International Journal of Agriculture and Nutrition 2026; 8(7): 126-137

ISSN Print: 2664-6064
ISSN Online: 2664-6072
NAAS Rating (2026): 4.69
IJAN 2026; 8(7): 126-137
www.agriculturejournal.net
Received: 11-05-2026
Accepted: 14-06-2026

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Environmental assessment of the impact of sodium-containing superabsorbent polymers on soil water dynamics: A review

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DOI: https://www.doi.org/10.33545/26646064.2026.v8.i7b.724

Abstract
Agriculture is facing acute water scarcity as a consequence of climate change, which necessitates a shift toward adopting sustainability-oriented practices in crop production. One of the key pillars of such sustainability is reducing irrigation water use, which can be achieved by adopting soil amendments that enhance the soil's ability to retain moisture (soil water). Sodium containing superabsorbent polymers (SAPs) have been found to influence soil water retention but their full range of effects on soil water movement and long term environmental impacts is not fully understood, and, hence, they are not widely employed on a large-scale scale. This research holds great significance as it offers a comprehensive overview of the mechanisms behind the impact of these polymers on permeability, water retention, infiltration, and evaporation, helping farmers and researchers choose the best polymer for their soil and environment, ultimately contributing to improved water use efficiency and agricultural productivity in arid and semi-arid areas. Selected studies demonstrated that adding SAPs at varying concentrations (0.05% - 2500 mg kg^{-1}) achieved significant increases in maximum water holding capacity (WHC_{max}) ranging from 34.9% to 205%, and reduced erosion rates by up to 99.57%; however, effects varied based on polymer type (PAA loses effectiveness over time, whereas PAM remains stable, or composites provide better balance), application concentration, and soil properties, as sodium alginate hydrogel and composite polymers exhibited superior balance between water retention and permeability. The selection of the optimal polymer depends on soil type and environmental conditions, and the research emphasizes the necessity of long-term field studies to assess sustainability and environmental impacts, develop unified mathematical models, and evaluate the economic feasibility of local applications.

Keywords: SAPs, soil water movement, infiltration, soil water holding capacity, permeability, sodium ion

1. Introduction

1.1. General Overview of the Problem: The Importance of Soil Water Movement in Agriculture, and the Need to Improve Irrigation Techniques and Soil Water Retention Capacity

To enhance agricultural productivity and sustainability, it is important to understand the movement of soil water. Soil water movement has an influence on soil plant water relations and in turn on plant growth, health and conservation and is thus an important component in agricultural management. To solve water scarcity and water use problem in agriculture, it is vital to improve irrigation technique and enhance soil water holding capacity. This study discusses the significance of soil water movement, the necessity of better irrigation methods and methods to increase the soil water holding capacity. The properties of soils with respect to water (moisture retention curve, hydraulic conductivity) are basic for controlling water flow and movement within the soil. These properties determine how water and soil solution flow in the soil will impact water availability to plants and nutrient uptake (Kargas *et al.*, 2022) [1]. Redistributing soil moisture is essential to ensure water supply in root zone particularly in arid regions. This allows for water to be carried deeper into the soil, something that is important for plant survival in drought conditions (Hillel, 2003) [2]. Soil is also the natural reservoir which controls the supply of fresh water. Soil water dynamics are associated with different phases like saturation, field capacity, and its dynamics are essential for sustainable use of water in agriculture (Jangir *et al.,* 2024) [3]. Traditional irrigation systems like flood and surface irrigation can therefore result in water loss and soil erosion. Modern methods, for instance drip irrigation, are able to supply water to the root zone with greater precision, so that less water can be lost and water is more efficiently used; advanced irrigation systems such as automation and smart controls ensure efficient water distribution, resulting in minimal environmental impact. These technologies are critical to cope with climate variability and it is important to increase the scarcity of water (Choudhary, 2024) [4]. Irrigation plan optimisation with soil and crop characteristics by micro planning can be used to promote sustainable agriculture and optimise water use (Jangir *et al.,* 2024) [3]. Organic mulch, deep plowing and leveling enhance moisture holding capacity, soil structure and reduce soil erosion. These practices are particularly beneficial in dryland and rain-fed areas (Ishfaq *et al.,* 2024). Soil amendments and organic mulch also may change the hydraulic properties of the soil, improving soil water retention and soil water movement. This is essential to avoid soil salinization, enhance crop productivity (Kargas *et al.,* 2023) [5]. Recognizing the importance of a wateruse-and-drainage management approach that incorporates groundwater resources components and environmenta concerns is essential for sustainable water use and soil health (El Gayar, 2024). Whilst there is a need to develop irrigation methods and ensure water storage ability in the soils (or water holding capacity), there are concerns on balancing water use efficiency with environmental protection. With greater competition for water resources, it is essential to have a holistic view of soil and water dynamics and the development of innovative water management strategies. To overcome these challenges, a cooperative approach between researchers, policy makers and farmers is necessary to promote sustainable agriculture practices and water conservation.

