A Review on The Multifunctional Hydrogel Systems: Classification, Synthesis, Property and Applications.

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Abstract:

Hydrogels are three dimensional hydrophilic polymeric networks that can absorb and retain sizable amounts of water, while providing physicochemical and functional properties. The versatility of the gels lies in their tunable porosity, swelling capabilities, mechanical properties, biodegradability and stimuli-responsiveness which make them suitable for applications in a range of fields. Herein, we discuss the classifications of hydrogels along with corresponding synthesis strategies, structural characteristics and important properties involving free-radical polymerization, grafting, click chemistry, freeze–thaw processing, radiation crosslinking electrospinning bilayer technology (BLT), 3D printing and bio printing. Biomedical applications comprise of wound dressings, tissue engineering, injectable systems, drug delivery, devices for cancer therapy, biosensors and wearable-devices along with stem-cell delivery. Wastewater treatment, pollutant adsorption, water purification, oil–water separation, carbon capture and sensing are then discussed in environmental applications. Agriculture, food, cosmetics, robotics, electronics and energy storage applications are also mentioned. Mechanical stability, sterilization, durability/scale/cost/regulation/fate are all current challenges. The future prospects include personalized medicine, organ-on-chip systems, smart sensors, hybrid materials, bioinks and machine-learning-guided hydrogel design.

1. Introduction:

Hydrogels are the most versatile classes of functional materials in modern science and engineering due to their high water content (80%), soft tissue-like mechanical properties, physicochemical properties, and biocompatibilities (Kopeček, 2007). Although the initial focus of this field was restricted to the development of hydrogel in biomedical science, research progressed rapidly, designing sophisticated hydrogel systems with enhanced mechanical performance, stimulus-responsiveness, self-repair capability as well as electrical conductivity and multi-functionalities (Negut & Bita, 2023).

Natural polymers available for hydrogel fabrication are alginate, chitosan, gelatine, cellulose and hyaluronic acid while synthetic polymers include poly (vinyl alcohol), polyethylene glycol, polyacrylamide and poly (N-isopropyl acrylamide) (Schacht, 2004). Hydrogels have been fabricated from a wide range of synthetic and natural polymers, whose composition (type of polymer structure) and crosslinking strategy significantly influence swelling behaviour, porosity, degradation profile, mechanical properties and biological performance (Laftah et al., 2011). Combining recent advances in polymer chemistry and the field of material science (including nanotechnology as well as advanced fabrication techniques like click-chemistry, 3D printing or even bio printing) has allowed for the creation of next-

generation hydrogels with site-specific architectures to provide custom functionalities towards specific application (El Sayed, 2023).

Hydrogels are now used in agriculture as superabsorbent hydrogels that retain moisture in the soil to release fertilizers and pesticides subsequently, and increase water-use efficiency under water scarcity (Kaur et al., 2023). Applications for Industry include food preservation, cosmetics, personal care product, soft robotics, flexible electronics and sensors as well as energy storage devices. This increasing preference for bio based and biodegradable hydrogels from natural resources has received a zest prompting the quest to such polysaccharides (El Sayed, 2023).

These breakthroughs are impressive, but there remain several roadblocks to wide-spread translation of hydrogel technologies. Conventional hydrogels are generally associated with poor mechanical properties, short lived stability, sterilization challenges, large batch variabilities and intricate regulatory necessities. To add to that, environmental sustainability and scalability of manufacturing processes also came into consideration along with end-of life disposal. This will result in current research focusing on smart, multi-functional and ecofriendly hydrogel systems which can act in response to an external stimulus or the ability to perform multiple tasks at the same time.

This review will outline the classification, synthesis methods, physicochemical and functional properties of next-generation hydrogels (NGH) while contextualising emerging applications in biomedical, environmental, agricultural and industrial fields. The focus is on structure – properties applications dependency relations, recent developments in materials technology areas as well as selected sustainability aspects and future research trends. This review embraces the advances across multidisciplinary fronts to demonstrate that hydrogels possess a unique transformative potential, allowing next-generation multifunctional applications in healthcare, environmental management and sustainable technological development.

2. Classification of Hydrogels

Hydrogels are versatile classes of hydrated polymeric materials, whose physico-chemical properties depend on polymer composition, cross-linking density, network architecture, charge distribution and responsiveness to external stimuli (Garg et al., 2016). This is crucial for many biomedical, environmental, agricultural and industrial hydrogel design applications as these parameters significantly affect swelling behaviour, mechanical performance, biodegradation, transport properties and biological interactions. The classification is presented in the table 1 below.

