Progress of Straw-based Super Absorbent Polymer in Modern Agriculture and Environmental Remediation

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Abstract: This work provides a comprehensive review of the current research on S-SAPs. It begins by outlining the primary preparation methods, which include raw material pretreatment, graft copolymerization, and performance modification. The paper then examines its diverse applications in modern agriculture, such as improving water use efficiency as a soil water-retaining agent, acting as a controlled-release carrier for fertilizers and pesticides to mitigate environmental pollution, and its potential in ameliorating saline-alkali land. Furthermore, it delves into its utilization in environmental remediation, particularly its capacity to adsorb and eliminate heavy metal ions and organic pollutants from water and soil. In essence, the exploration and utilization of S-SAPs offer a promising technological solution for addressing agricultural waste management, enhancing agricultural resource efficiency, and ecosystem restoration.

1. Introduction

The growth of the global population and economic development has escalated the production pressure on modern agriculture. To meet the increasing demand for food, agriculture heavily relies on the extensive application of chemical fertilizers and pesticides[1, 2]. Nonetheless, these practices have led to various environmental issues including soil degradation, water eutrophication, and heavy metal accumulation[3, 4]. Consequently, the challenge lies in sustaining grain production while mitigating environmental pollution and damage. The shift towards a sustainable agricultural model has emerged as a crucial global imperative and an inevitable trajectory.

The agricultural production process generates a significant amount of agricultural waste, with crop straw from wheat, rice, and corn being the primary component. Traditional disposal methods often involve on-site incineration, resulting in the wastage of biomass resources, air pollution, and threats to human health[5]. Straw, abundant in cellulose, hemicellulose, and lignin, presents an excellent raw material for the development of bio-based materials[6]. Therefore, promoting the conversion of agricultural waste, particularly straw, into valuable resources is crucial for sustainable agriculture.

Super absorbent polymers (SAPs) are polymer materials characterized by a three-dimensional network structure enabling them to absorb and retain water hundreds to thousands of times their weight. Conventional SAPs, predominantly derived from petroleum-based sources like acrylic acid and acrylamide, exhibit excellent water absorption capabilities but pose challenges in terms of biodegradability, potentially leading to environmental contamination[7]. Consequently, the exploration of eco-friendly bio-based SAPs utilizing renewable and biodegradable natural polymers such as starch, cellulose, and chitosan as feedstocks has emerged as a pivotal research avenue in the field[8].

Straw-derived cellulose serves as the structural framework for S-SAPs, with hydrophilic

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monomers integrated through techniques such as graft copolymerization to fabricate semi-synthetic, highly absorbent materials[9]. These composites synergize the outstanding water absorption capacity of synthetic polymers with the biodegradability inherent to natural polymers, thereby presenting considerable application potential in water-saving agriculture, soil amendment, and environmental remediation. This review comprehensively summarizes recent advances in the preparation, performance optimization, and practical utilization of S-SAPs, with a specific focus on their applications in agricultural and environmental fields. Additionally, it outlines future development directions and significant challenges, aiming to serve as a valuable resource for further research and practical implementation in this domain.

2. Preparation and Modification of S-SAPs

The preparation of S-SAPs fundamentally involves utilizing cellulose macromolecules from straw as the primary framework. The process entails the introduction of numerous hydrophilic groups, such as -COOH, -OH, and $-CONH_2$, via chemical methods, thereby facilitating the construction of a moderately cross-linked three-dimensional network structure.

2.1 Pretreatment of Straw

Straw is predominantly composed of cellulose (30-50%), hemicellulose (20-40%), and lignin (10-25%). To enhance cellulose reactivity and increase the accessibility of grafting sites, straw pretreatment is typically indispensable for the removal of lignin and hemicellulose. Currently, prevalent pretreatment strategies encompass both physical and chemical approaches. Physical treatments commonly employ techniques such as mechanical crushing and ball milling to reduce raw material particle size and augment specific surface area, thereby improving the efficiency of subsequent processing steps. This approach is often utilized as a preliminary pretreatment stage prior to chemical modification. Chemical treatment represents a widely adopted pretreatment method: alkaline treatment effectively induces cellulose swelling and removes a substantial fraction of lignin and hemicellulose[10]. Acid treatment, involving dilute sulfuric acid or nitric acid, primarily targets the hydrolysis of hemicellulose[11]. To further enhance the hydrophilicity and reactivity of cellulose, chemical modifications such as carboxymethylation or chemical modifications, such as 2,2,6,6-tetramethylpiperidine -1-oxy mediated oxidation can be implemented. The latter method selectively oxidizes hydroxyl groups on the cellulose surface to form carboxyl groups[8], thereby optimizing the grafting potential for S-SAP synthesis.

2.2 Synthetic Methods

Graft copolymerization stands as the most conventional and efficient approach for fabricating S-SAPs. Typically, this method entails initially creating active free radical sites on the cellulose main chain using initiators. Subsequently, hydrophilic monomers like acrylic acid and acrylamide polymerize at these sites to yield grafted side chains. Simultaneously, the introduction of crosslinking agents into the system (e.g., N,N'-methylene diacrylamide) facilitates cross-linking among the polymer chains, culminating in the formation of a water-insoluble yet highly swellable three-dimensional network structure[12]. In recent years, to enhance the environmental sustainability of products, researchers have increasingly turned to bio-based or non-toxic green crosslinking agents, such as citric acid[9].

The synthetic methods vary according to the reaction conditions and primarily include solution polymerization, suspension polymerization, radiation-initiated polymerization, and microwave-assisted polymerization[7]. Among these, solution polymerization is the most commonly employed in laboratory research because of its straightforward operation. In contrast, microwave and radiation methods have garnered increasing interest due to their high efficiency, energy conservation, and the absence of initiator residues[13].