1.2. Definition of Superabsorbent Polymers and Their Role in Improving Soil Water Retention

Superabsorbent polymers (SAPs) are known for their ability to significantly enhance soil water retention, making them valuable tools in agriculture, especially in water-scarce regions. These polymers, which may be synthetic, natural, or semi-synthetic, are capable of absorbing large amounts of water and releasing it slowly, thereby improving soil moisture levels and reducing the need for frequent irrigation. They also improve soil structure and nutrient availability, contributing to sustainable agricultural practices. Superabsorbent polymers are used as soil conditioners in arid regions to improve water use efficiency, as they help slow nutrient loss and provide systems for their slow release, thereby boosting crop yields and contributing to the promotion of environmentally friendly agricultural practices (Krasnopeeva *et al.,* 2022) [6]. Superabsorbent polymers can absorb up to 100,000% of their weight in water, significantly enhancing soil water-holding capacity (Singh *et al.,* 2023) [7]. This property is particularly beneficial in arid regions where water scarcity is a major challenge (Singh *et al.,* 2019) [8]. Studies have shown that superabsorbent polymers can increase soil porosity and reduce bulk density, thereby improving drainage and soil water retention (Muriithi *et al.,* 2024) [9]. For example, superabsorbent polymers have been shown to increase soil water-holding capacity by up to 34.9% in some soil treatments, The application of superabsorbent polymers can also affect soil texture, increasing clay content and reducing sand and silt content, thereby further enhancing soil water-holding capacity (Reyes *et al.,* 2025) [10]. Superabsorbent polymers have been shown to improve plant growth indicators such as plant height, number of leaves, and yield. For example, sweet pepper yield increased by 53.4% when soil was treated with superabsorbent polymers in a study conducted in Kenya (Muriithi *et al.,* 2024) [9]. In experiments with radish seeds, soil amended with superabsorbent polymers demonstrated sustained plant growth and health under reduced irrigation conditions, unlike the control groups that were not treated with polymers (Nnadi and Brave, 2011) [11]. The use of superabsorbent polymers was associated with improved plant health, as treated plants exhibited better color, larger leaf size, and better overall growth compared to untreated plants (Gubat *et al.,* 2025) [12]. The superabsorbent polymer is also non-toxic and eco-friendly, it is also suitable for sustainable agriculture, it can reduce the loss of nitrogen from leaching by as much as 45%, which helps to preserve soil fertility and eliminate pollution of the environment (Malik *et al.,* 2022) [13]. As a result of the use of biodegradable superabsorbent polymers like those made from shrimp shell waste and potato straw, the problem of non-biodegradable polymers (Gubat *et al.,* 2025) [12] can be solved. Superabsorbent polymers enhance the efficiency of the irrigation system and minimize water consumption, promoting responsible resource management, which falls under Sustainable Development Goals 6 and 12 to ensure sustainable consumption and land use (Reyes *et al.,* 2025) [10]. While there are many advantages to using superabsorbent polymers, their success can depend on soil type, polymer composition, and application rate. However, using too much polymer does not necessarily lead to better soil water retention (Reyes *et al.,* 2025) [10]. The price of superabsorbent polymers and their adoption by farmers may be a barrier particularly in developing areas. To this end, economic evaluations and region-specific studies have to be done to identify the best ways of their use (Malik *et al.,* 2022) [13]. In addition, using superabsorbent polymers for a prolonged period has a negative impact on soil health, and their interaction with other soil amendments need to be studied to ensure sustainable agriculture (Muriithi *et al.,* 2024) [9]. In conclusion, superabsorbent polymers (SAPs) offer a potentia solution for enhancing soil moisture retention and boosting agricultural production, especially in areas where water is scarce. Their use, however, needs to be carefully planned and managed so as to ensure that the benefits are maximized and the potential disadvantages are minimized. The development of low cost biodegradable superabsorbent polymers can be further developed to promote their use and benefits in sustainable agriculture.

1.3. How do sodium-containing polymers affect soil properties, including soil water movement?

Sodium-containing polymers significantly affect soil properties, particularly with regard to water movement and soil structure. These polymers can influence the rate of drainage and permeability, hydraulic conductivity, and the physical behavior of soil, especially under saline and alkaline conditions. The interaction of sodium ions with polymers can either reduce or exacerbate problems related to soil dispersion, drainage, and water retention, depending on the type of polymer and the concentrations used. Sodium ions in soil can increase swelling and reduce permeability, particularly in soils with high exchangeable sodium (ESP) content, due to the expansion and swelling of clay particles, which creates a surface film and reduces water movement into the soil (Ben-Hur *et al.,* 1992; So, 1993) [14, 15]. Studies have shown that soil water retention capacity decreases with increasing sodium ion content, as illustrated by the decline in parameters in Philip's water retention model (Wang and Fan, 2009) [16]. Sodium carboxymethyl cellulose (CMC) has been found to improve water retention properties in saline soils.

Prolongs the retention of the total water, improves the water-holding capacity of soil and salt flux (Zhang *et al.,* 2022) [17], and is beneficial for alkaline soils. Soils with low clay content are less affected by sodium than fine textured soils and therefore, the effect of sodium is more significant in fine textured soils (Obear and Soldat, 2014) [18]. Synthetic polymers like polyacrylamide can be used to stabilize soil aggregates and thus reduce soil dispersion and increase infiltration rates (Ben-Hur *et al.,* 1992; Ben-Hur *et al.,* 1989) [14, 19]. They have also proven their effectiveness in enhancing the hydrological characteristics of soils with high infiltration rate, reduced surface runoff and soil loss, and improved water storage and aggregate stability (Ruwanpathirana *et al.,* 2024) [20]. The polysaccharide polymers can affect the hydraulic conductivity of soil by enhancing the soil structure, playing important roles in various environmental and geotechnical applications (Taiba *et al.,* 2024) [21]. Soil and subsoil management under the irrigation system requires utilization of polymers in the irrigation water to maintain infiltration rates and the prevention of crust formation (Ben-Hur *et al.,* 1989) [19]. Moreover, modified chemicals and leaching strategies, based on the tools developed, *e.g.,* HYDRUS, can be used to increase the permeability of the subsoil, as the chemical and physical changes induced by sodium can be counteracted. Sodium containing polymers can enhance the properties of soils and the flow of water through them, but the benefits will vary based on soil type, polymer concentration, and application technique. Whereas in some soils sodium can cause unwanted soil properties, such as poor drainage or lower yields, especially in soils with high clay and ESP content (So, 1993; Balks *et al.,* 1998) [15, 22]. Therefore, it is essential to carefully consider soil characteristics and polymer types to achieve best practices in soil management and enhance soil productivity.

1.4. Significance of the Research: What is the motivation for conducting research in this field? What research gap will be addressed through this literature review?

