International Journal of Agricultural and Natural Sciences
E-ISSN: 2651-3617 17(2): 228-240, 2024
doi: 10.5281/zenodo.11408472
Review Article

WATER RETENTION POLYMERS TO COPE WITH DROUGHT DRIVEN BY CLIMATE CHANGE FOR A SUSTAINABLE VITICULTURE

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(Received 10th May 2024; accepted 26th May 2024)

ABSTRACT. Grapes have been extensively cultivated across the world due to their nutritious properties. However, ever worsening climate change events threaten the sustainability of grape production over most of the world. Grapevines suffer when sudden heavy watering followed by extended dry periods occurs, although most of them are known as resistant to water scarcity. For a sustainable viticulture on the face of climate change, various adaptation strategies are available to enhance viticulture management in anticipation of drought conditions. Some of them are the use of drought tolerant rootstock, proper managing the soil structure, mulching, compost utilization, beneficial plant-microorganism relationships, canopy management, applying deficit irrigation, shifting vineyards to more suitable areas, plant activator treatments, soil amendments including water retention polymers etc. Water retaining polymers have been reported to efficiently withhold water in soil for longer periods, besides making the soil structure much airy. Many studies indicated that water retaining polymers (hydrogels as 3-dimensional polymer networks) can reduce water consumption, minimize soil erosion and enhance soil hydraulic conductivity. Natural biopolymer-based hydrogels, including starch, chitosan and alginate-based polymers, offer benefits of environmental safety and sustainable productivity. Artificial hydrogels, formed via physical or chemical interactions, can be tailored for specific applications by modifying their mechanical strength, porosity and swelling behavior. However, challenges persist, including contrasting observations on absorption capacity and the increasing frequency of drought events due to climate change. Addressing these challenges requires the development of drought-tolerant crop varieties alongside innovative hydrogel-based approaches for sustainable agriculture under the changing climatic conditions.

Keywords: *Water deficit, global warming, water management, sustainable viticulture*

INTRODUCTION

Grapes, extensively cultivated across 7.5 million hectares, yield about 70 million tons globally. *Vitis vinifera* L., the primary species in the *Vitaceae* family, has been cultivated for 7000 years, now in over 60 countries. DNA studies trace the introduction of grapes to the Mediterranean via Greece [1]. Besides being highly nutritious, grapes are widely used in beverages. Grapevines also exhibit notable tolerance to both biotic and abiotic stresses, particularly drought [2]. In viticulture, the total amount of annual rainfall and timing are critical. Adequate moisture is essential during vegetative growth, but once flower buds emerge, dry soil is needed until fruit ripens. Prolonged moisture during the reproductive stage compromises fruit quality, resulting in watery and delayed maturation. Excessive water leads to uncontrolled vegetative growth, reducing fruit production and making vine management challenging. Overwatering causes vines to droop and become lanky, while moist conditions invite fungal and microbial attacks. Extra rainfall or water in summer can delay the reproductive stage and harm flowering buds. Hence, dry spells are necessary in vintage areas [3]. Grapevines, resistant to water scarcity, suffer when sudden heavy watering followed by extended dry periods occurs, especially for young vines [4, 5]. This is more problematic when rain is the main irrigation source. Insufficient water disrupts photosynthesis, causing stunted growth, small fruits, and overall low productivity [6]. Scientific surveys show a significant negative impact on grape plant growth without adequate water [7]. Interestingly, intentional water control is sometimes used to enhance compound concentrations [8, 9].

