

Exploring Hydrogels: Key Materials for Biomedical Applications

Introduction

Hydrogels are three-dimensional networks of hydrophilic polymers with the ability to retain a large amount of water, closely mimicking the properties of natural tissue. A key property of these materials is their biocompatibility, which ensures minimal adverse reactions when in contact with biological tissues¹. These distinctive properties render them highly useful in biomedical applications. Hydrogels can be derived from natural sources like collagen and alginate or can be chemically produced from polymers such as PEG and PVA. The natural versatility in composition and structure permits the customization of mechanical strength, biodegradability, and bioactivity to meet the requirements for targeted applications.



Key Material Types

Based on the source, hydrogels can be broadly classified into natural and synthetic categories. Each type has unique properties, advantages, and applications in biomedical fields. Comparative properties of natural and synthetic hydrogel polymers are summarized in **Table 1**.

Natural Polymers

Natural polymers such as collagen, gelatin, and alginate are favored for biomedical applications due to their excellent biocompatibility and biodegradability. Collagen supports cell growth and is widely used in tissue engineering; gelatin offers easy modification and gelation properties for drug delivery; and alginate forms biocompatible hydrogels ideal for cell encapsulation and wound healing.

Synthetic Polymers

Polyethylene glycol (PEG) is renowned for its biocompatibility and hydrophilicity, widely used in drug delivery and tissue engineering hydrogels. Polyvinyl alcohol (PVA) offers excellent mechanical strength, biocompatibility, and moisture retention, making it ideal for wound dressings and scaffolds. Polyacrylic acid (PAA) is valued for its water absorption and pH-responsive gelation, suited for controlled drug release and tissue regeneration.

Property	Natural Polymers	Synthetic Polymers
Source	Derived from biological materials (e.g., collagen, alginate)	Chemically synthesized (e.g., PEG, PVA)
Biocompatibility	Generally high, mimicking natural tissues	Varies; can be engineered for specific applications
Customization	Limited to natural variability	Highly customizable in terms of properties
Mechanical Strength	Typically, lower mechanical strength	Can be designed for high strength and durability
Biodegradability	Often biodegradable	Varies; some are designed for controlled degradation
Cost	Can be more expensive due to extraction	Generally, more cost-effective due to mass production

Table 1. Comparative Properties of Natural and Synthetic Polymers

Crosslinking Methods

Hydrogels can be crosslinked using physical methods (e.g., hydrogen bonding) or chemical methods (e.g., covalent bonds), depending on the desired application. These advances enhance the applicability of hydrogels through improved interaction with biological systems,

making them more effective in therapeutic and regenerative medicine. Representative hydrogel recipes with monomers, cross-linkers, initiators, and key biomedical applications are presented in **Table 2**.

Hydrogels (Name & Type)	Monomers / Polymers	Crosslinking Agents & Method	Initiators	Applications
pHEMA (Synthetic)	2-Hydroxyethyl methacrylate (HEMA)	Ethylene glycol dimethacrylate (EGDMA) UV/thermal crosslinking	Azobisisobutyronitrile (AIBN)	Contact lenses; ocular drug delivery
Silicone based Hydrogel (Hybrid)	3-[Tris(trimethylsiloxy)silyl]propyl methacrylate (TRIS), N,N-Dimethylacrylamide, 1-Vinyl-2-pyrrolidinone	Poly(ethylene glycol) dimethacrylate (PEGDMA) UV curing	Photoinitiator like, Diphenyl(2,4,6-trimethylbenzoyl) phosphine oxide (TPO) or Phenylbis(2,4,6-trimethylbenzoyl)phosphine oxide	High-oxygen-permeable contact lenses
PEG Hydrogel (Synthetic)	Poly(ethylene glycol) diacrylate PEGDA / tetra-PEG	Self-crosslink via thiol-Michael or UV	UV photoinitiators like, 2-Hydroxy-4'-(2-hydroxyethoxy)-2-methylpropiophenone , Lithium phenyl-2,4,6-trimethylbenzoyl phosphinate (LAP)	Surgical sealants; anti-adhesion
PVA Hydrogel (Synthetic)	Poly(vinyl alcohol)	Freeze-thaw or glutaraldehyde crosslinking	None (physical) / acid-catalyzed (chemical)	Wound dressings; cartilage replacement
Alginate Hydrogel (Natural)	Sodium alginate	Ionic gelation with Ca ²⁺	Not required	Dermal fillers; wound healing, microneedles
Hyaluronic Acid Hydrogel (Natural)	Hyaluronic acid	Carbodiimide / UV crosslinking	Photoinitiator like, Lithium phenyl-2,4,6-trimethylbenzoyl phosphinate (LAP)	Wound matrices; tissue scaffolds
Collagen/Gelatin Hydrogel (Natural)	Type I collagen / gelatin	Self-assembly or N-(3-Dimethylaminopropyl)-N'-ethylcarbodiimide / N-hydroxysuccinimide (NHS) crosslinking	Carbodiimide activation	Antimicrobial dressings; derma care
Chitosan Hydrogel (Natural)	Chitosan	Genipin (covalent) or Sodium tripolyphosphate (TPP) (ionic)	None (ionic); genipin reaction	Antimicrobial dressings; derma care
PVP Hydrogel (Synthetic)	Polyvinylpyrrolidone	N,N'-Methylenebisacrylamide (MBAA) UV crosslink or grafting	2-Hydroxy-4'-(2-hydroxyethoxy)-2-methylpropiophenone / Benzophenone	Lubricious coatings; personal care
PNIPAM Hydrogel (Smart, Synthetic)	N-Isopropylacrylamide (NIPAM)	N,N'-Methylenebisacrylamide (BIS) free-radical polymerization	Ammonium persulfate (APS) + N,N,N',N'-Tetramethylethylenediamine (TEMED)	Thermoresponsive systems, smart polymers