Many studies have investigated the effects of superabsorbent polymers in general on water retention in soil, but studies on the effects of sodium-containing polymers on water movement and soil structure in various soil texture and salinity conditions are limited. The impact of the use of sodium or the polymer separately has been studied, but the combined effect of adding sodium ions through superabsorbent polymers on soil hydraulic properties is not well known. Hence, more studies are required to examine the dual chemical and physical interactions between sodium ions and soil matrices in the application of superabsorbent polymers especially in alkaline and saline soils. Addressing this knowledge gap is essential to better formulate and utilize superabsorbent polymers to optimize soil water retention, while minimizing impacts on soil structure and fertility.

2. Theoretical Framework

2.1. Superabsorbent Polymers (SAPs): Definition, Structure, and Key Properties

Superabsorbent polymers (SAPs) are a group of functional macromolecules that have the property of absorbing and holding water in significant quantities, compared to their own weight. The high water absorbing capacity, biocompatibility and biodegradability are some of the unique properties of these polymers that makes them widely used in various applications. Superabsorbent polymers are usually made up of a network of loosely crosslinked three-dimensional structures that contain a hydrophilic hydroxyl structure and which can absorb a large amount of water without dissolving. This text will discuss the definition, structure and important characteristics of superabsorbent polymers and the significance of these materials.

2.1.1. Definition and Structure

1. **Definition:** Superabsorbent polymers are hydrophilic, chemically cross-linked polymers capable of absorbing and retaining large amounts of water or aqueous solutions. They can absorb up to 1,500 times their weight in water, forming a gel-like substance upon swelling (Pradhan and Pradhan, 2023; Friedrich, 2012) [23, 24].
2. **Structure:** Superabsorbent polymers have a three-dimensional network structure that is created by chemical or physical cross-linking. This network is built up of hydrophilic groups that bind and hold water molecules. Avoidability of cross-linking means that the polymers do not dissolve in water, and therefore, keep their structure when absorbing water. (Lavlinskaya and Sorokin, 2023; Jagota *et al.,* 2025) [25, 26].

2.1.2. Key Properties

1. **Water Absorption and Retention:** Superabsorbent material has a high capacity to absorb water, absorbing hundreds of times its weight, and is effective in uses that involve moisture-holding properties. It is due to the hydrophilic backbone of the polymer and due to the cross-linked network. (Pu, 2010; Idrissi *et al.,* 2024) [27].
2. **Biocompatibility and Biodegradability:** Many superabsorbent polymers, particularly those based on natural polymers, are environmentally friendly and biodegradable, making them suitable for applications in agriculture, medicine, and hygiene products (Santos, 2023; Barrera-Martínez *et al.,* 2023) [28].
3. **Stimulus Responsiveness:** Some superabsorbent polymers are smart polymers that react to changes in the environment, such as pH, temperature or ionic strength. This property is especially important in the field of drug delivery systems, where the delivery of encapsulated drugs is to be controlled. (Barrera-Martínez *et al.,* 2023) [28].
4. **Mechanical Strength and Flexibility:** Superabsorbent polymers can vary in strength and flexibility depending on the degree of cross linking. In general, the higher the

degree of cross linking, the more strength but less flexibility the material will have (Barrera-Martínez *et al.*, 2023) [28].

While superabsorbent polymers have numerous advantages, there are also some considerations and challenges to be addressed in their use. For instance, their positive effect on the environment, especially from petroleum based sources, is an issue of sustainability and biodegration. Attempts are being made to develop bio-based superabsorbent polymers using renewable resources to tackle these challenges (Jagota *et al.*, 2025) [26]. Other variables like the extent and nature of cross-linking, nature of monomers used and process of synthesis may also affect the behavior of superabsorbent polymers, so that it should be optimized according to the applications. (Lavlinskaya and Sorokin, 2023) [25].

2.2. Soil Water Movement: Definition of water movement in soil (infiltration, percolation, and evaporation) and its impact on agriculture

Water flow in soils is an integral part of the hydrological cycle and plays a direct role in the productivity of an agricultural system. Infiltration, permeability and evaporation are part of this movement, which is responsible for the way water enters the soil, circulates through it and leaves. A number of factors, such as soil texture, structure and management, which are fundamental to plant water availability, soil health and environmental sustainability, influence these processes. Hence, it is important to have a good understanding of these processes to develop irrigation strategies and promote agricultural sustainability.

2.2.1. Infiltration

Infiltration is the movement of water into the soil due to rainfall, irrigation or surface runoff. It is important for replenishment of soil moisture and groundwater, and has a direct impact on water availability to plants (Saha, 2024; Shukla and Lal, 2003) [29, 30]. Soil texture, structure, and compaction are all factors which influence the rate of infiltration. Infiltrations are prone to decrease with poor management practices and surface runoff and erosion are likely to increase (Haghnazari *et al.*, 2024; Shukla and Lal, 2003) [30]. Infiltrates slowly and diffusely, gradually, or more rapidly through root passages or holes made by earthworms in the soil. (Nimmo and Shillito, 2023) [31].

2.2.2. Permeability

Permeability is a soil property of allowing water to flow through its layers and is referred to as deep percolation (Saha, 2024) [29]. The hydraulic properties of the soil, including hydraulic conductivity, are important to permeability. These properties are spatiotemporally variable and thus have an impact on water movement and solute transport in agricultural irrigation systems (Kargas *et al.*, 2022) [1]. Practicing good soil management (preventing compaction and boosting organic matter) enhances soil permeability and water movement in soils. (Haghnazari *et al.*, 2024).

2.2.3. Evaporation: Evaporation refers to the loss of water from the soil surface into the atmosphere. It is influenced by climatic conditions, soil moisture content, and the type of surface cover. High evaporation rates reduce the soil moisture available to plants, necessitating the adoption of effective irrigation practices to maintain optimal soil moisture levels. Evaporation can be reduced using techniques such as organic mulching or growing cover crops, as these methods provide an insulating layer that conserves soil moisture (Jangir *et al.*, 2024) [3].