SUSTAINABLE VITICULTURE UNDER DROUGHT STRESS

Sustainable viticulture represents a dynamic strategy that incorporates eco-friendly methods into grape cultivation, striving to achieve a harmonious blend of economic viability, social responsibility, and environmental management. This comprehensive approach underscores the preservation of natural resources, minimizing chemical inputs and fostering biodiversity within vineyard ecosystems. Emphasizing soil health and deploying water conservation methods, sustainable viticulture aims to establish robust vineyards capable of adapting to evolving environmental circumstances. Notably, the implementation of sustainable viticulture practices has been associated with enhancements in soil structure, decreased soil erosion and improved water retention, thereby playing a pivotal role in fostering the sustainability of vineyards [10]. Climate change has heightened the risk of water scarcity, particularly notable in semi-arid regions essential for grapevine cultivation [11]. In order to ensure the sustainability of vineyards in these vulnerable areas in future, a strategic shift in vineyard management is imperative. Alongside the implementation of efficient irrigation practices, there is a critical need for additional adaptation measures, with a specific emphasis on adopting sustainable soil management practices [11, 12]. Water scarcity poses a threat to grapevine growth and yield, impacting producer income and causing economic losses in the grape industry. Depending on the growth stage and intensity, drought stress can affect gas exchange and plant metabolism, leading to stomatal closure, alterations in leaf structure, and oxidative damage with the production of reactive oxygen species [13]. Elevated temperatures causing increased transpiration rates result in a swift reduction in soil moisture. In drought conditions, alterations in photosynthesis driven by soil moisture changes adversely affect the overall carbon balance of the plant, consequently impacting grape quality [14]. Despite these challenges, sometimes water deficit can induce positive effects as well, especially on berry growth patterns such as reduced berry size and an increased skin-to-pulp ratio. Additionally, water-stressed plants exhibit decreased vegetative growth, resulting in more open canopies and improved carbohydrate partitioning to ripening berries [15].

ADAPTATION STRATEGIES AGAINST DROUGHT STRESS

Various adaptation strategies are available to enhance viticulture management in anticipation of drought conditions [16]. There are several strategies to mitigate the effects of drought stress on vineyards. Scientifically approved methods include increasing water use efficiency of plants [17] by the use of drought resistant or tolerant rootstock (e.g. Xynisteri, 140Ru, 1103P, 41B, 110R, 161-49C, Grenache and Carignan) [17-19], changing or managing soil structure and textural properties by cover cropping [20], mulching [21], compost utilization, minimized tillage, symbiotic plant-microorganism relationships, canopy management [22, 23] and agroforestry practices [10], modifying root growth structure [24], applying regular deficit [25] or partial root zone drying irrigation [10, 19], shifting vineyards to more suitable areas like terraced vineyards which are found to be capable of retaining up to 40 % higher percentage of precipitation [26], application of endogenous hormones and polyamines on foliage and berries, and use of certain soil amendments including water holding polymers etc. Water retaining polymers have been reported to withhold water in soil for longer durations, besides from making the soil structure much airy [27].

WATER RETENTION POLYMERS

Efficient supply of water and nutrients to the plant from soil, without negatively affecting the helpful microbes in soil is an important factor in defining the success of plantation [28]. Hydrogels are most commonly used 3-dimensional polymers that can absorb and release water in soils as and when required, especially in areas facing water shortage [29]. The composition and polymerization method of hydrogel defines its quality and usage. Synthetic polymers have some limits regarding their water holding capacity and possible effects on surroundings thus mixing them with organic polymers is a better choice [30]. The devotion to use of hydrogels in agriculture has led to a lot of work indicating hydrogel capability to repeatedly absorb, retain, and release significant amounts of water in relation to its weight. This cyclic process enables hydrogels to influence water movement in soil, impacting soil hydraulic properties such as water retention, saturated and unsaturated hydraulic conductivity, infiltration rate, and evaporation rate. The swelling capacity depends on factors such as the polymer's nature, including its ionic content, charge, and crosslinking agent, as well as environmental conditions like pH, osmotic potential, and temperature. The swelling process involves a transition from a solid to a fluid state without dissolution, driven by water diffusion, as the hydrogel interacts with its surroundings [28]. Superabsorbent polymers are important in agriculture for the controlled release of fertilizers. Conventional fertilizers, with their high-water solubility and rapid diffusion, lead to crops absorbing only 40–70% N and 80–90% P. Loading fertilizers onto SAPs improves their efficiency and prevents unnecessary environmental pollution. Thus, SAPs play a vital role in advancing agricultural development [31].

Super absorbent hydrogel (SAH) absorbs and release water again and again in soil. When soil starts drying, almost 85% of adsorbed water is released by these polymers back into soil solution, hence they increase time duration in between irrigations and act as buffer in soil against drought [32]. The interaction between a solution and polymers encompasses several mechanisms: hydration, hydrogen bonding, swelling of ionic polymers and osmosis. These mechanisms are pivotal in determining the swelling capacity and stiffness of the polymer. Through adjustments in the neutralization of the polymeric chain and control over the degree of crosslinking, one can tailor polymer behavior as needed [33]. Water retention polymers consist of elastic materials arranged in a three-dimensional network, having the capacity to absorb significant amounts of water. Hydrogels can be classified in various ways, including by their origin, synthesis method, or crosslinking technique [34]. SAHs are available in market, typically exhibiting 100 to 500 grams per gram of SAH water-absorbing capacity [35].

