Exploring Cutting-Edge Applications of Hydrogels in Post-Harvest Technological Advancements

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The surge in global population and evolving lifestyles has spurred an intensified demand for increased food production, prompting the need for enhanced food processing, logistics, and storage infrastructure to ensure both food safety and security (Sudheer et al. 2023). Hydrogels, intricate three-dimensional hydrophilic networks composed of polymeric chains interconnected through physical or chemical bonds (Batista et al. 2019), play a pivotal role in addressing these challenges. Recognized as colloidal gels, hydrogels disperse in water, exhibiting viscoelastic and structural properties due to the interplay of polymeric chain bonds and solvents integrated into the system (Ullah et al. 2022). The hydrogel's unique three-dimensional structure consists of a liquid phase, typically water or biological fluids, and a solid phase based on polymers or polymeric blends (Sudheer et al. 2023). In their swollen state and under specific pressures, hydrogels facilitate the absorption of target fluids without undergoing structural changes. The water sorption capacity of hydrogels is influenced by factors such as the nature and density of the polymer used and the crosslinking mechanism (Yang et al. 2021). In the creation of hydrogel matrices, synthetic compounds predominate, with chemical crosslinking being the prevalent method. Petroleum derivatives, including polyacrylamide, poly (sodium acrylate), poly (acrylic acid), and polyvinylpyrrolidone, are commonly employed in the formation of hydrogel matrices. Here, the primary objective here is to delineate hydrogels by exploring their classification, preparation, and various aspects of application.

Classification of hydrogel

Hydrogels, diversely classified based on composition and characteristics, include homopolymer hydrogels originating from a single monomer species, ensuring uniformity (Batista et al. 2019). Copolymer hydrogels, synthesized from different monomer species, exhibit block, random, or alternating configurations in the polymeric network chain (Sudheer et al. 2023). Another category is multicomponent hydrogels, formed by crosslinked synthetic, natural, or a combination of polymers, creating a network structure (Pirsa 2021). Homopolymer hydrogels maintain uniform monomer distribution (Cui et al. 2021). Electric charge-based classifications include cationic/anionic, neutral/non-ionic, amphoteric with both basic and acidic groups, and zwitterionic featuring anionic and cationic groups in each repeating unit (Sudheer et al. 2023). Additionally, hydrogels are classified by factors like crosslinking methods (chemical or physical), morphology, gel properties, mechanical capacity, functional attributes, and response modes, providing diverse avenues for categorization (Kaith et al. 2021; Behera and Mahanwar, 2020).

Preparation of hydrogel

Hydrogels, derived from natural polymers like collagen, gelatin, soy, fish proteins, starch, cellulose derivatives, sodium alginate, guar gum, xanthan gum, and chitosan, showcase diverse origins (Sudheer et al. 2023). The γ-polyglutamic acid (γ-PGA) hydrogel is prepared through chemical crosslinking using polyethylene glycol diglycidyl ether (PGDE) as the crosslinking agent, proving effective as a coating on shiitake mushrooms to extend storage life and quality for 30 days at 4 °C with a 1.0% γ-PGA hydrogel coating (Tao et al. 2021). Another innovative approach involves valorizing Carica papaya peel extract in the fabrication of biohydrogels for packaging fresh berries, using Schiff base hydrogels composed of dialdehyde starch and chitosan, incorporating the peel extract into the matrix (Dalei et al. 2023). Additionally, synthetic polymer-based hydrogels, including polyethylene glycol, polyvinyl alcohol, polyamidoamine, poly(N-isopropylacrylamide), polyacrylamide, and polyacrylic acid, offer versatile applications, while hydrogels derived from biopolymers like hyaluronate, alginate, starch, gelatin, cellulose, chitosan, and their derivatives showcase promising biomaterial applications due to their safety, wettability, and biocompatibility (Behera and Mahanwar 2020).

Uses of hydrogel

Hydrogels, intricate networks formed through chemical or physical crosslinking of hydrophilic polymers (Nath et al. 2023), exhibit remarkable water and fluid absorption capabilities. Cellulose-based hydrogels, known for their structural adaptability and stimuli-responsive properties, have gained attention in food packaging, functional food, safety, and drug delivery (Ullah et al. 2022). Despite continued academic exploration in food processing, commercial adoption lags due to a widespread lack of understanding in the public sector (Warkar and Kumar 2019). Naturally produced hydrogels, prized for biocompatibility, biodegradability, and abundance, emerge as promising materials. Ongoing research suggests that unlocking the full potential of hydrogels could lead to transformative innovations across various industries.