Table 2. Hydrogel Formulations: Composition, Crosslinking, and Uses

Key Applications

Hydrogels offer versatile solutions across biomedical field due to their unique ability to retain water and adapt to biological environments. They enable developments in wound healing, medical devices, and tissue engineering by supporting advanced therapies, drug delivery, and 3D cell culture solutions.

Medical Devices

Wound Healing

Hydrogels support wound healing by maintaining moisture, promoting cell growth, and delivering antimicrobial agents. Integrating smart polymers allow for continuous health monitoring, enabling real-time tracking of metrics like pH, glucose, or infection status for better care².

Contact Lenses and Dental Applications

Hydrogels are used in contact lenses for their oxygen permeability, softness, and ability to retain moisture—enhancing comfort during wear. In dentistry, the durability of hydrogels supports sustained drug release, stable tissue regeneration support, and periodontal repair with structural integrity and therapeutic function retained over long-term clinical use. Their biocompatibility and versatility make them valuable in both optical and oral care fields³.

Tissue Engineering

Hydrogels provide a scaffold that supports cell attachment, growth, and differentiation, crucial for tissue regeneration. They mimic the extra cellular matrix (ECMs) structure, allowing for the integration of cells and growth factors to form new tissues. Applications include cartilage repair, bone regeneration, and vascular tissue engineering.

3D Bioprinting

Hydrogels play a crucial role in 3D bioprinting as bioinks due to their high-water content, biocompatibility, and customizable properties. They support cell encapsulation, maintain viability, and mimic the extracellular matrix. This facilitates the precise construction of tissues and organs, aiding in regenerative medicine and personalized therapeutic solutions⁴.

Controlled Release Mechanisms

Hydrogels can encapsulate drugs and release them in a controlled manner, improving therapeutic efficacy and reducing side effects. They are particularly useful for localized delivery, where the drug is released at the target site over an extended period⁵. By regulating the drug's half-life, hydrogels enable sustained delivery for applications like cancer therapy or chronic wound management improving therapeutic efficacy and patient compliance.

Personal Care – Cosmetic Industry

Hydrogels play a pivotal role in personal care due to their hydration, biocompatibility, and tunable properties. With respect to formulations, they stabilize and control the release of active ingredients in creams and serums. Dermal fillers, which are primarily hyaluronic acid-based hydrogels, provide volume restoration, elasticity, and long-lasting effects. A key factor behind their durability is 1,4-butanediol diglycidyl ether (BDDE), the gold-standard crosslinking agent.⁶ BDDE covalently links HA chains, strengthening the hydrogel structure, improving elasticity, and reducing enzymatic breakdown. This translates to longer-lasting fillers, fewer re-treatments, and enhanced patient satisfaction. Beyond fillers, BDDE-crosslinked hydrogels are enabling next-generation cosmetic solutions. They provide a stable matrix for smart, responsive systems that deliver antioxidants, peptides, or UV filters precisely when needed, supporting skin health and rejuvenation. In high-end plastic surgery, injectable hydrogels support tissue regeneration and contouring with minimal invasiveness. Advanced personal care solutions utilize smart hydrogels which are responsive to pH, temperature, or enzymes, enabling targeted delivery of antioxidants, peptides, or UV filters for enhanced skin health and rejuvenation.