2.2.4. Impact on Agriculture

Soil water movement is very crucial for sustainable agriculture because it is required for the plants for water and it also prevents runoff and loss of soil nutrients (Jangir *et al.*, 2024; Shukla and Lal, 2003) [3, 30]. The deep understanding of soil water dynamics allows for the creation of water-balanced irrigation systems that conserve water and are able to efficiently meet crop water requirements, thereby optimizing agricultural productivity (Jangir *et al.*, 2024) [3]. Another aspect of water movement that has implications for plant growth, survival, and soil health (Kargas *et al.*, 2022) [1] is that it affects soil salinity and nutrient availability.

While these processes are understood, challenges exist with predicting and managing these processes under field conditions where the variability of climate, soil properties, and changes in farming activities require ongoing research to find ways to adapt to water sustainability and agricultural production resilience.

2.3. The effect of sodium ions on soil properties such as dispersion, permeability, and cohesion, and how can they affect water movement in the soil?

Sodium ions have a significant effect on soil properties such as dispersion, permeability, and cohesion, which directly affects water movement within the soil. The presence of sodium, especially at high concentrations, leads to soil dispersion, reduced permeability, and changes in cohesion, which affect the soil's ability to transport water and support plant growth. These changes are fundamental to understanding soil management and agricultural productivity.

2.3.1. Soil Dispersion and Structure

Sodium ions tend to cause soil dispersion as they reduce the structural strength of soil particles and have larger hydration shell than divalent ions like calcium which causes greater repulsion between fine particles and causes their dispersion (Parameswaran and Sivapullaiah, 2017) [32]. One of the major factors that affects the hydraulic conductivity of soil is dispersion of the clay particles which fill the pores and cause a decrease in the movement of water through the soil layers. (Yousaf *et al.*, 1987; So and Aylmore, 1993) [33, 15].

2.3.2. Permeability and Water Movement

High sodium concentrations reduce soil permeability due to the dispersion of fine particles and their blockage of pores, thereby limiting the soil's ability to transport water (Satar, 2021; Wang and Fan, 2009) [34, 16]. This decrease in permeability leads to poor drainage and surface water accumulation, which negatively affects plant growth and may result in reduced agricultural productivity (So, 1993; Wagenet and Jury, 1984) [15, 35].

2.3.3. Soil Cohesion and Strength

Studies show that sodium ions increase soil cohesion and ultimate strength; it has been observed that sodiumtreated soils have higher compressive and shear strength than untreated soils (Melani *et al.*, 2015) [36]. Although increased cohesion may seem beneficial in some respects, it can lead to soil hardening and difficulty in tillage, thereby limiting the ability of roots to penetrate and grow (Melani *et al.*, 2015; So and Aylmore, 1993) [36, 15].

2.3.4. Treatment Strategies

To reduce the negative effects of sodium ions, soil amendments can be used, such as gypsum (calcium sulfate), which will replace sodium with calcium ions, which will improve the aggregate and soil structure and permeability (Satar, 2021) [34]. Also, by controlling the sodium absorption ratio (SAR), and maintaining suitable electrolyte concentrations, soil dispersion is reduced and hydraulic conductivity (Yousaf *et al.*, 1987; He *et al.*, 2013) [33, 37] is retained.

While sodium ions can have negative effects on soil properties, knowledge of these effects can help develop effective management strategies for sodic soils. Damage caused by sodium can be reduced and soil health and productivity can be significantly improved by using the right amendments and irrigation practices..

2.4. How can sodium improve or impair the properties of polymers in soil?

The interaction between sodium and the soil's superabsorbent polymers (SAPs) is one that clearly impacts the properties of the superabsorbent polymers and can either enhance or diminish their performance. Superabsorbent polymers can be influenced by the presence of sodium ions in soil solutions, in terms of their swelling properties, water holding capacity, and mechanical strength. In agriculture, superabsorbent polymers are used to modify soil properties for better water absorption and soil structure, which is crucial for maintaining soil health and productivity. The effect of sodium on these polymers has been complex and varied; changes in ionic strength, polymer structure and soil conditions all play a role..

2.4.1. Improving Polymer Properties

1. **Water Retention and Swelling:** Common superabsorbent polymer is also called as sodium polyacrylate and can absorb a huge amount of water, which is utilized for enhancing the water holding capacity of the soil. Sodium ion can first promote the swelling of the polymer by increasing the osmotic pressure inside the polymer network, increasing the water absorption rate of the polymer in the deionized or low-salinity environment. (Lee and Lin, 2001; Zhao *et al.*, 2019) [38, 39].
2. **Soil Improvement:** Studies have shown that adding sodium polyacrylate to sandy soils improves mechanical properties such as shear strength and reduces permeability, which helps prevent soil liquefaction and enhances soil stability under dynamic conditions (Özbakan and Evirgen, 2022) [40].

2.4.2. Degradation of Polymer Properties

1. **Decreased Absorbency in Saline Environments:** High concentrations of sodium ions in the soil make superabsorbent polymers less effective in absorbing water. This is because of the ionic screening effect which causes reduction in the electrostatic forces of repulsion between polymer chains, resulting in shrinkage of the gel. (Lee and Lin, 2001; Lee and Wu, 1997) [38, 41].
2. **Leaching of Nutrients:** Sodium polyacrylates can cause increased leaching of nutrients such as nitrogen and phosphorus from certain types of substrates, leading to nutrient loss and environmental issues. Furthermore, the leaching of sodium itself may lead to soil alkalization, which negatively impacts soil health (Li *et al.*, 2012) [42].

2.4.3. Factors Affecting Sodium Interaction with the Polymer

1. **Ionic Strength and Cross-linking:** The amount of swelling of superabsorbent polymers is greatly affected by ionic strength of the solution they are surrounded by and the density of cross-links in the polymer. The swelling increases with decreasing ionic strength, and the stability of polymer structure increases with increasing crosslinking density. (Sohn and Kim, 2003; Sakohara *et al.*, 1990) [43, 44].
2. **Soil Texture and Polymer Concentration:** Soil texture and the amount of the superabsorbent polymer affects the effectiveness of both the superabsorbent polymer and soil water retention. The addition is more beneficial to coarser textured soils and higher polymer concentrations can result in improved soil water holding capacity (Yu *et al.*, 2017) [45]. Sodium can have beneficial effects on the swelling capacity of superabsorbent polymers and on soil water holding capacity at low concentrations but at high concentrations, it can have negative effects on the absorption capacity and cause environmental problems, including nutrient leaching and soil alkalisation. The relationship between sodium and superabsorbent polymers is complex and is dependent on ionic strength, cross-link density and soil conditions. This knowledge is key to maximizing the potentials of these polymers in farming uses and in the management of the environment.