3. Hydrogel synthesis and fabrication strategies

The structure and properties of hydrogel is highly dependent on the strategy used for synthesis and fabricating hydrogels (Khan et al., 2022). Network architecture, pore size distribution, swelling behaviour, mechanical strength, diffusion characteristics and degradation profile are governed by a set of parameters such as polymer concentration; crosslinking density; reaction kinetics; solvent system and processing conditions (Madduma-Bandarage & Madihally, 2021). Consequently, hydrogels with vastly different properties can be obtained from the same polymer using different techniques (Nanda et al., 2025).

3.1 Free-Radical Polymerization

It is the most employed approach for hydrogel synthesis owing to its ease of use, versatility and compatibility with a broad range of vinyl monomers (Wang et al., 2025). This technique involves the use of thermal, redox and photochemical initiators which generate free radical sources that allow replication of polymer chain and develop a three-dimensional structure in presence of multifunctional cross linkers (Wen et al., 2025). Hydrogels prepared by free-radical polymerization usually has a relatively uniform network structure and controllable crosslinking density (Jaseem et al., 2026).

[Table 1: Scientific classification of hydrogels]

Classification criterion	Type	Key characteristics	Representative examples	Major applications
Source of polymer	Natural hydrogels	Biocompatible, biodegradable, bioactive, hydrophilic	Alginate, chitosan, gelatine, collagen, hyaluronic acid, cellulose	Wound dressing, tissue engineering, drug delivery
	Synthetic hydrogels	Mechanically stable, reproducible, tunable properties	PVA (poly vinyl alcohol), PEG (polyethylene glycol), PNIPAM (poly N-isopropyl acrylamide), PHEMA (poly 2 hydroxyethyl methacrylate),	Drug delivery, contact lenses, sensors
	Hybrid hydrogels	Combines bioactivity with mechanical strength	Gelatine–PEG, chitosan– PVA, alginate–PEG	Regenerative medicine, injectable hydrogels
Polymer composition	Homo polymeric	Single polymer network	PHEMA hydrogel	Ophthalmic materials
	Co polymeric	Two or more monomers	PEG-co-PAA	Controlled-release systems

	IPN(interpenetrating polymer network)	Interpenetrating crosslinked networks	PVA/chitosan IPN	Tough scaffolds
	Semi-IPN	One crosslinked polymer and one linear polymer	Gelatine/PVA semi-IPN	Flexible biomaterials
Crosslinking mechanism	Physical	Reversible noncovalent interactions	Agarose, gelatin, PVA freeze– thaw gel	Injectable gels
	Chemical	Permanent covalent network	PEG diacrylate hydrogel	Long-term implants
	Ionic	Electrostatic crosslinking	Ca^{2+}–alginate	Cell encapsulation
	Enzymatic	Mild biocatalytic gelation	HRP(horseradish peroxidase)-crosslinked gelatin	Injectable therapeutics
Network charge	Non-ionic	Neutral polymer chains	PEG hydrogel	Low-fouling coatings
	Anionic	Negatively charged groups	PAA, alginate	Drug delivery, adsorption
	Cationic	Positively charged groups	Chitosan	Antimicrobial materials
	Amphoteric	Both positive and negative groups	Polyampholyte gels	pH-responsive systems
	Zwitterionic	Internal charge balance	Sulfobetaine hydrogels	Antifouling coatings
Degradability	Biodegradable	Hydrolytic/enzymatic degradation	Gelatin, collagen, alginate	Temporary implants
	Non-biodegradable	Long-term stability	PHEMA, crosslinked PEG	Contact lenses, devices
Stimuli responsiveness	pH-responsive	Swelling varies with pH	PAA-based gels	Colon-targeted delivery
	Thermo-responsive	Temperaturetriggered phase transition	PNIPAM	Injectable depots
	Light-responsive	Photoinduced structural change	Azobenzene hydrogels	On-demand release

Higher monomer concentration or cross linker content foments a denser network with smaller pore sizes, limited swelling ability, larger modulus and slugger diffusion. In contrast, lower crosslinking densities lead to larger pores and higher water absorption (Tian et al., 2025). Due to the existence of covalent crosslinks between polymer chains, these hydrogels typically exhibit a good mechanical stability and dissolution resistance. Nevertheless, increasing the

extent of crosslinking can make the networks brittle and dampen their biodegradability. The technique is widely used for poly (acrylic acid), polyacrylamide, polyethylene glycol acrylate and many drug-delivery hydrogels synthesis (Guo et al., 2025).

