention and crop productivity is summarized in Table 2.

Table 2 Effect of hydrogel on crop growth and moisture retention

Method of hydrogel application	Crop	Remarks	References
Seed drill and broadcast	Wheat	Enhancements in relative soil moisture contents (up to 33.25%) and wheat yield (3960 kg ha^{-1})	(Kausar et al., 2025)
Soil incorporation	Grapevine	Dry weight increased 34.4% and 35.5% and water productivity 25.5%	(Victorino et al., 2026)
Soil amendment	Tomato	Under drought stress, the availability water productivity was increased by adding hydrogels (0.5% and 0.3%) that stimulated the growth of tomato.	(Errahali et al., 2025)
Soil incorporation	Maize	The addition of 1% hydrogel to soil resulted in substantial gains in crop production and mitigation of environmental impacts for water-limited growing	(El Idrissi et al., 2025)

Economic and environmental advantages

i. Water savings

It is effective to reduce the evaporation loss and deep percolation that minimizes water usage and enhances plant survival and growth during drought (Saha et al., 2020). Hydrogels minimize the losses of evaporation by 20-30 percent as it preserves high soil moisture contents, which are essential in healthy crops development (Ashraf et al., 2021).

ii. Reduced runoff and erosion

Mulualem et al. (2021) mentioned that it implies very significant reduction in evaporation and erosion of the top soil and enhances the soil structure and infiltration. During drought, it can effectively improve plant growth, maturity and persistence, by decreasing soil water seepage and plant volatalization (Saha et al., 2020). By 2030, hydrogels will ensure high soil moisture retention; help reduce an evaporation loss, which is essential for good crop health (Ashraf et al., 2021).

iii. Cost-effectiveness

Although hydrogel has initially high cost, but its long-term economic benefit can be achieved by dominantly its positive effect on crop yields and water saving. It is found that application of Pusa hydrogel at 2.5 kg ha^{-1} can significantly help to increase the cane yield (75.2 t ha^{-1}) compared to control (69.5 t ha^{-1}) value (Singh et al., 2018). In arid and semi-arid areas hydrogel is viable and strategic in attaining high economic payoff by cutting down on water usage.

Challenges and environmental issues

i. High start-up cost

The high start-up cost is another significant challenge faced by smallholder farmers. The disadvantages of its consumption on large-scale also included the decreased benefit-cost ratio (Kaur et al., 2023). An excellent economic advantage can be obtained by utilizing hydrogels in low rainfall region by enhancing soil moisture storage, and resulting in the water demands with a reduction in labor expenses (Ashraf et al., 2021).

ii. Environmental concerns

Traditional synthetic hydrogels can present biodegradability challenges; eco-friendly solutions are being developed. Over the last few years, a significant change has occurred towards biodegradable and environmentally friendly hydrogel based on natural polymers, including starch, chitosan, alginate and cellulose to minimize the environmental risks of synthetic types. Long term use of synthetic hydrogel disrupts the soil health by alteration in soil aggregate, soil microorganism and imbalance of soil nutrient (Maksimova et al., 2023). The remaining solid particle of hydrogel transforms into microplastic absorbing the harmful substances and reducing biological processes of soil (Buchmann et al., 2024).

iii. Degradation rate

Natural hydrogel may require reapplication, resulting in added costs. However, biodegradable hydrogel types are preferred as they can decompose and cause minimal environmental impact (Kaur et al., 2023; Wu et al., 2024). Although biodegradable hydrogel has significant ecological benefits, biodegradable hydrogels have significant challenges. Their degradation is determined by different factors in the environment, including soil composition, temperature, and microbial diversity. The variability brings about unpredictable performance in various field conditions (Anuar et al., 2025; Garcia-Garcia et al., 2024). To work around these problems, future research should be aimed at creating hydrogels that would be of good balance in functionality and environmental sustainability. It implies exploring new materials and composite formulations that enhance biodegradability without compromising on important properties such as water retention and mechanical strength (Reddy, 2016).

Synthetic hydrogels can degrade over time, releasing potentially toxic byproducts that can negatively impact soil ecosystems (Sroka & Sroka, 2024). Hydrogel residues can become accumulated in the soils and this could contribute to the formation of acryl amide which can be detrimental to the health of humans and aquatic life (Sojka et al., 2007). Moreover, to implement the wet hydrogels in the field, special skills and heavy machinery are required. This might not be viable to the small-scale farmers. Studies indicate that synthetic hydrogels are capable of remaining in the soil over extended periods, adding to pollution and disturbing soil ecosystems (Saha et al., 2020). The necessity to use biodegradable alternatives to synthetic hydrogels to promote the health and ecological balance of soil in the agricultural system has been raised by concerns about the environmental persistence of synthetic hydrogels.