3. Research Methodology

3.1. Type: Review Paper

3.2. Study Selection Method: The study included research addressing the effect of polymers, particularly superabsorbent polymers (SAPs), on water movement in soil, with a focus on those containing sodium ions.

3.3. Criteria: The study included studies published in the last five [14] years that addressed the effect of sodium on superabsorbent polymers in a soil context (laboratory or field studies).

3.4. Screening: The search started with the studies identified in the research question and keywords, but not all of these were relevant, so only those that were relevant were selected. It was found that the relevant studies did not address the research gaps identified, so the relevant studies were screened again. On this basis, useful studies were identified that contribute to addressing the research gap of this study (Table 1).

Table 1: Studies Included in the Research and Criteria for Their Inclusion

Filters		
Search Entry Point	**Years of References Searched**	**Type of Reference**
How might sodium-containing superabsorbent polymers affect infiltration?	2020-2025	Research (scientific papers only)
4.1. The Effect of Superabsorbent Polymers on the Hydraulic Properties of Soil Effect of Superabsorbent Polymers on Infiltration.4.1.1		
Number of Available Studies: 52	Number of Matching Studies:15	Number of Selected Studies:6
How might sodium-containing superabsorbent polymers affect soil ?permeability	2025-2020	Research (scientific papers only)
4.1. The Effect of Superabsorbent Polymers on the Hydraulic Properties of Soil 4.1.2. Effect of Superabsorbent Polymers on Permeability		
Number of Available Studies:24	Number of Matching Studies:16	Number of Selected Studies:6
Effect of superabsorbent polymers on soil water holding capacity	2020-2025	Research (scientific papers only)
4.1. The Effect of Superabsorbent Polymers on the Hydraulic Properties of Soil 1.4.3. Effect of Superabsorbent Polymers on Soil Water Holding Capacity		
Number of Available Studies:100	Number of Matching Studies:12	Number of Selected Studies:6

4. Presentation and Analysis of Results

4.1. The Effect of Superabsorbent Polymers on the Hydraulic Properties of Soil

4.1.1. The Effect of Superabsorbent Polymers on Infiltration

Superabsorbent polymers are among the most important additives that influence drainage behavior in agricultural soils, as they cause a fundamental change in vertical and horizontal water movement due to their high water absorption capacity and swelling within the pores. Fu *et al.* (2022) [46] found that the use of a superabsorbent polymer derived from polyglutamic acid (*γ-PGA*) in sandy loam soil affects drainage under the influence of several factors. Modeling using (HYDRUS-1D) showed that soil bulk density and polymer application depth have a greater effect on cumulative water retention compared to the application rate itself, with the potential to reduce the proportion of water unavailable to plants when selecting the optimal dose and application depth. As Guo *et al.* (2020) [47] demonstrated that the addition of a superabsorbent polymer derived from polyglutamic acid (*γ-PGA*) at rates ranging from 0.05 to 0.20% resulted in a significant decrease in cumulative transpiration during the first 90 minutes by 32.4-52% compared to the control treatment, while field water content increased by 18.7-58.3%, indicating slower vertical water movement and increased water storage in the root zone. Misiewicz *et al.* (2022) [48] showed that the addition of superabsorbent polymers at concentrations of 1% or higher causes a dramatic effect on soil permeability, with permeability coefficients decreasing by hundreds of times within a few minutes, and potentially leading to complete blockage of water flow after approximately 67 minutes when the volume and quantity of polymer particles fill the effective pores. Ruwanpathirana *et al.* (2024) [20], however, reported different results for the biodegradable Fasal Amrit polymer at low concentrations (3 and 6 g m ^{2}) under various rainfall simulations, which led to improved infiltration rates with delayed surface runoff,$^{-}$ improved water storage, and reduced erosion, suggesting a better balance between soil water retention and water permeability to roots. In a comprehensive review, Adjuik *et al.* (2022) [49] that the application of biopolymers and synthetic polymers increases soil water retention while reducing saturated water conductivity and decreasing percolation by up to 90% due to the reduction of large pore space, while maintaining the long-term water availability to plants. Saha *et al.* (2020) [50] highlight the reduction in deep percolation rates and evaporation losses despite variations in soil texture and salinity (Table 2).

Table 2: Efect of superabsorbent polymers on percolation and soil water retention based on selected study results (prepared by the researcher)

Polymer Type	Application Rate or Concentration	Effect on Infiltration	Effect on Soil Water Retention	Study
Polyacrylic Acid (γ-PAA)	0.1-0.3	Decrease in cumulative infiltration	Reduction of unavailable water	Fu *et al.*, 2022 [46]
Polyacrylic Acid (γ-PAA)	0.05%	32.4% decrease	18.7% increase	Guo *et al.*, 2020 [47]
Polyacrylic Acid (γ-PAA)	0.10%	39.2% decrease	26% increase	Guo *et al.*, 2020 [47]
Polyacrylic Acid (γ-PAA)	0.15%	51% decrease	37.8% increase	Guo *et al.*, 2020 [47]
Polyacrylic Acid (γ-PAA)	0.20%	52% decrease	58.3% increase	Guo *et al.*, 2020 [47]
Superabsorbent Polymer (General)	1% (minimum limit)	Decrease in crack formation or complete blockage	High water retention	Misiewicz *et al.*, 2022 [48]
Fasal Amrit (biodegradable)	3 g/m2	Improvement in infiltration	Improvement in water storage	Ruwanpathirana *et al.*, 2024 [20]
Fasal Amrit (biodegradable)	6 g/m2	Improvement < 3 m2	Higher improvement	Ruwanpathirana *et al.*, 2024 [20]
Biopolymer Compounds	0.1-1%	Up to 90% reduction	Increased soil water retention	Adjuik *et al.*, 2022 [49]

4.1.2. The Effect of Superabsorbent Polymers on Permeability: Soil hydraulic conductivity is a fundamental problem in agricultural engineering where it is important in regulating the flow of water and nutrients in the root zone and subsoil. The effects of sodium-containing superabsorbent polymers (SAPs) on soil permeability are significant because they affect the water holding capacity and water movement in the soil. These polymers bind to the soil and take up a lot of water, reducing the volume of permeable soil by filling in spaces between soil particles, and slowing water drainage or leaching.