Recent Advances

Recent innovations in hydrogel technology focus on enhancing their functional properties and are summarized in **Table 3**.

Types of Hydrogels	Monomers/Polymers Used	Crosslinking Agents	Key Applications
Self-Healing Hydrogels	Chitosan , Tannic acid , Polyethylene glycol , 4-(Diethoxymethyl)benzaldehyde , 4-Aminophenylboronic acid hydrochloride , Poly(vinyl alcohol)	Hydrogen bonding, Ionic interactions, Imine bonds (benzaldehyde-amine) + Borate ester bonds (boronic acid-diol)	Wound dressings, tissue scaffolds ⁷
Stimuli-Responsive Hydrogels	TOChN@PNIPAm - TEMPO oxidized nanochitin (TOChN) and Poly(N-isopropylacrylamide) (PNIPAm) , 2-(Dimethylamino)ethyl methacrylate (DMAEMA) , PEDOT:PSS , Carboxymethyl cellulose, polythiophene, Acid-hydrolyzed cellulose	Dynamic boric acid ester bonds, hydrogen bonds, π - π stacking between DA groups and PEDOT:PSS, Covalent crosslinking, Electrostatic interactions	Tissue engineering, biosensors, Polymeric wearable sensors ⁸
Clay-Polymer Hybrid Hydrogels	Sodium alginate , Ethylene glycol , Acrylic acid , Silver nitrate	Chemical or physical crosslinking	Enhanced mechanical strength for wound healing, tissue engineering ⁹
ULAS Hydrogels		Chemical crosslinking via free radical copolymerization process	Biosensing, ECG monitoring, wearable biomedical devices ¹⁰
Injectable Hydrogels	GelMA , Methacrylated Alginate	Radical photopolymerization	Designed for minimally invasive delivery, forming <i>in situ</i> to fill irregular defects and deliver cells or drugs ¹¹

Table 3. Cutting-Edge Hydrogel Materials: Composition, Crosslinkers, and Their Biomedical Applications

Additives for Hydrogel

Additives are widely employed in hydrogel systems to enhance their performance and expand the functionality of hydrogel-based contact lenses. For instance, incorporating photo-absorbers like [2-\(4-Benzoyl-3-hydroxyphenoxy\)ethyl acrylate](#) into the hydrogel matrix can regulate light penetration during photopolymerization. This not only improves crosslinking control, spatial resolution, and mechanical robustness of the hydrogel but also enables the integration of UV and blue light filtering capabilities. Such enhancements are particularly valuable for protecting the eyes from harmful radiation, reducing digital eye strain, and improving overall comfort and safety for users in both medical and personal care applications.

Related Products

Monomers

Product No.	Product Name	Product Description
220892	1,4-Butanediol diglycidyl ether	≥95%
290815	2-Ethylhexyl acrylate	98%, contains ≥0.001-≤0.11% monomethyl ether hydroquinone as stabilizer
151238	Glycidyl methacrylate	97%, contains 100 ppm monomethyl ether hydroquinone as inhibitor
413216	2-(4-Benzoyl-3-hydroxyphenoxy)ethyl acrylate	98%
M55909	Methyl methacrylate	contains ≤30 ppm MEHQ as inhibitor, 99%
440159	3-(Trimethoxysilyl) propyl methacrylate	98%
234923	Butyl acrylate	≥99%, contains 10-60 ppm monomethyl ether hydroquinone as inhibitor
496758	Bis[2-(methacryloyloxy)ethyl] phosphate	
415324	<i>N</i> -Isopropylacrylamide	97%
408220	Sodium acrylate	97%
234893	Ethyl methacrylate	contains 15-20 ppm monomethyl ether hydroquinone as inhibitor, 99%
436909	Diurethane dimethacrylate, mixture of isomers	contains 225 ppm±25 ppm BHT as inhibitor, ≥97%
516155	2-Aminoethyl methacrylate hydrochloride	contains ~500 ppm phenothiazine as stabilizer, 90%
282731	2-Acrylamido-2-methyl-1-propanesulfonic acid	99%
292818	2-Hydroxyethyl acrylate	96%, contains 200-650 ppm monomethyl ether hydroquinone as inhibitor
477028	2-Hydroxyethyl methacrylate	≥99%, contains ≤50 ppm monomethyl ether hydroquinone as inhibitor
731129	<i>N</i> -Isopropylacrylamide	≥99%
234907	2-(Dimethylamino) ethyl methacrylate	contains 700-1000 ppm monomethyl ether hydroquinone as inhibitor, 98%
246840	Trimethylolpropane trimethacrylate	contains 250 ppm monomethyl ether hydroquinone as inhibitor, technical grade
V3700	Divinyl sulfone	contains hydroquinone as inhibitor, ≥96%

