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Review

Recent application developments of water-soluble synthetic polymers

Kantappa Halake, Mallinath Birajdar, Byoung Soo Kim, Harim Bae, CheongCheon Lee, Yoo Jin Kim, Sinwoo Kim, Hyun Jin Kim, Soohwan Ahn, Su Yeoung An, Jonghwi Lee *

Department of Chemical Engineering and Materials Science, Chung-Ang University, 221, Heukseok-dong, Dongjak-gu, Seoul 156-756, South Korea

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ABSTRACT

In the history of man-made macromolecules, water-soluble polymers have primarily maintained passive roles; examples include the uses of water-soluble polymers for viscosity control and as binders. The importance of water on earth has increased research into the development of active roles for water-soluble polymers. These expanding roles span from medical applications, such as drug delivery to environmental applications, such as the removal of heavy metals. The development of water-soluble polymers brings significant benefits to the structural engineering and production of nanomaterials and electronic materials. The current limits of the structure–property relationship have been challenged to meet these rapidly-developing application areas.

Contents

1. Introduction

Water-soluble synthetic polymers contain hydrophilic functional groups, such as ether, alcohol, amide, and pyrrolidone, which are often biocompatible and nontoxic. While linear polymers dissolve easily in water, cross-linked polymers form insoluble hydrogels. The use of strong hydrogen bonding or copolymerization is often an excellent strategy for the preparation of insoluble hydrophilic materials [1]. Among the available water-soluble polymers, polyethylene glycol, polyvinyl alcohol, polyacrylamide, polyvinylpyrrolidone, and poly(N-isopropylacrylamide) are common choices in leading application areas [2,3].

Water-soluble synthetic polymers have a broad range of applications in various fields including the food and pharmaceutical

* Corresponding author. Tel.: +82 1092701349.
E-mail addresses: jong@cau.ac.kr, leexx303@gmail.com (J. Lee).

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industries, in paint, textiles, paper, construction, adhesives, coatings, and water treatment [4–6]. Traditional uses include additions to thickening and anti-foaming agents, binders, lubricants, electrolyte solvents, dispersants, stabilizers, surfactants, laxatives, and excipients. In most applications, the polymers take a passive role as a subsidiary ingredient providing additional support [7]. With the recent developments of nanotechnology, environmental engineering, biomedical engineering, and information technologies, smart functions with biocompatible or environmentally-safe properties have received increased research and development [8–10]. As a result, water-soluble polymers are taking a more active role in novel applications. This is a natural progression; water-soluble macromolecules have evolved over millions of years to take active roles as in proteins, DNA, and lipids.

Novel applications of water-soluble synthetic polymers cover a wide range, from medical applications as drug delivery carriers and tissue engineering scaffolds to environmental applications as heavy metal removers [11,12]. Information technology fields also hold new opportunities for these materials as electrically-sensitive or optical films. Synthetic water-soluble polymers have been designed with properties never before realized in natural polymers to meet the requirements of these novel applications. Introducing reactive functional groups is a common method to address specific issues. This architectural freedom places water-soluble polymers in a key role for the fields of nanotechnology and smart materials. This short review summarizes recent trends in the applications of water-soluble synthetic polymers, with a focus on polyethylene glycol, polyvinyl alcohol, polyacrylamide, polyvinylpyrrolidone, and poly(N-isopropylacrylamide). Through this review, the smart functions and delicate structural control available to this class of materials via manipulation of strong hydrophilic interactions will be elucidated.

2. Polyethylene glycol (PEG) and its copolymers

PEG is a typical water-soluble polymer also known as polyethylene oxide (PEO) or polyoxyethylene, depending on its molecular weight. It has been utilized in various applications as a lubricating coating, osmotic pressure agent, electrolyte solvent, cosmetic ingredient, and medical laxative [13–23,1,24,25]. Recent progress in nanoscience and technology, as well as in environmental engineering, has created new opportunities for these polymers and is driving the development of novel properties [26–51].

