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Super absorbent polymer application under suboptimal environments: implications and challenges for marginal lands and abiotic stresses

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Abstract: World population is increasing at an alarming rate, and crop cultivation on marginal lands has emerged as an alternate option to feed the burgeoning population. However, marginal lands are characterized by poor soil health and other undesirable characteristics resulting in low crop production and less economic returns. Interest in the application of superabsorbent polymers (SAPs) for marginal lands has been increasing. The SAPs application increases the germination percentage, seedling growth, and grain yield of different crops. Being hydrophilic in nature, SAPs can absorb and retain a huge quantity of water, and thereby enhance the water use efficiency in crops. In addition, SAPs application also showed a positive influence on soil physico-chemical properties and enhanced the retention of water and nutrients. Marginal lands are frequently subjected to abiotic stresses such as drought, heavy metals, and salinity. The application of SAPs serves as a buffer against these abiotic stresses and reduces the risk of plant damage and hence crop failure. Over the past decade, focused efforts have been undertaken on SAPs application on arable lands, especially in arid regions. However, understanding about SAPs application on marginal lands is not well understood. The present review critically discusses the potential of SAPs application to enhance the productivity of marginal lands with a major focus on crop performance under different stresses. Current challenges hindering the wide application of SAPs are also discussed.

Key words: Crops productivity, environmental stresses, slow-release fertilizers, superabsorbent, water retention, water use efficiency

1. Introduction

The agricultural sector, including livestock and fisheries, is the main source of food for the whole population on the globe. In recent years, human-induced climate change has posed a great threat to global food security (Horn et al., 2022). It is widely accepted that climatic variability is an important contributor to the degradation of natural and productive lands (Hermans and McLeman, 2021), and exacerbates the damage to environmental sustainability (Mukhopadhyay et al., 2021). Land degradation is considered a major problem for both developed and developing countries, and is associated with desertification (Prăvălie et al., 2021). Nonetheless, it is estimated that an additional 147 million ha of cultivated land will be needed by 2050 to feed the increasing population (Lambin and Meyfroidt, 2011). Hence, the cultivation on marginal lands is regarded as an important way for ensuring global food security in a sustainable way (Zhu et al., 2016; Singh et al., 2018).

Marginal lands have received great attention for their potential to provide large land resources for crop production, and to improve food security (Awasthi et al., 2016; Singh et al., 2018). It is estimated that about 36% (1.3 billion ha) of total agricultural land comprises marginal lands. Moreover, one-third global population depends on marginal lands (Kuang et al., 2022). Marginal lands are typically characterized by low crop production and less economic returns than the ideal lands (Mellor et al., 2021). They are unsuitable for various ecosystem functions and agriculture practices (Kuang et al., 2016). The major reasons behind increasing the marginal lands are low soil quality, poor water supply, industrial pollution,

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inadequate land slope and transportation of soil particles (Pimentel, 2012). Additionally, the occurrence of various environmental stresses such as drought, salinity, metals toxicity and waterlogged conditions are major concerns for successful crop production on marginal lands. Production on marginal lands is also unavoidable due to the shrinkage of agricultural land. In a number of studies, different strategies have been proposed to increase the returns from marginal lands and to cope with environmental stresses. Firstly, researchers have adopted sustainable approaches oriented towards the efficient use of existing resources, while, ensuring environmental sustainability (Maddhesiya et al., 2021). Secondly, on the bases of technological innovations, intensive management practices are adopted on marginal lands to enhance the productivity per unit area. Unfortunately, intensive crop management practices are difficult to adopt, as existing cultivars have attained their maximum yield potential.

In recent years, a new practice known as the application of SAPs has emerged as a promising and environment-friendly approach for successful crop production in the world (Marzen et al., 2015; Kenawy et al., 2021; Nascimento et al., 2021). The application of natural SAP enhanced the soil's ability to store water and increased the vegetative growth even under stressed conditions (Figure 1). There is growing consensus that SAPs not only improve the physico-chemical properties of soil but also serve as buffers against abiotic stresses and reduce the risk of plant failure, during their establishment and subsequent growth phases. Scanty information regarding characteristics, application methods, roles and application areas in agriculture is available in the literature (Chang et al., 2021; Wang et al., 2021). Few reviews available on the subject matter are exclusively devoted towards the development history, synthesis of SPAs and their general application in the agriculture sector (Elshafie and Camele, 2021; Ai et al., 2021). Potential uses of SAPs for successful crop production on marginal lands were seldom discussed and hence relevant information largely remained elusive. The present review provides a critical appraisal of SAPs application to enhance crop performance with special emphasis on marginal lands and elaborates their effectiveness to cope with and enhance the abiotic stress tolerance in crops cultivated on marginal lands. It highlights the current state of knowledge, new progress made along with future research trends and major challenges hindering the wide-scale application of SAPs in agriculture.

2. Application of superabsorbent polymers in agriculture

In recent times, the use of SAPs has increased in different sectors such as medical, engineering, hygiene products, concrete additives and the agricultural sector (Dang et al., 2017; Song et al., 2017). Based on the source of origin, SAPs are categorized into two major groups i.e. natural

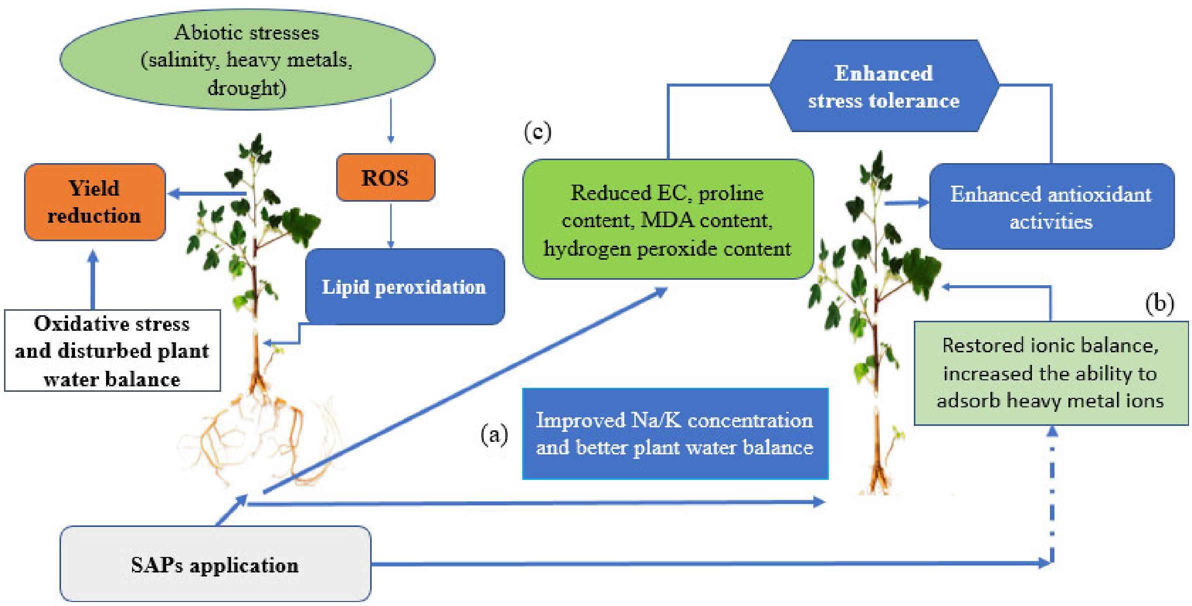

Figure 1. Impact of abiotic stresses on plants and superabsorbent polymers (SAPs)-induced stress tolerance. Upon exposure to abiotic stresses, reactive oxygen species are produced that cause oxidative damage to the plants. (a) Application of SAPs improves the Na/K concentration, and leads to better plant water balance, (b) SAPs application restores ionic balance, and increases the ability to adsorb heavy metal ions under high accumulation of heavy metals (c) Under drought stress, SAPs application reduces the electrical conductivity (EC), malondialdehyde (MDA) contents, and hydrogen peroxide (H_2O_2) contents resulting in enhanced plant tolerance under drought stress.

polymers (such as cellulose and starch) and synthetic polymers (such as polyacrylic acid and polyacrylamide) (Wei et al., 2016; Chang et al., 2021). The SAPs, also known as hydrogel or slush powder, are hydrophilic compounds characterized by the ability to absorb and retain water molecules (Montesano et al., 2015). The quantity of water absorbed by SAPs is much greater than the initial weight of material, and it largely depends on the ionic concentration of the solution (Horie et al., 2004). The SAPs can absorb approximately 400–1000 times more water than their initial weight in deionized/distilled water, out of which 95% of SAP's water is available to the crops through osmotic pressure difference (Zhao et al., 2019a). The use of SAPs for agricultural land both in rain-fed and irrigated areas can significantly enhance the water holding capacity and retention of nutrients, and reduce the irrigation frequency, soil compaction and water runoff (Abd EI-Rehirn et al., 2004). Due to their hydrophilic nature, SAPs have great potential for enhancing nutrients and water uptake (Mao et al., 2011; Ryan et al., 2018). It also has the capacity to enhance the emergence and seedling growth (Al-Humaid, 2005; Yazdani et al., 2007; de Barros et al., 2017; Rasanjali et al., 2019), crops yield (Rehman et al., 2011; Fernando et al., 2014; Fallahi et al., 2015; Taheri et al., 2017; Chaithra and Sridhara, 2018), seed oil contents (Shekari et al., 2015), water use efficiencies (Abedi and Mesforoush, 2009; Rostampour et al., 2012), and improve soil structure (Chaithra and Sridhara, 2018).