Typically composed of diverse hydrophilic polymers, hydrogels include synthetic options produced using fossil-based raw materials like hydroxyethyl methacrylate, hydroxy ethoxyethyl methacrylate, hydroxy diethoxyethyl methacrylate, methoxyethyl methacrylate, methoxy ethoxyethyl methacrylate, methoxy diethoxyethyl methacrylate, N-vinyl-2-pyrrolidone, vinyl acetate, acrylic acid, N-(2-hydroxypropyl) methacrylamide, polyacrylamide, polyacrylic acid, polyethylene glycol and polyvinyl alcohol, alongside bioresource polymers such as dextran, chitosan, alginate, cellulose, and gelatin etc. [29, 33]. Superabsorbent polymers are classified into starch derivatives, cellulose derivatives, and synthetic resins. These resins can further be categorized based on chemical processes into copolymers, carboxymethyl compounds and water-soluble polymer crosslinking resins. Additionally, they can be classified by final form into powder, film and fiber absorbent resins. Macromolecule water-absorbing resin is highly efficient, with water-absorbing capacity ranging from dozens to thousands of times its own mass. This surpasses ordinary natural materials, exhibiting exceptional water absorption and retention abilities [36]. Zwitterionic polymers, certain inorganic materials and interpenetrating polymer networks have been declared as water holding and salinity reducing polymers used in soils [37, 38].

Hydrogels can be prepared by mechanical and chemical methods. Grafting and crosslinking via radiations, polymerization of free radicles, enzymatic and chemical application, are chemical methods while mechanical methods include heating-cooling, freezing-thawing, hydrogen bonding, water repulsive interactions, ionic interactions and complex coacervation [39]. Hydrogels also serve as soil conditioners by stabilizing surface soils, preventing crusting, improving soil structure and promoting root growth. Application rates vary from 2.5 kg ha^{-1} for clayey soils (under 6-8 cm depth) and up to 5.0 kg ha^{-1} for sandy soil (up to 4 cm depth). Application can be by the dry method, where a dry polymer like polyallylamine or PVA is mixed with sandy soil, or the wet method, where a polymer solution is sprayed onto wetted topsoil for improving soil stability and facilitating sowing. This approach reduces water consumption, minimizes soil erosion and enhances soil hydraulic conductivity. Hydrogels can also be mixed with micronutrients and pesticides when applied wet [40].

Organic Gums

Gum Arabic is basic, anionic in nature with hard and stable texture. Being a gel forming polysaccharide in nature, it can hold water for longer periods [41]. Its use along with poly vinyl alcohol and chitosan has been proved for retaining water in the root zone of plants for longer duration [30]. Xanthan gum is easily available, cost-effective, exhibits superior tensile strength and enhances soil's resistance to repeated loading and cohesion, making it a valuable biopolymer for soil improvement [42, 43]. Xanthan gum treatment enhances soil water absorption during rainy seasons and water retention during dry spells, crucial for maintaining soil moisture and promoting vegetation survival. This intervention shows promise in addressing erosion and drought issues [44]. Moreover, it significantly improves water retention in sandy soil, leading to increased initial water content and better impermeability. Although it decreases the maximum dry density of soil specimens, it enhances germination and survival rates of vegetation. Overall, studies suggest that Xanthan gum treatment, along with Gellan gum, can effectively enhance soil water retention capacity [45, 46]. Fenugreek gum, primarily composed of galactomannan, forms viscous solutions with water due to its profuse hydroxyl groups and high molecular weight. Grafted or crosslinked derivatives of fenugreek gum exhibit promising potential as water-retaining agents. This non-toxic, biodegradable and highly soluble polymer serves as an alternative material for synthesizing water retention polymers. Although there is limited research on fenugreek galactomannan hydrogels, a cost-effective and environmentally friendly fenugreek galactomannan-borax polymer has demonstrated potential applications in agriculture [47].