Initiators

Product No.	Product Name	Product Description
441090	2,2'-Azobis(2-methylpropionitrile)	98%
900889	Lithium phenyl-2,4,6-trimethylbenzoylphosphinate	≥95%
517909	Luperox® A75, Benzoyl peroxide	75%, remainder water
511447	Phenylbis(2,4,6-trimethylbenzoyl)phosphine oxide	97%, powder
416665	<i>tert</i> -Butyl hydroperoxide solution	5.0-6.0 M in decane solution
11630	2,2'-Azobis(2-methylpropionitrile)	purum, ≥98.0% (GC)
415952	Diphenyl(2,4,6-trimethylbenzoyl)phosphine oxide	97%
410896	2-Hydroxy-4'-(2-hydroxyethoxy)-2-methylpropiophenone	98%
290785	Luperox® LP, Lauroyl peroxide	≥98%
160326	4,4'-Bis(diethylamino) benzophenone	≥99%
405655	2-Hydroxy-2-methylpropiophenone	97%
513474	Luperox® A75FP, Benzoyl peroxide	contains 25 wt. % water as stabilizer, 75%
723010	2-(Dodecylthiocarbonothioylthio)-2-methylpropionic acid	98% (HPLC)
196118	2,2-Dimethoxy-2-phenylacetophenone	99%
722995	4-Cyano-4-(phenylcarbonothioylthio) pentanoic acid	powder
124893	Camphorquinone	97%
440914	2,2'-Azobis(2-methylpropionamide) dihydrochloride	powder or granules, 97%
723037	2-Cyano-2-propyl dodecyl trithiocarbonate	97% (HPLC)
723274	4-Cyano-4-[(dodecylsulfanylthiocarbonyl) sulfanyl]pentanoic acid	97% (HPLC)
329541	Dicumyl peroxide	98%

Polyethylene Glycols

Product No.	Product Name	Product Description
435465	Poly(ethylene glycol)- <i>block</i> -poly(propylene glycol)- <i>block</i> -poly(ethylene glycol)	average M_n ~5,800
409537	Poly(ethylene glycol) methacrylate	average M_n 360, methacrylate, 500-800 ppm MEHQ as inhibitor
455008	Poly(ethylene glycol) diacrylate	average M_n 700, acrylate, 100 ppm MEHQ as inhibitor, 300 ppm BHT as inhibitor
202509	Poly(ethylene glycol) methyl ether	average M_n 2,000, methoxy, hydroxyl
475696	Poly(ethylene glycol) diglycidyl ether	average M_n 500, cross-linking reagent amine reactive, glycidyl
475629	Poly(ethylene glycol) diacrylate	average M_n 250, acrylate, 100 ppm MEHQ as inhibitor
437441	Poly(ethylene glycol) diacrylate	average M_n 575, cross-linking reagent polymerization reactions, acrylate, 400-600 ppm MEHQ as inhibitor
398802	Tetra(ethylene glycol) diacrylate	technical grade, cross-linking reagent polymerization reactions, acrylate, 100-150 ppm HQ as inhibitor, 150-200 ppm MEHQ as inhibitor
729140	Poly(ethylene glycol) methyl ether thiol	average M_n 2,000, chemical modification reagent thiol reactive, methoxy, thiol
P4338	Poly(ethylene glycol)	average M_n 3,350, hydroxyl, BioXtra
P2139	Poly(ethylene glycol)	average M_n 8,000, hydroxyl
81260	Poly(ethylene glycol)	average M_n 6,000, hydroxyl
81300	Poly(ethylene glycol)	average M_n 20,000, hydroxyl
202398	Poly(ethylene glycol)	average M_n 400, hydroxyl
81240	Poly(ethylene glycol)	average M_n 4,000, flakes
202444	Poly(ethylene glycol)	average M_n 3,350, hydroxyl, powder
81310	Poly(ethylene glycol)	average M_n 35,000, hydroxyl
P3265	Poly(ethylene glycol)	average M_n 400
202371	Poly(ethylene glycol)	average M_n 300, hydroxyl
335681	Ethylene glycol dimethacrylate	98%, cross-linking reagent polymerization reactions, methacrylate, 90-110 ppm monomethyl ether hydroquinone as inhibitor