Application of SAPs (with Stockosorb®, Luquasorb® and potassium polyacrylate) enhanced the water availability for better root growth (Shi et al., 2010; Bai et al., 2019). It has been reported that SAPs application (with Zeba®) significantly improved the emergence and stand establishment in black pepper (Rasanjali et al., 2019). Further, better seed germination and seedling vigor with application of SAPs were reported for rice (Rehman et al., 2011), sorghum (de Barros et al., 2017), black pepper (Rasanjali et al., 2019), and buttonwood (Al-Humaid, 2005). Fernando et al. (2014) and Chaithra and Sridhara (2018) established that the application of SAPs (with GAM-sorb and Pusa hydrogel + Pongamia leaf mulch) significantly increased the yield and related traits of maize (*Zea mays* L.) and tomato (*Lycopersicon esculentum*). In addition to the synthesis polymers, the application of natural polymers such as cellulose, starch, and chitosan, has been reported owing to their ability to retain water and maintain soil moisture (Motamedi et al., 2020). Cellulose is one of the abundant organic polymers with high charge density and the swelling rate has been reported to improve water absorbency (Song et al., 2019). Starch, a biomacromolecule polymerized of glucose, when applied as hybriding-starch and inorganic fillers significantly exhibited water absorbency (Olad et al., 2018).

Application of SAPs also influences various characteristics of the soil such as water holding capacity, aeration, soil structure, soil permeability, density, evaporation, microbial activity, erosion resistance and infiltration rate (Wu and Liu, 2008). Additionally, SAPs have been successfully used for controlled release of fertilizers and pesticides (Ekebafe et al., 2011). There is accruing consensus that SAPs also serve as buffers against abiotic stresses and reduce the risk of plant failure, during its establishment (Shi et al., 2010; Keshavarz et al., 2013). Under stressed conditions, the application of SAPs enhanced the uptake and availability of water and nutrients for plants and the translocation of photosynthates to reproductive sinks (Kenawy et al., 2021).

There are different methods used for SAPs application in agriculture. The most extensively used method is applying directly onto the soil (Wróblewska et al., 2012); however, this method may decrease soil water retention (Hejduk et al., 2012). Nevertheless, in recent studies, SAPs were also applied through seed coating (de Barros et al., 2017; Su et al., 2017), hydro-seeding, mixing with mulch material (Chaithra and Sridhara, 2018; Zhao et al., 2019), bio-fertilizers, coated with fertilizers and agrochemicals (Wu and Liu, 2008; Li et al., 2019). Moreover, these have also been applied in soilless media for horticultural crops, especially for tomato (Fernando et al., 2014). The quantity and method of application for SAPs depend on the prevailing agro-climatic conditions under which it is being applied, soil types and structure, physico-chemical properties of soil, type of crops, existing irrigation practices, and the quality of water for irrigation purposes (Sikder et al., 2021). In conclusion, SAPs have been used in agriculture as soil additives and seed coating for their amendments in order to save water loss and nutrients in the soil and minimize the negative impact of dehydration and moisture stress in crops. Different types of SAPs and their recommended doses for specific crops are listed in Table 1.

3. Application of SAP to enhance the productivity of marginal soils

A remarkable breadth of knowledge about the beneficial aspect of SAPs suggests that their potential can also be exploited to enhance plant production on marginal lands. Different studies have been conducted to evaluate the effectiveness of SAPs for problematic soils (Fallahi et al., 2015; Kumar et al., 2019). The application of SAPs enhanced plant growth by improving water holding capacity on marginal lands (Liu and Guo, 2001). Islam et al. (2011) reported that the application of SAPs significantly increased the above-ground biomass, yield and yield contributing traits, and relative water content of hulled oat (*Avena sativa* L.) grown on erosion-prone

Table 1. Effect of different superabsorbent polymers (SAP) on growth, establishment and productivity of different crop plants.

Type of SAP	Targeted crop	Applied SAP addictions (recommended dose)	Improvements in studied attributes	References
Stockosorb and Luquasorb	Populus (*Populus popularis*)	0.5%	Better moisture content for root growth	(Shi et al., 2010)
Stockosorb K-400 (TM)	Buttonwood (*Conocarpus erectus*)	0.4%–0.6% in sandy soil	Enhanced seedling growth	(Al-Humaid, 2005)
Zeba (Organic based SAP)	Black pepper (*Piper nigrum*)	2 g kg^{-1} soil with 8-day irrigation intervals	Improved emergence and stand establishment especially during nursery management	(Rasanjali et al., 2019)
GAM-sorb (Vietnam)	Tomato (*Solanum lycopersicum*)	3 g kg^{-1} of soil less growth media	Enhanced yield and resistance against diseases	(Fernando et al., 2014)
Superab A200	Cucumber (*Cucumis sativus*)	4 g kg^{-1} soil	Improved economic profitability and water use efficiencies	(Abedi and Mesforoush, 2009)
Superabsorbent polymers	Lettuce (*Lactuca sativa*)	6 g kg^{-1} soil	Enhanced seed yield up to 41%.	(Taheri et al., 2017)
Carbonyl amide polymer 25%	Rice (*Oryza sativa*)	2.5 kg ha^{-1}	Increased germination percentage, improved crop emergence, better stand establishment, and yield components	(Rehman et al., 2011)
Pusa hydrogel + Pongamia leaf mulch	Maize (*Zea mays*)	5.0 kg + 4 t ha^{-1}	Improved soil structure, enhanced crop growth, and attained higher yield	(Chaithra and Sridhara, 2018)
Agrogel	Sorghum (*Sorghum bicolor*)	7 kg ha^{-1}	When applied as coating improved seedling emergence, vegetative growth, and enhanced tolerance against abiotic stresses	(de Barros et al., 2017)
Potassium polyacrylate	Soybean (*Glycine max*)	7.5 kg ha^{-1}	Enhanced the nutrients uptake, improved the seed oil content	(Ryan et al., 2018)
Superabsorbent polymers	Maize (*Zea mays*)	15 kg ha^{-1}	Increased nutrients and water availability and improved the yield up to 37%.	(Mao et al., 2011)
Terrahydrogel Aqua	Winter wheat (*Triticum aestivum*)	30 kg ha^{-1}	Enhanced the seed weight, and improved quality traits	(Grabiński and Wyzińska, 2018)
Potassium polyacrylate and polyacrylamide copolymers	Cotton (*Gossypium hirsutum*)	60 kg ha^{-1}	Improved yield (up to 12%), and water use efficiencies (14%).	(Fallahi et al., 2015)
Superab A200 polymers	Forage sorghum (*Sorghum bicolor*)	75 kg ha^{-1}	Enhanced biomass production, and increased water use efficiency.	(Rostampour et al., 2012)
Taravat A200	Rapeseed (*Brassica napus*)	75 kg ha^{-1}	Improved seed yield, and oil contents	(Shekari et al., 2015)
Potassium polyacrylate	Tobacco (*Nicotiana tabacum*)	75 kg hm^{-2}	Enhanced moisture availability	(Bai et al., 2019)
Zeolite	Forage Millet (*Pennisetum glaucum*)	150 kg ha^{-1}	Enhanced biomass, and forage quality even under stress conditions	(Keshavarz et al., 2013)
Tarawat A200	Soybean (*Glycine max*)	225 kg ha^{-1}	Enhanced dry biomass, and improved seed quality traits	(Yazdani et al., 2007)

arid soil. In drylands, the application of SAPs increased plant growth by enhancing nutrient use efficiency and soil water retention. Soil amendments with SAPs enhanced the performance of maize and sorghum [*Sorghum bicolor* (L.) Moench] even in row-rainfall areas (Najafinezhad et al., 2015). Recently, Kumar et al. (2019) proposed the SAPs application (with nano clay-polymer composite) as a useful tool for obtaining higher benefits under rainfed conditions. Furthermore, it has been reported that the use of SAPs markedly enhanced the growth, yield indices, and water use efficiencies in cotton (*Gossypium hirsutum* L.) under prolonged saline- and drought-areas (Fallahi et al., 2015).

Based on the current state of knowledge and basic understanding, the following are the important aspects, uses and principles of SAPs application for marginal lands.

- SAPs act as water absorbent and soil conditioner.
- SAPs improve soil and water conservation that can increase water infiltration, soil porosity, soil aggregate structure and minimize water loss from the soil surface.
- SAPs decrease the use of pesticides, fertilizers and other chemical materials.
- SAPs improve water use efficiency by adjusting the plant's physiological functions.
- SAPs maintain soil water content and enhance microbial activity.
- SAPs cause heavy metal immobilization in the soil.
- SAPs are pollutant removing agents for water purification.