The addition of high concentrations of SAs (1% or greater) has a rapid effect on the permeability coefficient of soil, as shown by Misiewicz *et al.* (2022) [48], the permeability of the soil is reduced by hundreds of times in just a few minutes, which can cause a complete blockage of water flow. The permeability coefficient decreased to ~10 after 14 minutes, to a factor of 100 after 36 minutes, to a factor of 1000 after 63 minutes, and became fully blocked after about 67 minutes, as the size and number of the polymer particles were enough to fill the effective pores and turn the soil column into a nearly impermeable barrier. In a similar context, Yan *et al.* (2022) investigated the permeability of transparent hydrogel gels (Aquabeads) in different aqueous solutions and concluded that as the concentration of the solutes increased, the effective pore diameter of the gels decreased as did the permeability, with the critical salt concentration identified between 5-7 parts per thousand, indicating that ions like sodium might worsen the reduction in permeability due to a decrease in voids between the polymer particles.

However, Kwon *et al.* (2021) [51] presented a different perspective by enhancing the permeability of the superabsorbent polymers themselves through the introduction of polycationic salts and the addition of surfacemodified silica, suggesting that engineering modifications to the polymer may improve its hydraulic properties. On the other hand, Ng *et al.* (2020) demonstrated that natural biopolymers reduce gas permeability in compacted or densified clay soils by up to 100-fold by reducing large pores and their adhesion due to the viscous nature of the hydrated polymers, and this effect increases with higher soil water content because it provides more water to hydrate the biopolymers and facilitate their clogging of the pores. Biju and Arnepalli (2020) [52], however, observed a relative improvement in the permeability of biopolymer-modified sand-bentonite mixtures due to the aggregation of clay platelets, leading to positive soil restructuring and improved hydraulic behavior. Finally, Chai and Prongmanee (2020) [53] demonstrated that polymerized sodium bentonite exhibits particularly low permeability when exposed to concentrated cationic solutions (especially CaCl at a concentration of 0.6 M),$_2$ with a high ability to self-heal cracks, where the healing rate reached 76% for a 20 mm puncture, compared to 0% for unpolymerized bentonite (see Figure 1).

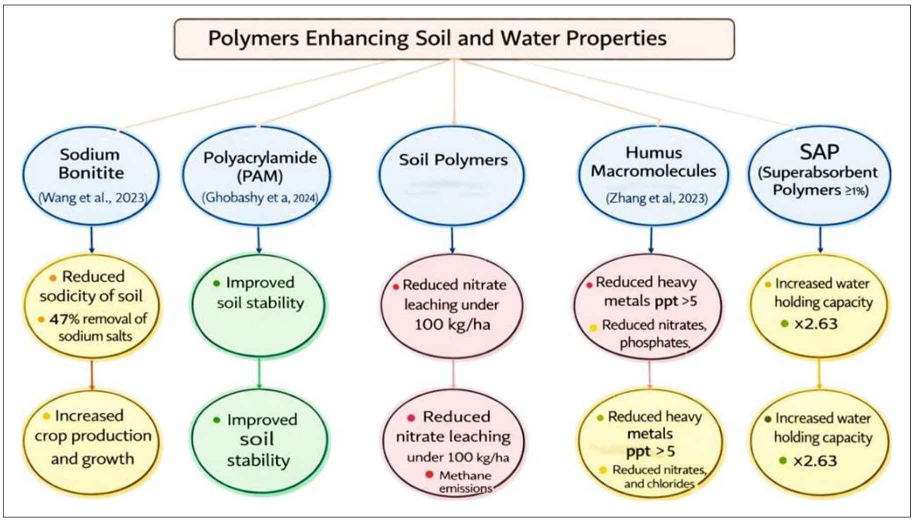

Fig 1: Comparison of the various mechanisms by which substances affect soil permeability (researcher's design).

4.1.3. The effect of superabsorbent polymers on soil water holding capacity (WHC)

Superabsorbent polymers (SAPs) have been shown to significantly enhance soil water holding capacity, which is critical for improving agricultural productivity, especially in water-scarce regions. These polymers can absorb and retain large amounts of water relative to their mass, making them effective soil amendments for increasing soil water retention and reducing the need for irrigation. The application of these polymers can improve soil physical properties, increase plant growth, and enhance water use efficiency. The following is a breakdown of the effects of superabsorbent polymers on soil water-holding capacity based on various studies. It has been shown that polymers significantly increase soil water retention. For example, a study showed that treating soil with 10 grams of polymer mixed with 200 mL of water per 500 grams of soil increased soil water-holding capacity by 34.9% compared to the control plot, with maximum soil water-holding capacity reaching 82.74 (Reyes *et al.*, 2025) [10]. In sandy soils, superabsorbent polymers can enhance soil water retention by increasing the available water capacity (AWC). The highly absorbent natural hydrogel increased the available water capacity by 26% in sandy soil compared to a commercial polymer, and there was a greater improvement as the hydrogel concentration increased (Palma *et al.*, 2024) [54]. The application of polymers in coarse-textured soils also led to a significant increase in soil water retention, as lignin-based hydrogel improved soil water retention under both high and low water potentials (Adjuik *et al.*, 2023) [55].