2.1. Nanotechnology applications

Park et al. have prepared dispersed and stable silver nanoparticles within a semi-IPN hydrogel using simultaneous free-radical crosslinking polymerization [52]. This hydrogel consists of poly(acrylamide) and Pluronic, which is an amphiphilic block copolymer of poly(oxyethylene)-poly(oxypropylene)-poly(oxyethylene) (PEO–PPO–PEO). Here, Pluronic plays both hydrophilic and hydrophobic roles in the preparation of the well-dispersed and stable silver nanoparticles in the gel network. The ability to play these roles is due to the existence of both hydrophilic (PEO) and hydrophobic (PPO) blocks in the Pluronic structure. The prepared hydrogel-silver nanocomposite material has also shown excellent antibacterial properties.

Recent progress in the area of 2D nanomaterials such as graphene has led to the development and usage of PEG and its copolymers as dispersion agents. Park et al. reported that graphene oxide (GO) is homogeneously miscible with water when water-soluble amine-terminated polyethylene glycol (NH_2–PEG–NH_2) is added, because of its non-covalent interaction with graphene [53]. This is one of the valuable applications of the water-soluble PEG polymer. Simple mixing and the subsequent reduction of aqueous GO with NH_2–PEG–NH_2 produces homogeneous and stable reduced graphene. This process for soluble graphene will open up further applications for graphene materials requiring wet processing.

2.2. Environmental applications

Environmental concerns have lead researchers to investigate water-soluble polymers for water purification. Wisniewska et al. studied the removal of colloidal alumina from water via a flocculation process using water-soluble PEG and PEO for the purification of waste water [54]. They also investigated the flocculation ability of water-soluble PEG and PEO. These studies have shown that the most efficient flocculation of alumina suspension takes place at a pH of 9 in the presence of PEO 218,000, thus water-soluble PEG and PEO are highly effective in the removal of colloids from water. Singh et al. developed a biohydrogen production technique using immobilized, anaerobic sludge as the seed culture. Palm oil mill effluent (POME) sludge was entrapped in PEG for continuous hydrogen production, where the POME was used as the substrate carbon source [55]. PEG has additional merits and was selected in this entrapment work for its simple immobilization procedure, high solubility, low toxicity, good mechanical properties, and highly porous structure, which helps to sustain immobilized cell viability. The PEG-immobilized biomass loaded reactor appears to be a better choice for continuous hydrogen fermentation, because it exhibited a higher hydrogen production rate, and also showed more stability when operated with low hydraulic retention times (HRTs).

Water-soluble particles benefit from recent progress in particle preparation technologies. Hong et al. have shown that it is possible to prepare thermo-sensitive microcapsules via a double emulsion using water-soluble Pluronic F127 as the core material and poly(ε-caprolactone) (PCL) and ethyl cellulose (EC) as the wall materials [56]. The prepared Pluronic encapsulated microcapsules proved capable of temperature-dependent releases of fluorescein isothiocyanate-dextran and blue-dextran as dyes. Oh et al. reported poly(N-isopropylacrylamide) (PNIPAm)-grafted Pluronic copolymers prepared via conventional, free-radical polymerization with different molar ratios of N-isopropylacrylamide (NIPAAm) onto an initiated macro radical of Pluronic using t-butylperoxybenzoate as an initiator [57]. They investigated the thermosensitive hydrogel properties of PNIPAm-grafted Pluronic, and observed the unique thermo-reversible gelation behavior through dynamic modulus measurements of the injectable hydrogels in aqueous solution. Aqueous solutions of the Pluronic-g-PNIPAm copolymers exhibited typical sol–gel transition behavior with variation in poly(NIPAAm) content over a wide range of copolymer concentrations. The sol–gel transition behavior was controllable with NIPAAm chain length. Applications of this behavior include injectable hydrogel systems for the controlled release of various protein drugs.

3. Polyvinyl alcohol (PVA)

Polyvinyl alcohol (PVA) is a unique water-soluble polymer, widely used in papermaking, textiles, and a variety of coatings. This is a biocompatibility polymer which is used as scaffolding for cell cultures, embolic materials, contact lenses and wound dressings. This polymer is being used in an increasing number of applications for both environmental engineering and electrical materials [58–72].

3.1. Environmental applications

Alcohols are widely used for clean energy sources. Aqueous isopropanol (IPA) is used in various industries as a cleaning agent. It is important to recycle used IPA; however, it is difficult to recycle