3.1. SAPs as water absorbent and soil conditioner

Different factors such as desertification, deforestation, drought, nonjudicious use of soil and water resources, salt-alkalization, soil erosion, waterlogging, and improper agricultural practices are responsible for increasing the marginal land area. These factors affect crop production in different ways; waterlogging, salinity and drought reduce the availability of water and nutrients and cause a significant reduction in the growth and productivity of crops. Drought stress, in particular, reduces the water availability to plant roots, and thereby showed a severe reduction in plant growth and development (Karl et al., 2009). Crop water requirement is highly dependent on crop types, their growing stage and habits, and weather conditions of a specific area. The use of SAPs in water deficit areas is well recognized in various studies (Behera and Mahanwar, 2020). The SAPs have high water absorbing and retaining capacity, and the ability to maintain the soil moisture and thereby can reduce the consumption of water by crops (Behera and Mahanwar, 2020). SAPs when applied as granules, after watering can absorb the water by swelling and then releasing the same slowly through diffusion, upon soil drying. The same practice also reduces evaporation losses; on swelling up, SAPs increase the soil porosity and resulted in a better oxygen supply to plant roots (Behera and Mahanwar, 2020). SAPs (mostly polyacrylate based), a new environmental-friendly approach, were successfully used as soil conditioners to promote crop growth in dry areas. Polyacrylate-based SAPs have low degradation rates, are easily degraded by microbial organisms, and avoid the accumulation of toxic substances in the soil (Cannazza et al., 2014). Application of hydrogels to the soil enhances the oxygen availability to plant roots (via increased soil porosity), better germination percentages, increment in seedling growth rates, and root growth, and results in reducing the erosion problems due to less compaction of soil (Kalhapure et al., 2016). SAPs as soil conditioners have been used since mid of the nineteenth century, as they are efficient in reducing nutrient leaching loss, enhance the water holding capacity, water use efficiency, infiltration rates, soil permeability, and cause a marked reduction in runoff and soil erosion that ultimately enhance the growth and productivity of crops (Ekebafe et al., 2011; Paradelo et al., 2019). Recently, Yakupoglu et al. (2019) reported that SAPs application with polyacrylamide and polyvinyl alcohol significantly reduced runoff and erosion, improved soil aeration and microbial activities, and enhanced crop performance. In conclusion, SAPs having high water absorbing and retaining capacity thus maintained soil moisture and reduced the consumption of water by crops.

3.2. SAPs as crop growth enhancer

The availability of water in the soil is essential for vegetative growth, and a shortage of water can cause a severe threat to the growth and survival of plants. The availability of quality water is mandatory for plants to obtain better growth rates. Due to their imbibing characteristics, SAPs have been successfully used to address these problems. Being hydrophilic in nature, SAPs have the ability to absorb a huge quantity of water. SAPs work as water binders in the soil, and increase the availability of water for the plants (Khalilpour, 2001). The application of SAPs as control release of pesticides reduces the environmental pollution (Roy et al., 2014), increases the availability of nutrients for plants (Li et al., 2015), and has emerged as a versatile tool for enhancing the crop performance under different abiotic stresses such as heavy metal (Rehman et al., 2019) and drought stress (Rasanjali et al., 2019). Alleviating the adverse effects of abiotic stresses can considerably increase the biological and grain yield of crops. Application of SAPs in combination with essential nutrients (N, P and K) has been reported owing to their ability to retain and slowly release the nutrients to plants (Zhengwen et al., 2011). The application of compound-SAPs (combination of essential nutrients and SAPs) enhanced the crop efficiency for irrigation and fertilizers and helped the plants to achieve maximum growth and productivity, especially in annual ryegrass (*Lolium multiflorum* L.) (Zhengwen et al., 2011).

The increment in the growth of tomato, and a decrease in water consumption (20%) are reported as the results of the SAPs application (El Sagan, 2015). Recently, Chaithra and Sridhara (2018) studied the effect of SAPs application (Pusa hydrogel, 5 kg ha^{-1}), and Pongamia Greenleaf mulch (4.0 t ha^{-1}) in rainfed maize cultivation. These authors concluded that the combined application significantly improved the soil properties and crop performances and resulted in a marked increment in grain yield. Similarly, Khadem et al. (2010) reported that the application of SAPs in combination with cow manure enhanced the availability of nutrients, and increase the grain yield (16.2%) of maize. The application of SAPs not only increased the growth, and yield traits, but also showed an improvement in nutrients and water use efficiencies in cotton under different irrigation regimes (Fallahi et al., 2015). Poor crop stand is considered a major limiting factor for crop production. The application of SAPs improves plant germination and establishment (Akhter et al., 2004). For example, application of SAPs increased the percentage of germinated seeds, the number of fertile tillers, plant height, grain size, and weight of rice (Rehman et al., 2011). In sugarcane, improved germination and better growth were reported as a result of SAPs application, grown in sandy soils. Likewise, the application of SAPs has been found to increase the yield of field crops (Fallahi et al., 2015; Hou et al., 2018), under normal and stressful conditions. In conclusion, the application of SAPs can retain a huge quantity of water and nutrients, that are slowly provided to plants. In addition, SAPs application to soil improves the germination rate, better seedling growth, increases grain yield, and enhances the water and nutrients use efficiencies of crops.

3.3. SAPs for controlled release of pesticides

The use of agrochemicals to increase production has increased in recent years, but most of these chemicals pollute the environment and cause severe ecological and health hazards. The use of SAPs for controlled release of pesticides has shown success in decreasing the leaching and other forms of chemical losses (Li et al., 2009), thereby minimizing environmental pollution, reduction in phytotoxicity, degradation and reducing moisture losses by evaporation (Roy et al., 2014). A study conducted by Yang et al. (2017), reported that the application of SAPs can reduce the residue of ^{14}C-carbendazim extractable (11%, a well-known fungicide), applied on red clayey soil. Due to the micro-molecular nature, the application of slow-release pesticides results in a reduction of leaching losses into the soil and extends the duration of activity. In the conventional application method, pesticides are rapidly released into the environment; contrarily, the controlled release pesticide involves the movement of active ingredient to the target surface/site by maintaining the fixed concentration level for a specific period of time (Mihou et al., 2007). Different techniques such as chemical attachment, matrix encapsulation and microencapsulation for controlled release formulations have been used in agriculture sector (Roy et al., 2014). Recently, controlled release from biodegradable polymers such as cellulose, polylactic acid, carboxymethyl cellulose and amylose has been a huge success. The SAPs such as chitosan, guar gum, pectin, alginate and carboxymethyl cellulose are commonly used for controlled release of pesticides in agriculture. Also, the application of SAP-based hydrogels as an attractive alternative for agro-chemicals is gaining popularity. Hydrogels of polymers, especially polysaccharides, have gained considerable interest as a promising approach because of their versatile characteristics. Polysaccharides, in general, have minimal side effects, are biocompatible, biodegradable and occur abundantly.

3.4. SAPs for controlled release of nutrients

Water and nutrients are essential components for better crop growth and productivity, and their deficiencies cause severe reduction in said traits (Wu and Liu, 2008). In the backdrop of increased food demand of a burgeoning population under climate change and dwindling natural resource base, the use of synthetic fertilizers especially nitrogen-based such as urea (containing 46% N) has increased tremendously (Zhang et al., 2016). Due to fixation and losses such as leaching, nitrification, runoff, and vaporization, plants cannot uptake the whole quantity of the applied nutrients, and multi-nutrient deficiencies occur in most cases (Timilsena et al., 2015) causing yield reduction and malnutrition. In addition, improper application of nitrogenous fertilizers especially urea results in huge economic losses, and causes serious environmental hazards due to its high solubility, low molecular weight, and low thermal stability which increase its volatilization, leaching and runoff losses (Rojas et al., 2013). Thus, prompting a search for an environmentally benign and cost-effective diverse approach. These losses can be reduced by using slow-release fertilizers; which have various advantages such as an increase in nutrient efficiency, sustainable nutrient supply for a prolonged period, and reduction in the phytotoxic and other adverse effects of these fertilizers (Jin et al., 2011; Fan et al., 2022). Fertilizer coating with SAPs has been optimized to sustain the nutrient release, and water supply to the roots (Ryan et al., 2018), as enhanced soil moisture content might increase the nutrient's availability (Table 2). The application of SAPs with organic matter successfully increased the soil moisture contents (Ryan et al., 2018). Moreover, SAPs coated fertilizers are also helpful for obtaining better crop growth, and maximum yield potential of crops grown in water-scarce areas (Weaver and Wong, 2011). The use of SAPs in combination with fertilizers is reported as a productive

Table 2. Different types of SAPs commonly used for slow release of nutrients.

SAPs type	Releasable nutrients	Impacts	Reference
Semi-IPNs superabsorbent (WSC-g-PAA/PVA/NP)	Nitrogen and phosphorus	Decreased leaching losses and increased water holding capacity.	(Li et al., 2015)
LR-g-PAA/MMT/Urea (leftover rice-g-poly (acrylic acid)/ montmorillonite/Urea)	Nitrogen	As slow-release fertilizer, commonly recommended for the agronomic and horticultural crops.	(Zhou et al., 2018)
Gum tragacanth acrylic acid based hydrogel	Potassium and phosphorus	Have more biodegradable capacity, upon application to the soil, it increased the percentage of soil organic carbon	(Kaith et al., 2015)
Compound-SAP	Nitrogen, phosphorus and potassium	As slow-release nutrient, provided a good source of essential plant nutrients	(Zhengwen et al., 2011)
Amide hydrogel and wheat straw-g-poly(acrylic acid)	Nitrogen	Used as a carrier for controlled urea release	(Guo et al., 2005); (Liang et al., 2009)
hydroxyethylcellulose hydrogel	Nitrogen	As slow-release nutrient, provided a good source of essential plant nutrients	(Ni et al., 2011)
Tragacanth gum/acrylic acid hydrogel		As controlled release fertilizer can enhance water-holding capacity of soil	(Kaith et al., 2013)

approach to attaining sustained release properties (Ni et al., 2009; Qiao et al., 2016). This combination of SAPs and fertilizers enhances the uptake of nutrients by roots, reduces evaporation losses, and needs of frequent irrigation (Wu and Liu, 2008). Different polysaccharides such as pectin, chitosan (Jamnongkan and Kaewpirom, 2010), and carboxymethyl cellulose are commonly used for the synthesis of SAPs, and their application as slow-release nutrients is well reported (Ito, 2007).