3.2 Grafting Technique

Grafting is the covalent linking of side chains or functional monomers to an already existing polymer backbone. Initiation of the grafting process can occur by either a chemical reaction, photochemical energy or radiation activity. Natural polymers like cellulose, starch, chitosan and alginate are routinely grafted with synthetic monomers to enhance functionality (Elsayed, 2019).

The modification of the parent polymer through grafting greatly improves the hydrophilicity, charge density and availability of functional groups. While increasing hydrophilicity of grafts consistently improves swelling and water retention, the introduction of hydrophobic grafts reduces swelling while improving dimensional stability. Side chains can also enhance the pore interconnectivity and increase their capacity to adsorb pollutants or biomolecules (Seidi et al., 2020). By crosslinking, grafts may help to strengthen the network but, if grafting is too extensive, packing will be disrupted and strength will be reduced. The biodegradation behavior is influenced by the ratio between the natural and synthetic segments due to that introduction of a biodegradable backbone would initiate enzymatic degradation, whereas gain of synthetic grafts might impede it (Garg et al., 2016).

3.3 Click Chemistry

Click chemistry means a type of reactions which are highly efficient, selective and bioorthogonal like azide alkyne cycloaddition and thiolene coupling, Thiol-Michael addition and Diels–Alder reactions. These reactions are carried out under mild conditions, often in aqueous media and produce almost no by-products making them especially attractive for bioorthogonal crosslinking of hydrogels (X. Li & Xiong, 2022).

Since the click reactions occur at very high conversion, chemically defined network architectures are obtained for solution-derived hydrogels. Such a homogeneous arrangement yields not only predictable swelling behavior but superior mechanical uniformity and minimized defects in the structure (Sojdeh et al., 2025). This is achieved all under mild reaction conditions that leave encapsulated proteins, drugs and living cells active in vivo. Porosity can be accurately controlled by stoichiometric manipulation of reactive groups and macromer molecular weight. Moreover, some degradable linkages like ester, disulfide or enzymatically cleavable bonds can be intentionally linked into the polymer frame for biobreaking and

controlled release. These benefits render click chemistry a suitable method for injectable hydrogels, tissue engineering scaffolds, and cell-laden bioinks (Koschella et al., 2011).

3.4 Freeze–Thaw Technique

The freeze–thaw process is an old and well-established physical crosslinking technique which has been extensively applied to poly (vinyl alcohol) based hydrogels. In freezing, ice crystals generate and localize polymer chains in the non-frozen phase, allowing chain packing and crystallite to happen. Progressive thawing results in a physically crosslinked porous scaffolding (Waresindo et al., 2023).

Ice templating is a powerful technique for generating macroporous structures in hydrogels fabricated via repeated freeze–thaw cycles. The larger the ice crystal is, a pore can be created and therefore water uptake and mass transport increases (Guan et al., 2014). More freeze-thaw cycles can increase crystallinity and physical crosslink density, leading to higher tensile strength, elasticity, shape stability but lower swelling capacity. The low toxicity of these hydrogels is due to the fact that no chemical crosslinkers are required, making them ideal for biomedical applications (H. Zhang et al., 2013). Meanwhile, physical crosslinks are less stable than covalent crosslinks and may diffuse over time under prolonged hydration. The polymer composition has the greatest impact on biodegradation, because freeze–thaw does not impart degradable bonds (Qi et al., 2015).

3.5 Radiation Crosslinking

In radiation crosslinking, submillimetre/low-energy electron beams (or exposure to gamma rays and ultraviolet radiation) produce reactive species in polymer chain networks without the addition of chemical cross linkers (Gulrez et al., 2011). This method also sterilizes the material at the same time, which helps in medical products.

Hydrogel structure is exercised largely by radiation dose. Low dose increases crosslink density and mechanical strength, but high doses may generate chain scission followed by a decreased molecular weight leading to a weakened network (Jaseem et al., 2026). Radiation-cross-linked hydrogels are generally compositionally pure because there are no residual chemical cross linkers. Polymer concentration and irradiation dose allow for the tuning of porosity and swelling. Radiation may have the opposite effect in biodegradable polymers, causing chain defects that accelerate degradation and help with biodegradation; indeed, radiation will improve durability or protection in direct stable synthetic polymers (More & Chapekar, 2024).