2.3 Performance Optimization and Modification

To accommodate various applications, optimizing the performance of S-SAPs has emerged as a primary research focus. This optimization primarily aims to enhance the water absorption rate, gel strength, and salt resistance, while also imparting specialized functions.One common strategy is the construction of interpenetrating polymer networks (IPNs). Introducing a second polymer network, such as polyvinyl alcohol or sodium alginate, into S-SAPs results in the formation of semi-interpenetrating or fully interpenetrating structures[14, 15]. This approach effectively improves the mechanical properties and water retention capacity.Inorganic nanocomposites, such as montmorillonite, kaolin, silica, biochar, and other nanomaterials, serve as additional crosslinking sites within the network of SAPs[16]. These fillers not only boost the stability and mechanical strength but also enhance the resistance to salt and its water absorption rate.

Furthermore, new properties can be imparted to SAPs through functionalization modifications, which involve introducing specific functional groups or integrating them with functional materials. For example, the incorporation of humic acid can improve the capacity to promote plant growth. The adsorption capacity for targeted pollutants can also be enhanced by forming composites with materials like metal-organic frameworks and polyoxometalates[17, 18].

3. Application in Modern Agriculture

3.1 Soil Water-Retaining Agents and Amendments

Water scarcity significantly limits agricultural production in arid and semi-arid regions. When S-SAPs are applied to the soil, they function as micro-reservoirs that rapidly absorb and store water during irrigation or rainfall. Subsequently, they slowly release water to crop roots as soil moisture diminishes, thereby markedly improving the soil water-holding capacity and water-use efficiency[19]. Additionally, the swelling and contraction of S-SAPs during the dry-wet cycle promotes the formation of soil aggregates, enhances aeration and permeability, and mitigates soil compaction. Furthermore, the organic matter generated from the degradation of S-SAPs can be reintegrated into the soil, contributing to increased soil fertility.

3.2 Fertilizer Slow-Release Carrier

The nutrient utilization rate of conventional chemical fertilizers typically falls below 50%. Losses due to leaching, runoff, and volatilization not only result in resource wastage but also environmental pollution. S-SAPs can function as effective slow-release carriers for fertilizers. By embedding or integrating nutrients such as nitrogen, phosphorus, and potassium into their network structure, these materials can be engineered to possess both water retention and slow-release capabilities. As S-SAPs absorb water and expand, they gradually release nutrients along with the water, thereby synchronizing nutrient supply with crop absorption and significantly enhancing fertilizer utilization efficiency[20]. Research indicates that S-SAPs loaded with urea can effectively mitigate nitrogen leaching losses[6], while those loaded with phosphate can diminish phosphorus fixation in the soil[19].

3.3 Controlled Release Pesticide System

Excessive use and inefficient application of pesticides can pose significant environmental and food safety risks. The incorporation of pesticides into the three-dimensional network structure of S-SAPs facilitates the development of a controllable release system. This system safeguards the active ingredients of pesticides from premature degradation, extends their efficacy duration, and minimizes their dispersion into non-target environments[21]. By modifying the structure and composition of S-SAPs, the release rate of pesticides can be accurately regulated, thereby ensuring effective pest control while reducing pesticide usage and its detrimental effects on the ecosystem.

4. Application in Environmental Remediation

4.1 Heavy Metal Ion Adsorption

The discharge of heavy metals into the environment from industrial wastewater, mining operations, and agricultural chemical applications poses a significant risk to both ecological integrity and human well-being. S-SAPs are rich in functional groups of carboxyl (-COOH) and hydroxyl (-OH), enabling them to effectively adsorb heavy metal ions such as Pb^{2+}, Cd^{2+}, Cu^{2+}, and Zn^{2+} through mechanisms such as ion exchange, electrostatic attraction, and surface complexation[18]. The three-dimensional structure of S-SAPs offers a large specific surface area and numerous active sites for adsorption. In comparison to conventional chemical remediation techniques, this material presents benefits such as ease of use, cost-effectiveness, and biodegradability in adsorption processes, making it an environmentally friendly and sustainable remediation approach.

4.2 Removal of Organic Pollutants

Organic pollutants, including dyes from printing and dyeing wastewater, phenolic compounds from chemical wastewater, and residual pesticides from farmland runoff, represent significant challenges in water environmental management. S-SAPs demonstrate remarkable adsorption capabilities for these pollutants[18]. The primary mechanisms underlying their effectiveness include hydrogen bonding, hydrophobic interaction, and van der Waals force. Enhancing the adsorption selectivity and capacity for specific organic pollutants can be achieved by introducing hydrophobic groups into the material or by combining it with high specific surface area materials, such as activated carbon and biochar[22].

5. Summary

S-SAPs presents a promising solution to the pressing challenges in agriculture, including water scarcity, excessive reliance on chemical fertilizers and pesticides, and environmental pollution. This technology not only facilitates the high-value utilization of straw but also integrates multiple functions, such as efficient water retention, controlled nutrient release, and environmental restoration. It holds significant potential for application in water-saving agriculture, precision fertilization, and pollution control. Although advancements are still required regarding large-scale production costs, performance in real-world conditions, and long-term ecological safety, the ongoing progress in green chemistry, materials science, and biotechnology may lead to cleaner synthetic processes and the design of multifunctional, intelligent responsive materials. Furthermore, systematic application verification and risk assessment will enhance the efficacy of S-SAPs, which is anticipated to play an increasingly vital role in fostering the sustainable transformation of agriculture and protecting the ecological environment, thereby providing essential material support for advancing green development.

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