3.5. SAPs as soil microbes' enhancer

The application of soil microorganisms as bio-fertilizers (BFs) has increased in recent years (Nezarat and Gholami, 2009). Beneficial soil microorganisms positively influence crop growth, as some of these have the ability to fix atmospheric nitrogen for plants, and enhance the solubilization of minerals like phosphorus solubilizing bacteria (Gholami et al., 2009). Soil microorganisms interact with plants and play a pivotal role in nutrient cycling. The involvement of soil microbes in the provision of soil ecosystem services is well known (Barrios, 2007). In recent years, several studies have been conducted to appraise the potential of SAPs application to improve the physico-chemical properties of soil, and promote the growth of crops (Busscher et al., 2009). However, the interaction between SAPs application and soil microbial properties is not well understood and many germane issues pertaining to this aspect still need researcher attention. A study conducted by Li et al. (2014) reported that SAPs application with Jaguar C and Jaguar S (extracted from natural plants) somehow increased the soil microbial activity under wheat cultivation; which may lead to increase in nutrients availability to plant roots, and higher crops yield (Tu et al., 2003). This approach works efficiently even under suboptimal conditions. For example, Li et al. (2013) demonstrated that the application of SAPs with Jaguar C and Jaguar S significantly improved the soil microbial biomass carbon (19%–32%) and soil microbial respiration (37%–52%) under water deficit conditions. These authors further reported that SAPs application to cabbage (*Brassica rapa*) fields, can enhance the soil microbial activities (Li et al., 2013). Also, SAPs are cross-linked macromolecules, used for the absorption and retention of water into the soil. SAPs applied with BFs successfully improved the soil physical properties, and created a congenial environment for inoculant functioning (Dorraji et al., 2010; Li et al., 2019). Arboxymethylcellulose/acrylic acid (CMC/AAc), a well-known biodegradable polymer, created a favorable environment for microorganisms, and the biodegradability of this polymer can also enhance the emergence percentage and growth of plants (Sutradhar et al., 2015). In a recent study, Li et al. (2019) studied the synergetic effect of SAPs and BFs (*Bacillus sp*. L-56 and *P. beijingensis* BJ-18). These authors found combination of SAPs and BFs improved the soil fertility status, and growth of cucumber (*Cucumis sativus* L.) and wheat. In crux, the combined application of SAPs with BFs has the potential for increasing the water and nutrients availability to the plants, thereby enhancing the growth and yield of different crops.

4. Application of SAPs under different abiotic stresses

4.1. Application of SAPs under salinity stress

Salinity is a major environmental constraint for arid and semiarid areas that limits crop growth, and productivity (Bose et al., 2014). Salinity stress adversely affects plant growth due to osmotic stress, ionic toxicity and mineral deficiencies (Hussain et al., 2021). Moreover, salinity stress also disturbs physiological, biochemical and molecular processes in plants (Munns and Tester, 2008; Bose et al., 2014). As an outcome of specific ionic toxicity and osmotic imbalance, the production of reactive oxygen species (ROS) is increased, which causes damage to the cellular membranes, DNA structure and proteins (Munns and Tester, 2008). At field level, salinity reduces the emergence percentage by posing physiological drought that causes reduced uptake of water and ions and also retards the growth and yield contributing traits (Bhutta and Hanif, 2010). In recent years, various approaches have been developed in the quest for better crop performances under saline environments. In this connection, the application of SAPs has been found as a cost-effective and environment-friendly approach for enhancing crop performance under saline conditions (Marandi et al., 2006; Dehkordi, 2017). In past, SAPs such as Alginate-Poly (Marandi et al., 2006), and sodium polyacrylate (Ma et al., 2004) were successfully applied for enhancing crop growth e.g., tomatoes, lettuce and cucumber (Sayed et al., 1991), annual rye grass (Ahmad and Verplancke, 1994), and cabbage (*Brassica oleracea* L.) (Silberbush et al., 1993), under saline conditions. In addition, several types of SAPs have showed higher tolerance against salinity, of which, sodium acrylate-co-acrylamide, potassium methacrylate (Raju et al., 2002), sodium polyacrylate (Ma et al., 2004), semi-2 IPN PVA/PSA hydrogel (Li et al., 2004), and Stockosorb K 410 (Hüttermann et al., 1997) were commonly used. Previously, Chen et al. (2004) showed that the application of SAP (Stockosorb K410) enhanced the root and shoot growth, improved Ca^{2+}/Na^{+} concentration, enhanced Ca^{2+} uptake, and thus conferred tolerance under salinity stress. Moreover, Seyed et al. (2010) also demonstrated that the application of SAPs significantly increased the water holding capacity in the presence of salts. Similar findings were reported by (Dorraji et al., 2010) who demonstrated that SAP application (with Superab A200) resulted in the highest aerial and root biomass, increased soil water holding capacity, productivity, and water use efficiency of maize grown under saline conditions. In a recent study, Zhao et al. (2019) concluded that SAPs application remarkably increased the water storage capacity, and minimized evaporation losses. Another study by Kant et al. (2008) revealed that the application of SAPs (hydrogel) enhanced the plant N and P contents, growth traits and availability of water and nutrients, and reduced soil Electrical conductivity, nitrate and proline content, and electrolyte leakage of plants under saline environment. Under salinity stress, improved tolerance was also attributed to decrease swelling of SAPs owing to support the anionic electrostatic repulsion. These encouraging findings suggest that SAPs application can significantly enhance the morpho-physiological traits and appears to be highly effective in alleviating salinity stress. However, a thorough understanding of molecular mechanisms of SAPs mediated improvement in salinity tolerance is required for a better insight.

4.2. Application of SAPs under heavy metal toxicity

Soil contaminated with heavy metals severely affects plant growth and development. Different physical, biological and chemical techniques have been developed for the remediation of contaminated soils; however, these techniques are costly, time consuming and often exert their own cons on environment (Mishra et al., 2017). Accruing interest in the remediation of heavy metals has stressed the need to improve the existing approaches and the application of SAPs has emerged as a sustainable approach to remediate contaminated soils. It is unequivocal that SAPs have the ability to adsorb heavy metals ions, dyes and organic pollutants from the soil and wastewater (Rehman et al., 2019). Application of SAPs including humic substances, zeolites, expands clay and porous ceramics results in decreasing the bioavailability of heavy metals for plants by restoring the ionic balance within the soil environment. SAPs have a high density of metal chelating groups in the gel and are well suited to bind heavy metals and thus have the ability to decrease their availability for plants. High ability to adsorb heavy metals ions, ease in handling, cost-effectiveness, and a high degree of recyclability and biodegradability have increased the use of SAPs in the agricultural sector. A study conducted by Moghadam (2017) revealed that the application of SAP significantly enhanced the total chlorophyll content, and yield traits (1000-grain weight) and alleviated the arsenic-induced oxidative stress in wheat by activating the enzymatic antioxidants (SOD and CAT). Moghadam (2016) revealed that combined application of SAP (SUPERAB-A200) with foliar spray of ascorbic acid significantly enhanced performance of wheat grown under cadmium (Cd) contaminated soil. Moreover, Moghadam (2016) also evaluated the role of SAP in mitigating the adverse effect of Cd stress, and demonstrated that SAPs application positivity enhanced the chlorophyll content, seed weight, and ascorbic acid content; while it prevented the Cd accumulation in wheat. Another study by Huang et al. (2016) concluded that SAPs can decrease the adsorbent of lead (Pb) and Cd by 50% and 80%, respectively in maize. The corresponding values were 69% and 33%, respectively for the soybean (*Glycine max* L.) crop. In general, soil

amendment with SAPs shows greater adsorption capacity for heavy metals and pollutants, restores the ionic balance, and thus enhances the plant's ability to withstand heavy metal-induced stress on contaminated soil.