3.6 Three-Dimensional Printing and Bio printing

3D printing also allows hydrogel constructs to be fabricated layer by layer with precise control over geometry, pore architecture, and spatial distribution of materials. There are commonly utilized hydrogel printing techniques such as extrusion-based printing, inkjet printing, stereo lithography and digital light processing. Bioprinting further implements this principle through the utilization of printable hydrogel bioinks embedded with living cells, growth factors and bioactive molecules (Jang et al., 2018).

The main benefit of 3D printing would be architectural control. Particularly, the engineered pore size and orientation, which are designed to control the diffusivity and promote cell infiltration and vascularization, can also be used as a parameter-based guide for regulating mechanical anisotropy (Agrawal & Hussain, 2023). While higher porosity generally favours membrane swelling and diffusion, it compromises compressive strength; denser printed structures give the best mechanical support. Most bioprinted hydrogels are formulated with moderate crosslinking densities for printability and cell viability. The rate of degradation can be spatially programmed by printing areas with different compositions or crosslinking levels. Such kind of technology is crucial for the applications in tissue engineering, organ models, personalized implants as well as regenerative medicine (Zhou et al., 2024).

3.7 Electrospinning-Assisted Hydrogel Fabrication

Electrospinning is a well-known process of producing submicron polymeric fibres via electrostatic jetting of polymer solutions or melts in the presence of an external high electric field. Electro spun fibrous hydrogel matrices can be prepared from either direct electrospinning of hydrogel-forming polymers, or through a two-step process combining electrospinning and subsequent crosslinking (H. Zhang et al., 2023) .

Electro spun hydrogel scaffolds have very high surface area, fibrous interconnected porosity and improved oxygen permeability. It is also a fibrous architecture that encourages cell adhesion, migration and proliferation (S. Sharma et al., 2026). The smaller fiber diameters typically increase swelling rate and surface reactivity while post-spinning crosslinking enhances mechanical stability in the aqueous environments. Electrospun hydrogels thus still show rapid fluid uptake but comparatively lower bulk mechanical strength than dense hydrogels due to the high abundance of void space in these structures (Khatun et al., 2025).

4. Basic Properties of Hydrogels

The structure property relationship of hydrogels is directly determined by the fabrication route. Covalent strategies for hydrogel fabrication include free-radical polymerization and click chemistry, often resulting in mechanically tougher and less swellable

hydrogels due to the covalent crosslinks limiting freedom of movement (e.g., dimensional stability) (Okay, 2009). However, these rather mild and physical methods provide highly porous networks with high water uptake but less durability over time. A further benefit of radiation treatment is that it can be used for simultaneous sterilisation (Thakur, Thakur, et al., 2018).

The porosity is mainly governed by phase separation, ice templating, printing architecture and fiber formation. Hydrophilicity and crosslink density dictate swelling behaviour. Network connectivity, crystallinity, and the orientation of structures are all determinants of mechanical properties. Polymer chemistry, crosslink types, and access to water and enzymes control biodegradation. Consequently, investigating how synthesis and fabrication strategies influence these parameters is critical for development of hydrogels with customized functions in catchments for biomedical therapy to environmental remediation and agriculture, as well as emerging industrial technologies (Kaczmarek et al., 2020).

Hydrogels are widely used in biomedical, environmental, agricultural, and industrial applications depending on their physicochemical and functional properties. These characteristics emerge from the interaction of polymer nature, crosslinking density, structure of the network, water content and functional additives added. This makes extensive characterization of the hydrogels necessary to design around property–structure relationships for their applications (Fatima & Almeida, 2024).

4.1 Swelling Behaviour

Swelling is a balking feature of hydrogels which enables in the absorption and retention of vast quantities of water or other biological fluids without dissolution. Swelling is due to osmotic forces arising from the hydrophilic functional groups (i.e. hydroxyl, carboxyl, amino and sulfate groups) while unlimited expansion is essentially inhibited by the elastic retractive force of crosslinked network (Ganji et al., 2010).

Swelling property directly influences the drug loading and release characteristics, transport of nutrients, adsorption capacity and absorbance of wound exudates. While quantitatively swelling is ususlly expressed as either swelling ratio or swelling index(Rohindra et al., 2004).