Food packaging

Hydrogels, when formulated with carboxymethylcellulose and polyvinylpyrrolidone, offer promising attributes for efficient packaging materials, boasting durability, biodegradability, and favorable mechanical properties (Gregorova et al. 2015). Employing a solution casting method, PVP–CMC hydrogel films are prepared without chemical crosslinking agents, relying on physical stimuli like heat and temperature, making them suitable for packaging systems with humidity control for water-rich food products (Batista et al. 2019). A novel strategy introduces porous hydrogel-based packaging materials for transporting delicate fruits (Wang et al. 2023b). Hydrogels, like those composed of tamarind polysaccharide and polyvinyl alcohol, designed to maintain seafood freshness, exhibit quick self-healing, good tissue fitting, and freezing tolerance capabilities (Wang et al. 2023a). Molecularly imprinted hydrogels (MIHs) offer a viable alternative to conventional packaging, selectively binding antioxidants and enhancing antioxidant properties in resulting active films (Benito-Peña et al. 2016). Coating shiitake mushrooms with 1.0% γ-PGA hydrogel significantly retards decay, water and weight losses, and vitamin C degradation during storage (Tao et al. 2021). The CMC/NFC/$KMnO_4$ hydrogel extends the shelf life of bananas by simultaneously controlling ethylene and humidity in food packaging, serving as a humidity/ethylene absorbent and ensuring prolonged freshness (Pirsa 2021).

Sensor

Hydrogels have emerged as highly promising materials, garnering significant attention in recent years, particularly in the realms of biosensors and packaging. With exceptional bioactivities, stimuli responsiveness, embedding ability, swelling, biodegradability, non-toxicity, and cost-effectiveness, CH-based hydrogels are meticulously analyzed for their potential applications in intelligent food packaging systems (Yang et al. 2021). In an investigation focusing on PVP-CMC-based hydrogel food packaging, the breathability of the material is assessed for its impact on the preservation of quality and shelf life of "table grapes" (Saha et al. 2015). A practical, cost-effective, and non-destructive sensing strategy is devised to monitor biogenic amines (BAs) in real-time, providing a valuable tool for assessing food spoilage (Luo et al. 2021). The application of a hydrogel biosensor emerges as a rapid, cost-effective, and non-destructive method for assessing the quality of food, particularly in evaluating the freshness of fish (Nath et al. 2023). A functional hydrogel incorporating silver ions, D-glucose pentaacetate, and agarose serves as an effective tool for monitoring the growth of biogenic amines, providing insights into the freshness of fish (Nath et al., 2023).

Antimicrobial

Hydrogels have found recent applications in the food packaging system, primarily due to their commendable antibacterial capacities (Batista et al. 2019). This study introduces an antibacterial packaging material achieved by incorporating methyl-β-cyclodextrin/*Satureja montana L.* essential oil inclusion complexes into soy soluble polysaccharide hydrogel (Cui et al. 2021). Nanocomposite hydrogels and chitosan films impregnated with nanoparticles exhibit distinct antimicrobial activities, showcasing potential applications in active food packaging (Li et al. 2022). The Hydrogel Film demonstrates the ability to prolong the freshness of strawberries for up to 8, 19, and 48 days at 25.0, 5.0, and 0 °C, respectively, by retarding ripening, dehydration, microbial invasion, and respiration rate (Zhang et al. 2023). The incorporation of antimicrobial agents like Ag, ZnO, and CuO nanoparticles into hydrogels enhances their antimicrobial activities, suggesting a viable strategy to extend the shelf life of packaged foods by encapsulating preservatives, antioxidants, desoxidants, and antibacterial agents within CH-based hydrogels (Restuccia et al., 2010). Among various films, the AgNPs@GT-3/EC film emerges as a standout, exhibiting exceptional UV-light shielding, superior mechanical properties, optimal humidity regulation, oxygen barrier capabilities, enhanced thermal stability, and impressive bacteriostatic rates against S. aureus and E. coli of up to 99% (Shan et al. 2024).

Shelf-life extension

Copper nanoparticles (Cu-NPs) in chitosan-polyvinyl alcohol (Cs-PVA) benefit the preservation of physicochemical quality and increase bioactive compound levels in kidney-shaped tomatoes, extending their storage period (Hernández-Fuentes et al. 2023). The utilization of C. papaya peel extract in the film enhances thickness, moisture content, and opacity, demonstrating versatile performance with antimicrobial and antioxidant activities, water-barrier properties, and biodegradability (Dalei et al. 2023). The developed biohydrogel films extend the shelf life of fresh berries, showcasing potential as sustainable packaging materials. The study on bacterial cellulose and guar gum (BC-GG) based PVP-CMC hydrogel film as an alternative food packaging material highlights superior resistivity to oxygen and water vapor permeability, reducing weight loss and maintaining moisture levels in packed fruits (Bandyopadhyay et al. 2019). Cs-PVA-Cu-NP complexes in jalapeño pepper production improve postharvest quality, while additional studies show their application to tomato plants enhances yield, fruit quality, defensive systems, and increases vitamin C and lycopene contents (Hernández-Hernández et al., 2018; Rivera-Jaramillo et al., 2021).

Conclusion

In conclusion, hydrogels stand at the forefront of innovative materials with versatile applications, driven by their unique properties and diverse compositions. The escalating global demand for enhanced food production and preservation has underscored the importance of advanced technologies, such as hydrogels, in improving food processing, storage, and safety. In essence, the journey through the realm of hydrogels reveals not only their scientific intricacies but also their immense potential in addressing contemporary challenges. As we delve deeper into the crossroads of chemistry, biology, and materials science, hydrogels emerge as a promising frontier, promising advancements that will continue to shape our future in diverse and unexpected ways.

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