4.3. Application of SAPs under drought stress

The application of SAPs is a useful technique for combating drought stress in crops and alleviating its detrimental effects (Smagin et al., 2014). SAPs, as water retaining materials, can store a huge quantity of water and nutrients and release them slowly when required by plants (Figure 2) (Yazdani et al., 2007). SAPs application conserved soil water and nutrients and enabled easy access for plants, reduced oxidative stress and increased biomass production of maize under drought conditions. Moreover, SAPs (acrylamide–potassium acrylate copolymer) also significantly increased plant growth, chlorophyll contents, photosynthesis efficiency, and relative water content, and enhanced the activities of antioxidant enzymes such as SOD, and POD in areca (*Areca catechu* L.) under severe water deficit conditions (Li et al., 2018). Likewise, Bagherifard et al. (2020) stated that soil amendment with SAPs (A200) improved the morpho-physiological attributes and yield-related traits of caper (*Capparis spinosa* L.) under drought conditions. Further, Tongo et al. (2014) also reported that the application of SAPs (Aquasorb) significantly enhanced the chlorophyll contents, and antioxidant enzyme activities, and successfully reduced the adverse effects of drought on *Acacia victoriae*. Similarly, Nazarli et al. (2010) reported that SAPs application significantly increased the chlorophyll content of sunflower (*Helianthus annuus* L.) under drought conditions. Application of SAPs (with stockosorb and zeolite) showed significant positive effects on morphological traits (such as plant height), and soil characteristics (such as EC, pH, field capacity, available water, soil bulk density, and porosity) under water deficit conditions (Yousefian et al., 2018). It has been found that seeds of *Caragana korshinskii* coated with SAPs showed enhanced emergence percentage and seed vigor, and manifested reduced electrical conductivity, proline contents and reactive oxygen species to ROS under drought stress (Su et al., 2017). It was found

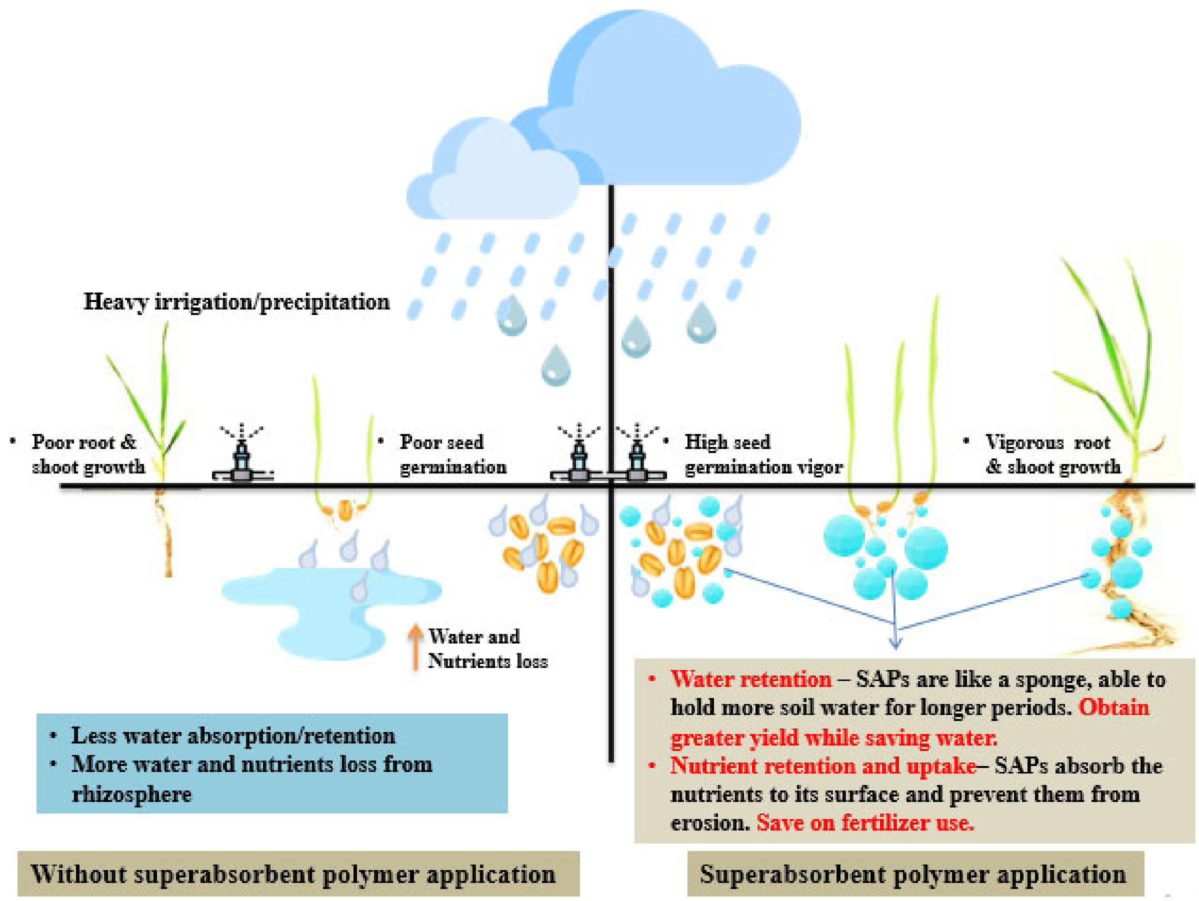

Figure 2. Application of superabsorbent polymers (SAPs) for enhancing water and nutrient retention and uptake. SAPs are hydrophilic in nature thereby sustaining water supply for a prolonged period. Soil amendments with SAPs improved soil physicochemical properties, nutrient retention and uptake thereby improving seedling growth.

that the use of SAPs favored the water holding capacity of the soil, and increased the yield traits of *Calendula officinalis* L. under water deficit conditions (Nejatzadeh-Barandozi, 2019). A recent study conducted by Abrisham et al. (2018) revealed that the application of SAPs increased the soil cation exchange capacity, enhanced growth indices and emergence of *Seidlitzia rosmarinus* under water deficit conditions. In conclusion, above discussed studies indicate that the application of SAPs, either soil applied or seed coating, can improve the morpho-physiological and yield traits, and enhance the activities of enzymatic antioxidants in plants which is helpful for plants to overcome drought stress.

5. Constraints

During the last decade, the use of SAPs in agriculture has gained popularity, especially to cope with crop production on marginal lands and alleviate abiotic stresses. However, many limitations related to the application of SAPs exist and need to be resolved to harness full benefits. Some of the SAPs are too costly and have diversified chemistry, therefore, it is difficult to adopt on the field scale by resource-poor farmers. Secondly, there is a lack of unified standards for gels formation. Some types of SAPs somehow have less water retention capacity, identification of these types is mandatory for wider application, especially on marginal lands. Due to high molecular weights, some types showed relative low effectiveness and hydrophilic properties. Degradation of SAPs is a slow process, and on average 5–7 years are required for complete degradation. During the degradation process, fungus attack is increased. The polymers are nontoxic in nature; however, some types have a carbon-carbon (C-C) high molecular bond, rendering them to bacterial degradation. The existence of environmental pollutants especially heavy metals reduces the effectiveness of SAPs, especially on marginal lands. Some types can dehydrate rapidly in a short period of time; thus, they lose their absorbed water quickly. Consequently, the water absorption capacity of SAPs decreases sharply in problematic soils having more Ca^{2+} and Al^{3+} ions. A higher application rate of SAPs not only decreases their effectiveness, but also the rewetting, and other hydraulic properties (Geesing and Schmidhalter, 2004).

6. Conclusions and perspectives

Superabsorbent polymers, as an environment-friendly approach, have the potential to achieve the maximum benefits from marginal lands. Application of SAPs enhances the germination rates, seedling growth, and seed yield in various crops. SAPs, being hydrophilic in nature, enhance water and nutrient use efficiencies, and retained soil water retentions. Under stress conditions, SAPs improve Ca^{2+}/Na^{+} concentrations, reduce EC, osmotic effects, and MDA content, and restore ionic balance, thereby enhancing the crop's ability to withstand abiotic stresses.

However, polymers purposefully introduced in the field till now have some limitations. Their commercial application depends on environmental fate, sustainability, and cost-effectiveness. A copolymer (vinyl acetate and maleic anhydride) initially launched in the market under the trade name Krilium was removed just because of high cost, application complexity and poor distribution in the field. Although, most of the researchers performed experiment/s at small scale in the greenhouse or laboratory conditions yet cost value of many crops is substantially exceeded when SAPs are applied at a large scale. Also, SAPs modulate the EC and pH of soils depending on the synthetic material and chemical structure of polymers and physicochemical characteristics of the soils. Therefore, future studies should consider these aspects for rationalization. Biodegradable polymers can be developed from the farm and agro-industrial waste. The production of SAPs with enzymes, microbes, and plants represents a cleaner and safer way. Likewise, the development of novel polymers through the use of modern techniques provides key opportunities to increase crop production on marginal lands. The rapid growth in nanotechnology has led to the exploration of SAP composites for applications in biotechnology and biomedical technologies, but this approach needs to be used for various agricultural applications. Additionally, a cost comparison of various preparation techniques (such as bulk polymerization, solution polymerization and radiation polymerization) should be done to explore the cost-effectiveness. New ideas to prepare the SAPs especially for environmentally and economically acceptable, with improved mechanical properties, characteristics with fast response time, maximizing water absorption and release capacity, and biodegradability in all types of soils are just a few examples of SAPs with a smart future.

Conflict of interest

The authors declare no conflict of interest.

References

Abd EI-Rehirn H, Hegazy E, Abd El-Mohdy H (2004). Radiation synthesis of hydrogels to enhance sandy soils water retention and increase performance. Journal of Applied Polymer Science 93: 1360-1371.

Abedi KJ, Mesforoush M (2009). Evaluation of superabsorbent polymer application on yield, water and fertilizer use efficiency in cucumber (*Cucumis sativus*). Iran Journal of Irrigation Drainage 3: 100-111.

Abrisham ES, Jafari M, Tavili A, Rabii A, Zare Chahoki MA et al. (2018). Effects of a super absorbent polymer on soil properties and plant growth for use in land reclamation. Arid Land Research and Management 32 (4): 407-420.