Superabsorbent polymers, particularly polyacrylic acid (PAA), are synthetic materials that enhance the soil's maximum water-holding capacity (WHCmax) and improve soil stability and aeration. In a study examining the effect of PAA on soil microbial activity in sandy and loamy soils, it was found that the use of PAA increases soil water-holding capacity in both soil types, but its effect on microbial activity varies depending on soil type, polymer concentration, and moisture conditions. A suppression of microbial respiration was observed in sandy soils at high

PAA concentrations, while the effect in loamy soils varied with moisture fluctuations. This highlights the dual role of SAPs in improving soil water retention alongside potential effects on microbial activity and nutrient cycling depending on environmental conditions and polymer concentration (Buchmann *et al.*, 2025) [56].

Other studies show that polyacrylic acid and polyacrylamide (PAA + PMA) form three-dimensional gels that enhance soil water retention and structural stability, but PAA is affected by cycles of drying and wetting and by chemical and structural changes that reduce its reabsorption capacity, suggesting the formation of stable solid residues over time, whereas PAM exhibits greater stability under these conditions (Neff and Buchmann, 2025) [57].

A mixture of polymers such as polyacrylamide and sodium polyacrylate (PMA + PAAS), as well as hydroxypropyl methylcellulose and polyvinyl alcohol (PVA + HPMC), has varying effects on improving soil properties; in particular, PAAS contributes to increasing soil porosity and improving water retention. The polymer mixture also enhances erosion resistance and increases root mass, reflecting the importance of the polymer's chemical composition and its impact on soil properties (Zhang *et al.*, 2023) [58]. The use of sodium alginate-derived hydrogel in sandy loam soils demonstrates the ability to improve tomato plant growth unde drought conditions by increasing soil water and nutrient retention, while acknowledging the absence of phytotoxicity of this polymer, which proves its feasibility in agricultural water management (El Idrissi *et al.*, 2023) [59].

A superabsorbent hydrogel based on polyvinylpyrrolidone (PVP) treated with sodium hydroxide was also developed; this hydrogel demonstrates a high capacity to increase soil water retention and release fertilizers gradually, thereby promoting the growth of pea plants under water stress (Ghobashy *et al.*, 2024) [60]. Finally, a polymeric composite of sodium alginate (SA) and modified dimethyl ether (MDE) with acrylic acid and acrylamide exhibits superior water absorption and soil water retention capabilities, as well as high therma stability, making it a promising material for various agricultural and industrial applications (Wang *et al.*, 2023) [61].

These studies (Table 3 and Figure 2) confirm the significant importance of sodium polyacrylates and sodiumcontaining polymers as effective agents for enhancing soil water-holding capacity, while taking into account their impact on soil microbial activity and surrounding environmental conditions (Buchmann *et al.*, 2025; Neff and Buchmann, 2025; Zhang *et al.*, 2023; El Idrissi *et al.*, 2023; Ghobashy *et al.*, 2024; Wang *et al.*, 2023) [56-61].

Table 3: Polymer composition and its effect on soil water-holding capacity (prepared by the researcher)

Polymer Type	Descriptive Effect	Numerical Value	Agricultural Benefit	Interpretation	Study
Polyacrylic Acid (PAA)	Increased maximum water holding capacity of soil	Concentration 25-2500 mg/kg	Increased water retention and improved plant growth	Enhances soil water retention	Buchmann *et al.*, 2025 [56]
Polyacrylic Acid (PAA)	Reduced microbial activity	Up to 100% reduction	Reduced soil biological activity	May negatively affect microorganisms	Buchmann *et al.*, 2025 [56]
Polyacrylic Acid + Methacrylic Acid (PAA + PMA)	Changes in soil structure under drought cycles	Cross-linking the hydrogel network	Improved soil aggregation	Network formation improves soil stability	Neff and Buchmann, 2025 [57]
Polyacrylamide + HPMC	Reduced soil erosion and improved water retention	99.57% reduction in erosion	Decreased soil loss	Improves soil stability	Zhang *et al.*, 2023 [58]
Polyacrylamide + PVA	Improved soil structure and water retention	98.3% reduction in erosion	Enhanced plant growth	Improves water availability	Zhang *et al.*, 2023 [58]
Polyacrylamide + PAAS	Reduced soil bulk density	96.38% reduction in erosion	Improved soil aeration	Enhances root growth	Zhang *et al.*, 2023 [58]
Sodium Polyacrylate (PAAS)	Increased biomass production	145.23% Increase in root mass	Increased crop yield	Improves soil fertility	Zhang *et al.*, 2023 [58]
Sodium Alginate	Improved soil water retention under drought	1.5-5% concentration	Increased plant resistance	Reduces drought stress	El Idrissi *et al.*, 2023 [59]
Sodium Alginate	Reduced irrigation requirements	30-70% water saving (Daily Amount of Required Water "DARW")	Water conservation	Improves irrigation efficiency	El Idrissi *et al.*, 2023 [59]
PVP + NaOH	Improved fertilizer efficiency	When the filler content is 5% (5 wt.%)	Better nutrient use efficiency	Enhances plant nutrition	Ghobashy *et al.*, 2024 [60]
AM-based polymer (MDE)	Increased soil water holding capacity	39% increase	Improved soil moisture	Supports agricultural sustainability	Wang *et al.*, 2023 [61]
AM-based polymer (MDE)	Improved soil stability	When the filler content is 5% (5 wt.%)	Enhanced durability	Improves long-term soil performance	Wang *et al.*, 2023 [61]