Market awareness and availability

The known advantages have been realized, yet the adoption of the technique is constrained by the lack of knowledge and adequate supply by farmers in Pakistan. High upfront costs and non-availability of extension services are also contributing factors to its awareness and availability. The government has also announced subsidies in such programs that could enhance adoption as was the case with regional programs. Studies emphasize the significance of demonstrations and buying in large quantities to overcome these challenges and make hydrogels popular in Potohar Plateau.

Conclusion

This review elaborates the detail summary of role of hydrogel technology and how it works as a reforming tool of moisture conservation in rainfed area of Potohar Punjab, Pakistan. Based on the research studies it reveals that poor soil quality and health, water shortage and changing climatic variation such as prolong drought and floods affects the agriculture production in the rainfed areas. The hydrogel is used for improving water holding capacity in soils, and keeping water available to plants for longer period. In this review article, we have explained different aspects of hydrogel starting with how it is made, types of hydrogels, their properties and methods of application and how it is useful in the agriculture sector, as well as their advantages and disadvantages in relation to water conservation in rainfed areas of Punjab Pakistan. Hydrogels are becoming popular as a viable strategy of conserving water in Potohar Plateau. It takes up water and releases it slowly in the root zone and it is highly effective particularly in the period characterized with low rainfall. It assists to supports crop against drought stress condition and consequently in general crop production increase. Moreover, the creation of biodegradable and climate-adaptive hydrogel variants also supports their adoption into sustainable, climate-adaptive agriculture. However, the extensive application of hydrogel technology in Pakistan is not only discouraged by a number of practical shortcomings. The low level of awareness among farmers, lack of technical knowledge on how to properly apply the products and issues surrounding the affordability of the products and the accessibility of the markets, all remain problems that limit its wider application. It will be necessary to deal with these barriers by integrated and collaborative actions, which include capacity-building programs of farmers, enhanced extension services, and financial support mechanisms such as subsidies, and group-based purchasing systems to reduce costs. Moreover, local field experiments and long-term studies are necessary to maximize application guidelines and measure the long-term efficacy of hydrogels under dryland agriculture systems.

Recommendations

In order to get fast return using hydrogels, apply it in high-value crops, i.e., vegetables and orchards. Combine hydrogels with other sustainable practices like organic fertilizers, mulching, conservation tillage, liming and drip irrigation. These measures not only increase the level of water retention but also enhance the health of the soil and the productivity of crops (Muhammad et al., 2025). Hydrogels should be purchased in large quantity to reduce the input costs. The large initial cost of hydrogels is also a significant impediment to farmers, particularly because the economic rewards are not assured and are dependent on the type of crop, soil, and local weather. To address this issue, request government for subsidies, this in certain cases may cover up to 50 percent of expenses (Reddy, 2016). Future research should focus on adoption of low cost, eco-friendly hydrogels, derived from local agro waste (wheat straw, rice husk, cellulose), to ensure environmental protection and sustainability of soil health. Development of pH, temperature and moisture sensitive hydrogels should be encouraged for targeted and timed delivery of water and nutrients in unpredictable rainfall conditions. Application of hydrogels in conjunction with drip irrigation, soil sensors and IoT devices would improve water management and reduce irrigation requirements by 30-50%. Another aspect on future research is enlargement field trials and cultivating crop varieties that are resistant to drought and yield up to 25–40% using hydrogel. More effort should be done on implementing government subsidy, public-private partnership and bulk purchases to lower the cost for the smallholder farmers in Potohar region. For climate-smart agriculture systems, combine application of hydrogels with conservation tillage, mulching, organic amendments and agroforestry should be encouraged. More research efforts are needed to apply advanced hydrogels for slow-release fertilizer to reduce nutrient loss and environmentally pollute. Furthermore, more efforts in research are required to develop and manufacture low cost, locally produced hydrogels such as nano enhanced and microbial. Hydrogel technology should be considered as an important component of national-level solutions for promotion of rainfed agriculture and food production. Valorisation of agri-residues to create hydrogel products should be promoted for sustainable bioeconomy and decrease waste.

Conflict of Interest: Authors have no competing interest.

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