Ahmad M, Verplancke H (1994). Germination and biomass production as affected by salinity in hydrogel treated sandy soil. Pakistan Journal of Forestry 44 (2): 53-61.

Ai F, Yin X, Hu R, Ma H, Liu W (2021). Research into the super-absorbent polymers on agricultural water. Agricultural Water Management 245: 106513.

Akhter J, Mahmood K, Malik K, Mardan A, Ahmad M et al. (2004). Effects of hydrogel amendment on water storage of sandy loam and loam soils and seedling growth of barley, wheat and chickpea. Plant Soil and Environment 50 (10): 463-469.

Al-Humaid A (2005). Effects of hydrophilic polymer on the survival of bottonwood (*Conocarpus erectus*) seedlings grown under drought stress. European Journal of Horticulture Sciences 70 (6): 283-288.

Awasthi A, Singh K, O'Grady A, Courtney R, Kalra A et al. (2016). Designer ecosystems: A solution for the conservation-exploitation dilemma. Ecological Engineering 93: 73-75.

Bagherifard A, Hamidoghli Y, Biglouei MH, Ghaedi M (2020). Effects of drought stress and superabsorbent polymer on morpho-physiological and biochemical traits of Caper (*Capparis spinosa* L.). Austrain Journal of Crop Science 14 (1): 13-20.

Bai G, Geng, W, He D (2019). Effects of super absorbent polymer with different application rates on soil characteristics and flue-cured tobacco growth in Qinba mountain area. Journal of Zhejiang University 45 (3): 343-354.

Barrios E (2007). Soil biota, ecosystem services and land productivity. Ecological Economics 64 (2): 269-285.

Behera S, Mahanwar PA (2020). Superabsorbent polymers in agriculture and other applications: a review. Polymer-Plastics Technology and Materials 59 (4): 341-356.

Bhutta WM, Hanif M (2010). Genetic variability of salinity tolerance in spring wheat (*Triticum aestivum* L.). Acta Agriculturae Scandinavica - B Soil and Plant Science 60 (3): 256-261.

Bose J, Rodrigo-Moreno A, Shabala S (2014). ROS homeostasis in halophytes in the context of salinity stress tolerance. Journal of Exprimental Botany 65 (5): 1241-1257.

Busscher W, Bjorneberg D, Sojka R (2009). Field application of PAM as an amendment in deep-tilled US southeastern coastal plain soils. Soil Tillage Research 104 (2): 215-220.

Cannazza G, Cataldo A, De Benedetto E, Demitri C, Madaghiele M et al. (2014). Experimental assessment of the use of a novel superabsorbent polymer (SAP) for the optimization ofwater consumption in agricultural irrigation process. Water 6 (7): 2056-2069.

Chaithra G, Sridhara S (2018). Growth and yield of rainfed maize as influenced by application of super absorbent polymer and Pongamia leaf mulching. International Journal of Conservation Science 6 (5): 426-430.

Chang L, Xu L, Liu Y, Qiu D (2021). Superabsorbent polymers used for agricultural water retention. Polymer Testing 94: 107021.

Chen S, Zommorodi M, Fritz E, Wang S, Hüttermann A (2004). Hydrogel modified uptake of salt ions and calcium in Populus euphratica under saline conditions. Trees 18 (2): 175-183.

Dang J, Zhao J, Du Z (2017). Effect of superabsorbent polymer on the properties of concrete. Polymers 9 (12): 672.

de Barros AF, Pimentel LD, Araujo EF, de Macedo LR, Martinez HEP et al. 2017. Super absorbent polymer application in seeds and planting furrow: it will be a new opportunity for rainfed agriculture. Semina Ciências Agrárias 38 (4): 1703-1714.

Dehkordi DK (2017). Effects of a hydrophilic polymer soil amendment on stress tolerance of Eucalyptus saligna. Horticulture Environment Biotechnology 58 (4): 350-356.

Dorraji SS, Golchin A, Ahmadi S (2010). The effects of hydrophilic polymer and soil salinity on corn growth in sandy and loamy soils. Clean Soil Air Water 38 (7): 584-591.

El Sagan M (2015). Effect of polymer on drought tolerance of tomato (*Solanum lycopersicum* L.). European Journal of Academic Essays 2 (9): 72-82.

Elshafie HS, Camele I (2021). Applications of absorbent polymers for sustainable plant protection and crop yield. Sustainability 13 (6): 3253.

Fallahi HR, Kalantari RT, Aghhavani-Shajari M, Soltanzadeh MG (2015). Effect of super absorbent polymer and irrigation deficit on water use efficiency, growth and yield of cotton. Notulae Scientia Biologicae 7 (3): 338-344.

Fan Z, Tian X, Zhai S, Liu Z, Chu P, Li C, Sun S, Li T (2022). Co-application of controlled-release urea and a superabsorbent polymer to improve nitrogen and water use in maize. Archives of Agronomy and Soil Science 68 (7): 914-928.

Fernando T, Aruggoda A, Disanayaka C, Kulathunge S (2014). Evaluating the effects of different watering intervals and prepared soilless media incorporated with a best weight of super absorbent polymer (SAP) on growth of tomato. Journal of Engineering Technology 2: 2279-2627.

Geesing D, Schmidhalter U (2004). Influence of sodium polyacrylate on the water-holding capacity of three different soils and effects on growth of wheat. Soil Use Management 20 (2): 207-209.

Gholami A, Shahsavani S, Nezarat S (2009). The effect of plant growth promoting rhizobacteria (PGPR) on germination, seedling growth and yield of maize. International Journal of Biology and Life Sciences 1 (1): 35-40.

Grabiński J, Wyzińska M (2018). The effect of superabsorbent polymer application on yielding of winter wheat (*Triticum aestivum* L.). Research for Rural Development 2: 55-61

Guo M, Liu M, Zhan F, Wu L (2005). Preparation and properties of a slow-release membrane-encapsulated urea fertilizer with superabsorbent and moisture preservation. Industrial and Engineering Chemistry Research 44 (12): 4206-4211.

Hejduk S, Baker SW, Spring CA (2012). Evaluation of the effects of incorporation rate and depth of water-retentive amendment materials in sports turf constructions. Acta Agriculturae Scandinavica-B Soil and Plant Science 62: 155-164.

Hermans K, McLeman R (2021). Climate change, drought, land degradation and migration: exploring the linkages. Current Opinion in Environmental Sustainability 50: 236-244.

Horie K, Barón M, Fox R, He J, Hess M et al. (2004). Definitions of terms relating to reactions of polymers and to functional polymeric materials (IUPAC Recommendations 2003). Pure and Applied Chemistry 76 (4): 889-906.

Horn B, Ferreira C, Kalantari Z (2022). Links between food trade, climate change and food security in developed countries: A case study of Sweden. Ambio 51 (4): 943-954.

Hou X, Li R, He W, Dai X, Ma K et al. (2018). Superabsorbent polymers influence soil physical properties and increase potato tuber yield in a dry-farming region. Journal of Soil Sediments 18 (3): 816-826.

Huang Z, Sun P, Zhong J, Chen Y (2016). Application of super absorbent polymer in water and fertilizer conversation of soil and pollution management. Transictions of the Chinese Society of Agriculral Engineering 32 (1): 125-131.

Hussain S, Hussain S, Ali B, Ren X, Chen X et al. (2021). Recent progress in understanding salinity tolerance in plants: Story of Na^+/K^+ balance and beyond. Plant Physiology and Biochemistry 160: 239-256.

Hüttermann A, Reise K, Zomorrodi M, Wang S (1997). The use of hydrogels for afforestation of difficult stands: water and salt stress. Afforestation in semiarid regions. Datong China 167-177.

Islam MR, Eneji AE, Ren C, Li J, Hu Y (2011). Impact of water-saving superabsorbent polymer on oat (Avena spp.) yield and quality in an arid sandy soil. Scientific Research and Essays 6 (4): 720-728.

Ito K (2007) Novel cross-linking concept of polymer network: synthesis, structure, and properties of slide-ring gels with freely movable junctions. Polymer Journal 39 (6): 489-499.

Jamnongkan T, Kaewpirom S (2010). Potassium release kinetics and water retention of controlled-release fertilizers based on chitosan hydrogels. Journal of Polymers and the Environment 18 (3): 413-421.

Jin S, Yue G, Feng L, Han Y, Yu X et al. (2011). Preparation and properties of a coated slow-release and water-retention biuret phosphoramide fertilizer with superabsorbent. Journal of Agriculture and Food Chemistry 59 (1): 322-327.

Kaith BS, Jindal R, Kapur GS (2013). Enzyme-based green approach for the synthesis of gum tragacanth and acrylic acid cross-linked hydrogel: its utilization in controlled fertilizer release and enhancement of water-holding capacity of soil. Iranian Polymer Journal 22 (8): 561-570.

Kaith BS, Jindal R, Kumar V (2015). Biodegradation of Gum tragacanth acrylic acid based hydrogel and its impact on soil fertility. Polymer Degradation and Stability 115: 24-31.

Kalhapure A, Kumar R, Singh VP, Pandey D (2016). Hydrogels: a boon for increasing agricultural productivity in water-stressed environment. Current Science 1773-1779.

Kant C, Aydin A, Turan M (2008). Ameliorative effect of hydro gel substrate on growth, inorganic ions, proline, and nitrate contents of bean under salinity stress. Journal of Plant Nutrition 31 (8): 1420-1439.