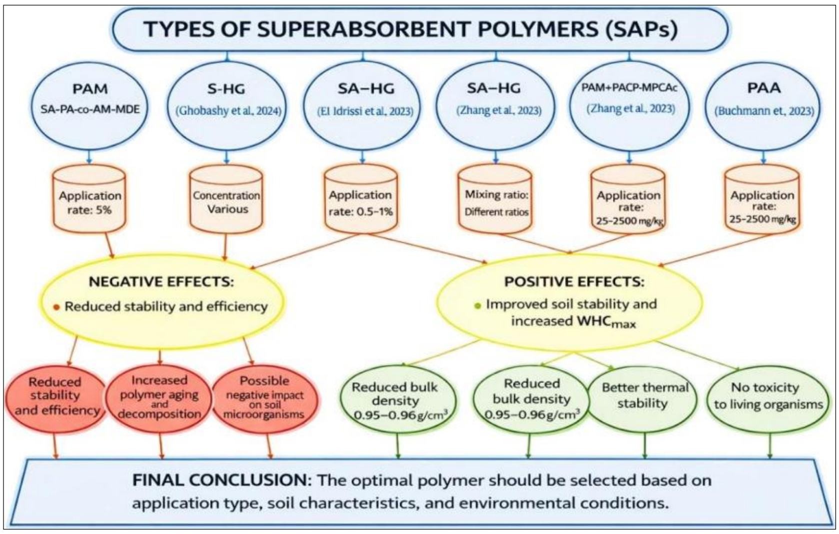

Fig 2: Comparison of the various polymer mechanisms affecting soil permeability to select the most suitable one.(researcher's design)

5. Discussion

Main findings from previous studies and critical analysis of these findings is highlighted in this section. Although superabsorbent polymers containing sodium have been shown to increase soil water holding capacity by up to 205% (Reyes *et al.*, 2025) [10], inconsistencies regarding their impact on soil hydraulic properties are still apparent. The basic effect of the type and concentration of the polymer is illustrated by the results of studies by (Buchmann *et al.*, 2025) [56] which found a very sharp reduction in the permeability of soil (up to 100%) when a polyacrylic acid (PAA) was applied, while a study by (Wang *et al.*, 2023) [61] showed only a slight increase in the water-holding capacity of soil (39%) on the use of composite mixture (SA-g-PAA-co-AMMDE). Research has also shown that *Na+* ions are important in flocculating soil particles in neutral to alkaline soils, but may cause soil structure degradation and particle dispersion in highly alkaline soils or soils with high sodium ion concentration (Melani *et al.*, 2015; Satar, 2021) [36, 34]. Therefore, the polymer mix might be a more environmentally friendly option as sodium alginate hydrogels were found to have a more favorable combination of soil water holding capacity and permeability than the monomeric polymers (El Idrissi *et al.*, 2023) [59]. The majority of these studies have only taken place over short periods of time (usually less than 1 year) and there is a lack of data on the real-life long-term sustainability of the technology in terms of polymer ageing and the decline of the polymer's effectiveness after repeated cycles of drying and wetting (Neff and Buchmann, 2025) [57]..

Long-term effects on the hydraulic properties of soil

Although sodium-containing polymers help reduce permeability and increase soil water retention, their use must be carefully considered to avoid negative effects on soil structure and plant health, especially since high sodium concentrations can lead to soil salinization, which harms crops and soil fertility. Research must continue to identify mechanisms for managing these polymers in a way that ensures agricultural sustainability and the balance of soil ion concentrations.

6. Research Gaps and Recommendations

6.1. Key Research Gaps

Despite significant progress in understanding the effects of superabsorbent polymers on soil water movement, several key research gaps remain:

1. **Studies on saline and alkaline soils:** Most current studies have been conducted on neutral or slightly alkaline soils, while scientific knowledge lacks a comprehensive understanding of the effect of sodiumcontaining polymers in soils with high sodium concentrations or strongly alkaline soils (pH > 8.5), particularly in arid and semi-arid regions (Satar, 2021) [34].
2. **Long-term studies on polymer aging:** There is a clear lack of studies extending beyond 3-5 years to assess the gradual decline in polymer effectiveness under repeated natural conditions of drying and wetting, particularly the effects of thermal and chemical degradation on the polymer (Neff and Buchmann, 2025) [57].
3. **Unified mathematical models:** Studies lack a unified, predictive mathematical model linking polymer concentration, soil type, and environmental conditions to effects on permeability and soil water retention (Ruwanpathirana *et al.*, 2024) [20].
4. **Potential Environmental Impacts:** There is a lack of comprehensive studies on the long-term effects of polymers on soil biodiversity, microbial activity, and potential impacts on groundwater (Buchmann *et al.*, 2025) [56].
5. **Widespread field applications:** A significant lack of studies at the actual farm level -rather than just in laboratories- to assess the economic and practical feasibility of application at production scales (Zhang *et al.*, 2023) [58].

6.2. Recommendations for Future Research

1. Conduct long-term field studies (5-10 years) on local soils with varying characteristics (sandy, clayey, saline, alkaline) to assess sustainability and environmental impacts.
2. Develop advanced mathematical models that integrate hydrophysical data with the chemical properties of the polymer and soil to provide accurate predictive tools.
3. Study the mechanisms of chemical interaction between sodium ions, polymers, and soil particles under various environmental conditions.

4. Assess the economic and environmental feasibility of large-scale application, including production and application costs and expected agricultural returns.
5. Optimize polymer formulations to minimize the negative effects of sodium in soil and increase long-term stability, particularly in harsh environments.

7. Conclusion

Sodium-containing superabsorbent polymers represent a promising tool for addressing water scarcity challenges in agriculture, as they have demonstrated the ability to increase soil water-holding capacity by up to 205% (Reyes *et al.*, 2025) [10] and reduce erosion rates by up to 99.57% (Zhang *et al.*, 2023) [58]. However, their effectiveness varies significantly depending on the type of polymer used, its concentration, specific soil characteristics, and environmental conditions, necessitating a careful and scientifically guided selection. This review underscores the urgent and pressing need for systematic, interdisciplinary research that combines laboratory studies with longterm field studies, alongside the development of unified mathematical models and a comprehensive assessment of environmental and economic impacts. Only through this integrated approach can safe, sustainable, and effective applications of this promising technology be ensured in sustainable agriculture, particularly in arid and semi-arid regions suffering from severe water scarcity.

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