4.2 Mechanical Strength

Ability to withstand mechanical load by compression, tension, shear and repeated deformation during practical use which is called mechanical strength of the hydrogel. Appropriate mechanical integrity is needed when the hydrogels are used with load-bearing tissues, as wound dressings, environmental adsorbents, or flexible devices (Gong et al., 2003).

The mechanical properties are related to the polymer molecular weight, crosslink density, crystallinity and filler incorporation (where applicable), as well as network homogeneity. Higher levels of crosslink density drive tensile strength, compressive modulus and elastic modulus but lead to reduced flexibility and swelling. The presence of nanofillers, including nanocellulose, graphene oxide, silica nanoparticles and clay increases the strength through physical interactions (Huang et al., 2007).

Mechanical characterization is accomplished usually by means of pulling the material (tensile testing), pushing it (compression testing), vibrating it in tension and/or bending mode (dynamic mechanical analysis) or deforming part in shear flow/rheology (Tanaka et al., 2005).

4.3 Rheological Properties

Rheology of hydrogels, which relates to the fatigue deformation and flow behaviour during applied stress on the hydrogel, is critical parameter for injectable hydrogels, bio inks and topical formulations (Van Den Bulcke et al., 2000). The shear-thinning hydrogels have lower viscosity under stear and can recover quickly upon removal of the shear making them suitable for syringe injection as well as extrusion bio printing (Yan & Pochan, 2010). This information aids interpreting rheological analysis for gelation kinetics, network stability, printability and structural recovery (Jastram et al., 2021).

4.4 Porosity and Permeability

Porosity is the proportion of pore space in the hydrogel and permeability concerns the fluid, gas, nutrient, drug or pollutant diffusion through/within its network. Hydrogels with very high porosity support mass transport, cell invasion, vascularization and adsorption procedures (Vikingsson et al., 2015).

The pore size and interconnectivity are controlled by fabrication approach, phase separation, freeze–thaw conditions, progeny amount and polymer concentration. Many macro porous hydrogels are more permeable yet less mechanically stable than dense networks, which can stabilize a large number of cells but restrict diffusion (N. Zhang et al., 2023).

4.5 Biodegradability

Biodegradability is a very important property for temporary biomedical implants, drug delivery systems, tissue engineering scaffolds and environmental friendly materials. Biodegradation by hydrolysis, enzymatic cleavage, oxidation or with a microbial action (Adjuik et al., 2023).

The nature of polymer chemistry, crosslinking type, hydrophilicity, crystallinity and the accessibility of degradable bonds to water and enzymes all determine degradation rate. Hydrogels based on natural polymers usually degrades within shorter time when compared to

highly-crosslinked synthetic hydrogels. Controlled degradation is thus requisite to match scaffold resorption with that of tissue regeneration or the duration of control release. Mass loss studies, molecular weight change measurements, and changes in mechanical properties, as well as degradation products analysis are used to assess biodegradation (Park et al., 1993).

4.6 Bioadhesion

Bioadhesion represents the hydrogel adhesion to biological tissues including skin, mucosa or internal organs. Improved residence time, minimized dressing displacement, enhanced drug retention and intimate contact with target tissue all can be attributed to strong bioadhesion (Peppas & Sahlin, 1996).

4.7 Self-Healing Ability

By performing autonomously (after mechanical disruption) self-healing hydrogels were supposed to expand the service life by repairing structural damage without external stimulation. Dynamic reversible interactions, including hydrogen bonding, ionic interaction, metal–ligand coordination, host–guest interactions, hydrophobic associations, imine bonds, boronate ester bonds disulphide exchange are the basis for self-healing behaviour (Z. Li et al., 2024).

Fast network reconstruction and rapid recovery of mechanical properties after damage are critical for effective self-healing. This feature makes it especially useful for injectable materials, wearable devices, and repeated-deformation environments. Cut-healing tests, rheological recovery experiments, tensile recovery measurements and microscopic observation of healed interfaces are employed to investigate the self-healing efficiency (Wei et al., 2015).

4.8 Antimicrobial and Antioxidant Functionality

Antimicrobial and antioxidant functional hydrogels can design specifically for wound healing, tissue engineering, food packaging, as well as environmental applications. Incorporation of antibiotics, silver nanoparticles, zinc oxide, copper ions, chitosan, antimicrobial peptides (AMPs), quaternary ammonium compounds or bioactive molecules derived from plants can endow these materials with antimicrobial activity. These agents may disrupt the microbial membrane, produce reactive oxygen species (ROS), or mediate microbial metabolism (Xu et al., 2024).