Super Absorbent Polymers

Polyvinyl alcohol has exceptional stability against light and heat. In addition to that, being a synthetic cationic polymer, has inherent toughness and strength against wear and tear. It has been suggested as a favorable nominee for the production of hydrogel microspheres in agriculture. 30% solution of PVA reduced water evaporation from earth surface by 13%. When copolymerized with certain bioactive polysaccharides, physicochemical and mechanical characteristics of the resulting copolymer enhance [30]. Polyester, acrylic acids, polyacrylamide and Na-polyacrylate have an absorbance capacity of around 500 g. Unfortunately, their mechanical properties, non-biodegradability and sensitivity towards salinity make their use limited. However, when applied along with clay like kaolin, the strengths are maximized [31]. Use of acrylamide-co-acrylic acid as super absorbent resin not only retained water in soil for longer periods but also offered a more available form of water to the newly germinating plants [48]. Hydrogels composed of cross-linked polymers, specifically the co-polymer polyacrylamide (XPAM) and potassium polyacrylate (XPAA), also enhance soil water accessibility during periods of drought [49]. Sodium polyacrylate ensures more even moisture distribution in the field under frozen conditions, along with reducing the ice-grain formation in the soils [50].

Cellulose And Starch-Based Polymers

Chitosan is a cationic polymer with high tensile strength while being biodegradable at the same time. Owing to its long straight chain forming ability and deliberate hydrogen bonding qualities, its use in hydrogels is very appreciable [51]. Carboxymethyl cellulose (CMC) despite being a derivate of cellulose, readily absorbs water due to its hydrophilic carboxyl group which also limits its gel expansion after a certain limit. Hydrogels composed of CMC exhibit superabsorbent qualities and are biocompatible. Nonetheless, their application is constrained by their inadequate mechanical properties [29]. Super absorbent polymer (SAP) is a cross-linked polymer known for its remarkable water retention capabilities owing to its intricate 3-D network structure filled with hydrophilic groups. It finds extensive application as a water-retaining agent in gardening, where it enhances irrigation efficiency and improves soil physical properties. Along with being an effective synergist for fertilizers [52]. Corn straw is a cellulosic water retention material, composed of 40% cellulose, 35% hemicellulose and around 10-15% lignin, having hydroxyl, carboxyl, phosphate, ether, and amino groups [53]. These functional groups pull together monomers and cross-linking agents, resulting in a superabsorbent nutritional resin [54]. With its hydrophilic groups, corn straw cellulose is readily utilized to produce superabsorbent resin for horticulture. However, its production cost is high. Furthermore, at low doses, its interaction with fertilizers is less effective, making less water and fertilizer available to plants [52]. The carboxyl group of γ-glutamic acid exhibits strong hydrophilic properties, forming hydrogen bonds with water molecules. This interaction leads to driving water molecules to penetrate and diffuse into the polymer, resulting in over 600 g water absorption and expansion, forming a hydrogel [55]. The cellulose derivatives sodium CMC (Na-CMC) and hydroxy ethyl cellulose (HEC) can be utilized as a polysaccharide/whey-based hydrogel. This hydrogel, in comparison to acrylate-based counterparts, exhibits comparable swelling properties and high biodegradability. Na-CMC, acting as a polyelectrolyte, enhances swelling capacity and sensitivity to environmental stimuli. However, its usage alone may result in poor cross-linking efficiency due to electrostatic repulsion. Combining Na-CMC with HEC prevents intramolecular crosslinking, stabilizing macromolecules in a three-dimensional polymer network during hydrogel formation [56].

Silk Sericin (SS)

Silk sericin, rich in polar amino acids with carboxyl and hydroxyl side chains, boasts water absorption and provides effective barrier properties against water loss from the soil. With thermal stability below 200 °C [57], it possesses weak mechanical strength compared to petroleum-derived polymers. To address this, blending SS with substances like polyvinyl alcohol or glycerol and/or crosslinking it using various agents like glutaraldehyde, polyphenols, certain enzymes, carbodiimides and oxidized polysaccharides can do the job [58-61]. SS shows promising results in field applications due to its biodegradability, barrier properties and high-water absorption capacity, potentially improving water and nutrient holding efficiency of soils [57, 62, 63]. According to a recent study, inclusion of 1% SS-based hydrogel in the sandy loam soils led to a 9.40% augmentation in the available plant water [64]. Silk fibroins have sol-gel transition linkage in the hydrogels which makes possible high water retention [65].

Konjac Glucomannan (Kgm)

KGM has garnered significant research attention in recent years due to its superior water absorption and film formation capabilities in comparison to starch. Used as the foundational material for the preparation of soil agents, KGM is found in abundance naturally as macromolecular polysaccharides derived from the tubers of the amorphophallus konjac plant. The O-acetyl (-OCH_3) groups situated at the 6^{th} C-position of the sugar residues play a crucial role in enhancing the solubility and swelling attributes of KGM [66]. Konjac flour crosslinked, via liquid media containing $CaCl_2$, with sodium alginate and lignosulfonate absorbs water efficiently and retains water for long period [67].