Karl TR, Melillo JM, Peterson TC, Hassol SJ (2009). Global climate change impacts in the United States. Cambridge University Press.

Keshavarz L, Farahbakhsh H, Golkar P (2013). Effects of different irrigation and superabsorbent levels on physio-morphological traits and forage yield of millet (*Pennisetum americanum* L.). American-Eurasian Journal of Agricultural and Environmental Sciences 13 (8): 1043-1049.

Khadem S, Rousta M, Chorom M, Khadem S, Kasraeyan A (2010). The effects of different rates of super absorbent polymers and manure on corn nutrient uptake, Proceedings of the 19th world congress of soil science: soil solutions for a changing world, Brisbane, Australia, pp. 1-6.

Khalilpour A (2001). Study the application of superabsorbent polymer (BT773) on controlling soil erosion and conservation. Report of Research Project. Tehran Research Center of Natural Resources. Ministry of Jihad Agriculture. Tehran, Iran.

Kenawy ER, Seggiani M, Hosny A, Rashad M, Cinelli P, Saad-Allah KM, El-Sharnouby M, Shendy S, Azaam MM (2021). Superabsorbent composites based on rice husk for agricultural applications: Swelling behavior, biodegradability in soil and drought alleviation. Journal of Saudi Chemical Society 25 (6): 101254.

Kuang W, Liu J, Dong J, Chi W, Zhang C (2016). The rapid and massive urban and industrial land expansions in China between 1990 and 2010: A CLUD-based analysis of their trajectories, patterns, and drivers. Landscape and Urban Planning 145: 21-33.

Kuang W, Liu J, Tian H, Shi H, Dong J et al. (2022). Cropland redistribution to marginal lands undermines environmental sustainability. National Science Review 9 (1): p.nwab091.

Kumar S, Meena RS, De N, Gurjar D, Singh A et al. (2019). Effect of polymers and nutrient management on sesame (*Sesamum indicum*) under custard apple (*Annona squamosa*) based agri-horti system. The Indian Journal of Agricultural Sciences 89 (11): 1871-1875.

Lambin EF, Meyfroidt P (2011). Global land use change, economic globalization, and the looming land scarcity. Proceedings of the National Academy of Sciences 108 (9): 3465-3472.

Li J, Jiang M, Wu H, Li Y (2009). Addition of modified bentonites in polymer gel formulation of 2, 4-D for its controlled release in water and soil. Journal of Agriculture and Food Chemistry 57 (7): 2868-2874.

Li J, Liu L, Zhou H, Li M (2018). Improved viability of areca (*Areca catechu* L.) seedlings under drought stress using a superabsorbent polymer. Horticultural Science 53 (12): 1872-1876. doi.org/10.21273/HORTSCI13586-18

Li X, He J, Zheng Y, Zheng M (2014). Environmental safety assessment on the new super absorbent polymers applied into a soil-Chinese cabbage system. Huan jing ke xue Huanjing kexue. 35 (2): 780-785. https://europepmc.org/article/med/24812978

Li X, He JZ, Liu YR, Zheng YM (2013). Effects of super absorbent polymers on soil microbial properties and Chinese cabbage (*Brassica chinensis*) growth. Journal of Soil Sediments 13 (4): 711-719.

Li X, Li Q, Su Y, Yue Q, Gao B et al. (2015). A novel wheat straw cellulose-based semi-IPNs superabsorbent with integration of water-retaining and controlled-release fertilizers. Journal of the Taiwan Instititute of Chemical Engineers 55: 170-179.

Li Y, Li X, Zhou L, Zhu X, Li B (2004). Study on the synthesis and application of salt-resisting polymeric hydrogels. Polymers for Advanced Technology 15 (1-2): 34-38.

Li Y, Shi H, Zhang H, Chen S (2019). Amelioration of drought effects in wheat and cucumber by the combined application of super absorbent polymer and potential biofertilizer. PeerJ 7: e6073. doi.org/10.7717/peerj.6073

Liang R, Yuan H, Xi G, Zhou Q (2009). Synthesis of wheat straw-g-poly (acrylic acid) superabsorbent composites and release of urea from it. Carbohydrate Polymers 77 (2): 181-187.

Liu L, Guo QX (2001). Isokinetic relationship, isoequilibrium relationship, and enthalpy– entropy compensation. Chemical Reviews 101 (3): 673-696.

Ma S, Liu M, Chen Z (2004) Preparation and properties of a salt-resistant superabsorbent polymer. Journal of Applied Polymer Science 93 (6): 2532-2541.

Maddhesiya PK, Singh K, Singh RP (2021). Effects of perennial aromatic grass species richness and microbial consortium on soil properties of marginal lands and on biomass production. Land Degradation & Development 32 (2): 1008-1021.

Mao S, Islam MR, Xue X, Yang X, Zhao X et al. (2011). Evaluation of a water-saving superabsorbent polymer for corn (*Zea mays* L.) production in arid regions of Northern China. African Journal of Agricultural Research 6 (17): 4108-4115.

Marandi GB, Sharifnia N, Hosseinzadeh H (2006). Synthesis of an alginate–poly (sodium acrylate-co-acrylamide) superabsorbent hydrogel with low salt sensitivity and high pH sensitivity. Journal of Applied Polymer Science 101 (5): 2927-2937.

Marzen M, Iserloh T, Casper MC, Ries JB (2015). Quantification of particle detachment by rain splash and wind-driven rain splash. Catena 127: 135-141.

Mellor P, Lord RA, João E, Thomas R, Hursthouse A (2021). Identifying non-agricultural marginal lands as a route to sustainable bioenergy provision-a review and holistic definition. Renewable and Sustainable Energy Reviews 135: 110220.

Mihou A, Michaelakis A, Krokos F, Mazomenos B, Couladouros E (2007). Prolonged slow release of (Z)-11-hexadecenyl acetate employing polyurea microcapsules. Journal of Applied Entomology 131 (2): 128-133.

Mishra J, Singh R, Arora N (2017). Alleviation of heavy metal stress in plants and remediation of soil by rhizosphere microorganisms. Frontier in Microbiology 8: 1706.

Moghadam HRT (2016). Application of super absorbent polymer and ascorbic acid to mitigate deleterious effects of cadmium in wheat. Pesquisa Agropecuaria Tropical 46 (1): 9-18.

Moghadam HRT (2017). Super absorbent polymer mitigates deleterious effects of arsenic in wheat. Rhizosphere 3: 40-43.

Montesano F, Parente A, Santamaria P, Sannino A, Serio F (2015). Biodegradable superabsorbent hydrogel increases water retention properties of growing media and plant growth. Agricure and Agricultural Sciences Procedia 4: 451-458.

Motamedi E, Motesharezedeh B, Shirinfekr A, Samar SM (2020). Synthesis and swelling behavior of environmentally friendly starch-based superabsorbent hydrogels reinforced with natural char nano/micro particles. Journal of Environmental Chemical Engineering 8 (1): 103583.

Mukhopadhyay R, Sarkar B, Jat HS, Sharma PC, Bolan NS (2021). Soil salinity under climate change: Challenges for sustainable agriculture and food security. Journal of Environmental Management 280: 111736.

Munns R, Tester M (2008). Mechanisms of salinity tolerance. Annual Review in Plant Biology 59: 651-681.

Najafinezhad H, Tahmasebi Sarvestani Z, Modarres Sanavy SAM, Naghavi H (2015). Evaluation of yield and some physiological changes in corn and sorghum under irrigation regimes and application of barley residue, zeolite and superabsorbent polymer. Archive of Agronomy and Soil Scieence 61 (7): 891-906.

Nazarli H, Zardashti MR, Darvishzadeh R, Najafi S (2010). The effect of water stress and polymer on water use efficiency, yield and several morphological traits of sunflower under greenhouse condition. Notulae Scientia Biologicae 2(4): 53-58.

Nejatzadeh-Barandozi F (2019). Investigation of super absorbent polymers and zinc sulfate on the yield and yield components of *Calendula officinalis* L. Acta Scientiarum Polonorum Hortorum Cultus 18 (2): 105-113.

Nezarat S, Gholami A (2009). Screening plant growth promoting rhizobacteria for improving seed germination, seedling growth and yield of maize. Pakistan Journal of Biological Sciences 12 (1): 26-32.

Ni B, Liu M, Lü S (2009). Multifunctional slow-release urea fertilizer from ethylcellulose and superabsorbent coated formulations. Chemical Engineering Journal 155 (3): 892-898.

Ni B, Liu M, Lu S, Xie L, Wang Y (2011). Environmentally friendly slow-release nitrogen fertilizer. Journal of Agricultural and Food Chemistry 59 (18): 10169-10175.

Nascimento CDV, Simmons RW, de Andrade Feitosa JP, dos Santos Dias CT, Costa MCG (2021). Potential of superabsorbent hydrogels to improve agriculture under abiotic stresses. Journal of Arid Environments 189: 104496.

Olad A, Doustdar F, Gharekhani H (2018). Starch-based semi-IPN hydrogel nanocomposite integrated with clinoptilolite: Preparation and swelling kinetic study. Carbohydrate Polymers 200: 516-528.

Paradelo R, Basanta R, Barral MT (2019). Water-holding capacity and plant growth in compost-based substrates modified with polyacrylamide, guar gum or bentonite. Scientia Horticulturae 243: 344-349.