Poly(ethylene oxide)

Product No.	Product Name	Product Description
182028	Poly(ethylene oxide)	average M_v 600,000 (nominal), powder, hydroxyl, BHT as inhibitor
181986	Poly(ethylene oxide)	average M_v 100,000 (nominal), powder, hydroxyl, BHT as inhibitor
189456	Poly(ethylene oxide)	average M_v 900,000 (nominal), powder, hydroxyl, BHT as inhibitor
372781	Poly(ethylene oxide)	average M_v 1,000,000 (nominal), powder, hydroxyl, BHT as inhibitor
182001	Poly(ethylene oxide)	average M_v 300,000 (nominal), powder, hydroxyl, BHT as inhibitor
372773	Poly(ethylene oxide)	average M_v 400,000 (nominal), powder, hydroxyl, BHT as inhibitor
181994	Poly(ethylene oxide)	average M_v 200,000 (nominal), powder, hydroxyl, BHT as inhibitor
189464	Poly(ethylene oxide)	average M_v 4,000,000 (nominal), powder, hydroxyl, BHT as inhibitor

Polyvinyl Alcohols

Product No.	Product Name	Product Description
341584	Poly(vinyl alcohol)	M_w 89,000-98,000, 99+% hydrolyzed
363170	Poly(vinyl alcohol)	M_w 13,000-23,000, 87-89% hydrolyzed
363146	Poly(vinyl alcohol)	M_w 85,000-124,000, 99+% hydrolyzed
363073	Poly(vinyl alcohol)	average M_w 31,000-50,000, 87-89% hydrolyzed
363138	Poly(vinyl alcohol)	M_w 31,000-50,000, 98-99% hydrolyzed
348406	Poly(vinyl alcohol)	average M_w 13,000-23,000, 98% hydrolyzed
363103	Poly(vinyl alcohol)	average M_w 146,000-186,000, 87-89% hydrolyzed

Natural Polymers and Others

Product No.	Product Name	Product Description
448869	Chitosan	low molecular weight
448877	Chitosan	medium molecular weight
419419	Chitosan	high molecular weight
523682	Chitosan oligosaccharide lactate	average M_n 5,000
417963	Chitosan	from shrimp shells, practical grade
283215	Poly(allylamine hydrochloride)	average M_w ~17,500 (GPC vs. PEG std.)
535311	Poly(<i>N</i> -isopropylacrylamide)	M_n ~40,000
192031	Poly(acrylic acid) partial sodium salt solution	average M_w ~5,000 by GPC, 50 wt. % in H ₂ O
420344	Poly(acrylic acid sodium salt)	average M_w ~2,100
290734	Dabco® 33-LV	33 wt. % solution of triethylenediamine in dipropylene glycol
180947	Alginic acid sodium salt	powder
900496	Gelatin methacryloyl	gel strength 300 g Bloom, 80% degree of substitution
435007	Hydroxypropyl cellulose	average M_w ~80,000, powder, 20 mesh particle size (99% through)
42000501	PRONOVA® UP VLVG	very low viscosity sodium alginate, viscosity <20 mPa.s, 1 %(20 °C)(low), guluronate monomer units ≥60 %
900622	Gelatin methacryloyl	gel strength 300 g Bloom, degree of substitution 60%
900629	Gelatin methacryloyl	gel strength 300 g Bloom, degree of substitution 40%
924474	Hyaluronic acid	Low Viscosity, Low endotoxin
114235	1,3,5-Triallyl-1,3,5-triazine-2,4,6(1 <i>H</i> ,3 <i>H</i> ,5 <i>H</i>)-trione	98%
454990	Poly(ethylene glycol) methyl ether acrylate	average M_n 480, contains 100 ppm MEHQ as inhibitor, 100 ppm BHT as inhibitor

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