Gelatin Based Hydrogels

Natural hydrogels hold promising position in agriculture due to their ability to retain substantial water and facilitate the controlled release of fertilizers and agrochemicals [68]. Biopolymeric hydrogels are made up of different materials including gelatin [69]. These biopolymeric hydrogels hold water, nutrients and condition the soil, besides improving plant resistance against diseases without having any negative effect on environment [39]. Gelatin, derived from collagen in animal's skin and bones, is used to create superabsorbent hydrogel composites through graft polymerization. These hydrogels, developed with kaolin powder and crosslinked with glutaraldehyde, serve as effective soil conditioning agents. Additionally, a gelatin hydrogel, formed by co-polymerizing gelatin and agar with acrylic acid and methyl acrylate, proves eco-friendly, biodegradable, and cost-effective, making it a promising solution for water retention in drought affected soil [70]. Gelatin hydrogels crosslinked with alginate are suitable for the controlled release of urea fertilizer [71]. Gelatin hydrogel created through cross-linking with di-aldehyde xanthan gum also serves as an effective material for controlled release of the fertilizer [72].

Lignin Based Hydrogels

Researchers propose a novel method for creating an agricultural hydrogel from lignin to enhance water retention in soil, by cross-linking lignin with poly (ethylene glycol) di-glycidyl ether in an alkaline solution. Lignin hydrogel shows potential to improve soil water retention and thus beneficial under drought conditions [67]. Lignin can be chemically cross-linked and copolymerized with cellulose, paper waste, wood pulp, PVA, konjac flour and Na alginate to enhance water retention in soil, slow down the release of nutrients in soil and to improve photosynthetic ability of plants [39, 73].

Citric Acid

To get an entirely biodegradable and eco-friendly water retention polymer, citric acid can be used as a natural, easily degradable, non-toxic substitute for chemical crosslinkers. Hydrogels crosslinked with citric acid demonstrate both sufficient stiffness to retain their form and a high swelling ratio [56].

PROSPECTS AND CHALLENGES

Biopolymers, regardless of having multiple uses, still have some limitations. Synthetic hydrogels are more absorptive, have longer chain lengths and are more durable [74]. On the other hand, being derived from petroleum, their synthetic nature suggests a low level of biodegradability, causing toxicity concerns for plants and consumers [64]. Biosynthetic gels are, however, famous for their water holding capabilities, besides being biodegradable, environment friendly and biocompatible with soil microflora [73]. Although they exhibit lower water absorption capability than synthetic counterparts, necessitating a higher quantity for effective use, are less efficient in enhancing infiltration rates or reducing leachate along with being susceptible to rapid degradation, requiring modification through cross-linking processes to ensure stability in soil and improve adsorption properties. Chemical cross-linking, such as introducing acrylate monomers, can be beneficial but it may introduce potentially harmful monomers during hydrogel decomposition. Still, polymers derived from natural sources are believed to decompose more easily and have less environmental impact. On the other hand, synthetic SAPs have the clear advantage of being cost-effective, exhibiting high-water absorption capacity. However, their slow degradation can potentially have negative impacts on the environment and plant growth. Hence, along with synthetic polymers, the use of modified natural polymers cannot be neglected [75]. Certain hydrogels can mitigate fertilizer losses through leaching into underground water tables, reducing overall fertilizer requirements and minimizing environmental pollution. Additionally, they enhance soil porosity. As they swell to absorb water, they reduce the bulk density and promote vital ventilation and oxygenation for germinating seeds and growing roots [76]. These polymers, in addition to controlling the hydraulic qualities of soil, also improve the physical structure of the soil [77]. When ample amount of moisture is present in soil these hydrogels absorb the extra water, many times their weight, and use it in plant's rainy hours [78].

In order to optimize water retention polymers in agriculture, prioritizing stress tolerance, durability, biodegradability and cost-efficiency are important. Optimizing synthesis methods, avoiding contaminants and toxic cross linkers, rigorous testing, dosage assessment and regulatory approvals are crucial. Tailoring the dose of water retention polymers according to the soil and crop needs makes their use more affordable. Exploring biodegradable polymers for sustainable and cost-effective agriculture is important. Biopolymer-based water retention is a milestone for biodegradable crop protection. While a single polymer may not excel in all areas, ongoing researches will for sure bring significant advances in this area [76].

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