Pimentel D (2012). Global economic and environmental aspects of biofuels. CRC press.

Prăvălie R, Patriche C, Borrelli P, Panagos P, Roşca B et al. 2021. Arable lands under the pressure of multiple land degradation processes. A global perspective. Environmental Research 194: 110697.

Qiao D, Liu H, Yu L, Bao X, Simon GP, Petinakis E, Chen L (2016). Preparation and characterization of slow-release fertilizer encapsulated by starch-based superabsorbent polymer. Carbohydrate polymers 147: 146-154.

Raju KM, Raju MP, Mohan YM (2002). Synthesis and water absorbency of crosslinked superabsorbent polymers. Journal of Applied Polymer Science 85 (8): 1795-1801.

Rasanjali K, De Silva C, Priyadarshani K (2019). Influence of super absorbent polymers (saps) on irrigation interval and growth of black pepper (*Piper nigrum* L.) in nursery management. OUSL Journal 14 (1): 7-25. doi.org/10.4038/ouslj.v14i1.7458

Rehman A, Ahmad R, Safdar M (2011). Effect of hydrogel on the performance of aerobic rice sown under different techniques. Plant Soil Environment 57 (7): 321-325.

Rehman TU, Shah LA, Khattak NS, Khan A, Rehman N et al. (2019). Superabsorbent Hydrogels for Heavy Metal Removal, Heavy Metal Ions Removal. IntechOpen.

Rojas R, Morillo J, Usero J, Delgado-Moreno L, Gan J (2013). Enhancing soil sorption capacity of an agricultural soil by addition of three different organic wastes. Science of Total Environment 458: 614-623.

Rostampour MF, Yarnia M, Khoee FR (2012). Effect of polymer and irrigation regimes on dry matter yield and several physiological traits of forage sorghum. African Journal of Biotechnology 11(48): 10834-10840.

Roy A, Singh S, Bajpai J, Bajpai A (2014). Controlled pesticide release from biodegradable polymers. Central European Jounral of Chemistry 12 (4): 453-469.

Ryan Q, Geetha K, Shanker A (2018). Effect of organic manures and super absorbent polymers on nutrients uptake and economics of soybean [*Glycine max* (L.) Merrill]. International Journal of Chemical Studies 6 (4): 2694-2698.

Sayed HE, Kirkwood R, Graham N (1991). The effects of a hydrogel polymer on the growth of certain horticultural crops under saline conditions. Journal of Experimental Botany 42 (7): 891-899.

Seyed DS, Golchin A, Ahmadi S (2010). The effects of different levels of a superabsorbent polymer and soil salinity on water holding capacity with three textures of sandy, loamy and clay. Journal of Water and Soil 24: 306-3016.

Shekari F, Javanmard A, Abbasi A (2015). Effects of super-absorbent polymer application on yield and yield components of rapeseed (*Brassica napus* L.). Notulae Scientia Biologicae 7 (3): 361-366.

Shi Y, Li J, Shao J, Deng S, Wang R et al. (2010). Effects of Stockosorb and Luquasorb polymers on salt and drought tolerance of Populus popularis. Scientia Horticulturae 124 (2): 268-273.

Sikder A, Pearce AK, Parkinson SJ, Napier R, O'Reilly RK (2021). Recent trends in advanced polymer materials in agriculture related applications. ACS Applied Polymer Materials 3 (3): 1203-1217.

Silberbush M, Adar E, De Malach Y (1993). Use of an hydrophilic polymer to improve water storage and availability to crops grown in sand dunes I. Corn irrigated by trickling. Agriculture Water Management 23 (4): 303-313.

Singh K, Awasthi A, Sharma SK, Singh S, Tewari SK (2018). Biomass production from neglected and underutilized tall perennial grasses on marginal lands in India: a brief review. Energy, Ecology and Environment 3 (4): 207-215.

Smagin A, Sadovnikova N, Nikolaeva E (2014). Thermodynamic analysis of the effect of strongly swelling polymer hydrogels on the physical state of soil and sediment samples. Eurasian Soil Science 47 (2): 78-88.

Song J, Zhao H, Zhao G, Xiang Y, Liu Y (2019). Novel semi-IPN nanocomposites with functions of both nutrient slow-release and water retention. 1. Microscopic structure, water absorbency, and degradation performance. Journal of Agricultural and Food Chemistry 67 (27): 7587-7597.

Song X, Zhu C, Fan D, Mi Y, Li X et al. 2017. A novel human-like collagen hydrogel scaffold with porous structure and sponge-like properties. Polymers 9 (12): 638.

Su LQ, Li JG, Xue H, Wang XF (2017). Super absorbent polymer seed coatings promote seed germination and seedling growth of Caragana korshinskii in drought. Journal of Zhejiang University Science B 18 (8): 696-706.

Sutradhar SC, Khan MMR, Rahman MM, Dafadar NC (2015). The Synthesis of Superabsorbent Polymers from a Carboxymethylcellulose/acrylic Acid Blend Using Gamma Radiation and its Application in Agriculture. Journal of Physical Science 26 (2): 23-39.

Taheri H, SoltaniMohammadi A, Alemzadeh Ansari N (2017). Effects of superabsorbent polymer on the number and leaf area of lettuce under drought stress. Journal of Water Science Engineering 7 (15): 71-80.

Timilsena YP, Adhikari R, Casey P, Muster T, Gill H et al. (2015). Enhanced efficiency fertilisers: a review of formulation and nutrient release patterns. Journal of the Science of Food Agriculture 95 (6): 1131-1142.

Tongo A, Mahdavi A, Sayad E (2014). Effect of superabsorbent polymer aquasorb on chlorophyll, antioxidant enzymes and some growth characteristics of Acacia victoriae seedlings under drought stress. Ecopersia 2 (2): 571-583.

Tu C, Koenning S, Hu S (2003). Root-parasitic nematodes enhance soil microbial activities and nitrogen mineralization. Microbial Ecolology 46 (1): 134-144.

Wang W, Yang Z, Zhang A, Yang S (2021). Water retention and fertilizer slow release integrated superabsorbent synthesized from millet straw and applied in agriculture. Industrial Crops and Products 160: 113126.

Weaver DM, Wong MT (2011). Scope to improve phosphorus (P) management and balance efficiency of crop and pasture soils with contrasting P status and buffering indices. Plant Soil 349 (1-2): 37-54.

Wei J, Yang H, Cao H, Tan T (2016). Using polyaspartic acid hydrogel as water retaining agent and its effect on plants under drought stress. Saudi Journal of Biological Sciences 23 (5): 654-659.

Wróblewska K, Debicz R, Babelewski P (2012). The influence of water sorbing geocomposite and pine bark mulching on growth and flowering of some perennial species. Acta Scientiarum Polonorum Hortorum Cultus 11 (2): 203-216.

Wu L, Liu M (2008). Preparation and properties of chitosan-coated NPK compound fertilizer with controlled-release and water-retention. Carbohydrate Polymer 72 (2): 240-247.

Yakupoglu T, Rodrigo-Comino J, Cerdà A (2019). Potential benefits of polymers in soil erosion control for agronomical plans: A laboratory experiment. Agronomy. 9 (6): 276.

Yang Y, Wang H, Huang L, Zhang S, He Y et al. (2017). Effects of superabsorbent polymers on the fate of fungicidal carbendazim in soils. Jounral of Hazardous Material 328: 70-79.

Yazdani F, Allahdadi I, Akbari GA (2007). Impact of superabsorbent polymer on yield and growth analysis of soybean (*Glycine max* L.) under drought stress condition. Pakistan Journal of Biological Sciences 10 (23): 4190-4196.

Yousefian M, Jafari M, Tavili A, Arzani H, Jafarian Z (2018). The effects of superabsorbent polymer on Atriplex lentiformis growth and soil characteristics under drought stress (Case Study: Desert Research Station, Semnan, Iran). Journal of Rangeland Science 8 (1): 65-76.

Zhang S, Yang Y, Gao B, Wan Y, Li YC et al. (2016). Bio-based interpenetrating network polymer composites from locust sawdust as coating material for environmentally friendly controlled-release urea fertilizers. Journal of Agricultural and Food Chemistry 64 (28): 5692-5700.

Zhao C, Zhang M, Liu Z, Guo Y, Zhang Q (2019a). Salt-tolerant superabsorbent polymer with high capacity of water-nutrient retention derived from sulfamic acid-modified starch. ACS omega 4 (3): 5923-5930.

Zhao W, Cao T, Dou P, Sheng J, Luo M (2019). Effect of various concentrations of superabsorbent polymers on soil particle-size distribution and evaporation with sand mulching. Scientific Report 9 (1): 1-9.

Zhengwen Y, Baitian W, Hongliu W, Hao Y (2011). Application of nutrient and super absorbent polymer compound and effect of fertilizer slow-release. Trans. Chinese Society of Agricultural Engineering 27: 56-62.

Zhou T, Wang Y, Huang S, Zhao Y (2018). Synthesis composite hydrogels from inorganic-organic hybrids based on leftover rice for environment-friendly controlled-release urea fertilizers. Science of the Total Environment 615: 422-430.

Zhu XG, Chang TG, Song QF, Finnan J, Barth S et al. 2016. A Systems approach guiding future biomass crop development on marginal land, Perennial Biomass Crops for a Resource-Constrained World. Springer, pp. 209-224.