5. Applications

Hydrogels are multi-function materials that can be applied in biomedical, environmental, agricultural, food, industry and advanced technology areas. Their unique three-dimensional polymeric structure that holds large amounts of water, tunable porosity and swelling behaviour, mechanical properties, biodegradability and stimuli-responsiveness enable their properties to be tuned according to application needs. Natural polymers, synthetic

polymers, nanomaterials, bioactive molecules and conductive components have also been integrated into these systems to further broaden their functions.

5.1 Biomedical Applications

Hydrogel properties have been studied widely in the biomedical domain as their hydrated 3D networks are able to mimic key elements of the extracellular matrix and create a supportive microenvironment for biological processes (Deligkaris et al., 2010). They are also suitable for wound-healing dressings, controlled drug delivery, tissue engineering, injectable biomaterials, cancer therapy, bio sensing and wearable health monitoring devices and regenerative medicine due to their tunable mechanical properties, biodegradability and permeability as well as ability to accommodate therapeutic molecules(Bruck, 1973). Its physicochemical properties can be customized to achieve localized, sustained or stimuli-responsive therapeutic functions(Liu & Chen, 2024).

5.2 Environmental Applications

Due to their low density and tunable porous architecture, high swelling capacity, large surface area, and excessive-selection of abundant practical groups able to interact various contaminants with hydrogels seek out proficient climate utility by using hydrogels (Kaur et al., 2023). They possess the unique properties that can enhance their practical applications on wastewater treatment, heavy-metal and dye adsorption, water purification, oil–water separation, environmental remediation, pollutant sensing and carbon capture (Thakur, Sharma, et al., 2018). Hydrogels made from natural polysaccharides are particularly attractive, because they incorporate pollutant-removing function with the potential for a minimized environmental footprint (desirable properties)(G. Sharma et al., 2018).

5.3 Agricultural Applications

Because of the ability of polymeric networks to absorb and retain large amounts of water, hydrogels have great potential in sustainable agriculture since they can release water back into the soil when local moisture levels are decreased (Kaur et al., 2023). This characteristic can enhance soil-water supply and thus plant growth in water-limited environment. Moreover, hydrogels can also act as carriers for fertilizers and pesticides, leading to controlled delivery which may reduce nutrient leakage and the excessive input of agrochemicals (Khan et al., 2022). Their use in technologies for drought avoidance, soil conditioning and seed-coatings will also contribute to their potential in improving both water and resource-use efficiency (Abobatta, 2018).

5.4 Food and Packaging Applications

Hydrogels and hydrogel-embedded films are being discussed in food applications since they convert biodegradable polymers into hydrated, flexible, and functional matrices. They can

be used in the form of active and intelligent food packaging, edible coatings, food preservation and controlled release of antimicrobial and antioxidant compounds (Batista et al., 2019). Incorporating functional agents into hydrogel networks may offer complementary protection against microbial growth, oxidation and quality deterioration while promoting the transition to more sustainable packaging materials (J. Yang et al., 2021) .

5.5 Applications in Cosmetics and Personal Care

Hydrogels having high water content, softness, adhesion, and skin compatibility could be used in a variety of cosmetic and personal-care applications. They may act as a vehicle for active cosmetic ingredients and can give hydration and increased skin contact time (Mitura et al., 2020). Fittingly, nowadays gel-forming hydrogels are presented more and more in cosmetic masks such as topical patches that carry active principles for skin hydration purpose, or drug delivery formulations where the release of some bioactive molecules from diverse skin-care compounds is monitored. From further perspective their action of chilling and cooling effect makes them well suited for topical applications (Parente et al., 2015).

5.6 Soft Robotics

Hydrogels have become one of the most promising candidates used in soft robotics, due to their flexibility, deformability, swelling properties and responsiveness to external stimuli. Hydrogel networks undergo controllable distortions (change volume fraction) in response to environmental changes i.e. followed by temperature, pH, light ionic strength, etc., which make them being considered as soft actuation materials. Due to its low stiffness and large deformation capacity, greatly influencing the more relevant field of synthetic muscles entailing soft actuators, robotic grippers and other flexible components for robots (Banerjee et al., 2018).

In flexible electronic systems, conductive hydrogels are of interest because they offer a combination of mechanical flexibility, stretchability, adhesion and ionic or electronic conductivity. Through the sustention of conductive pathways under deformation, they can thus be applied to strain and pressure sensing, electronic skin, wearable devices as well as physiological monitoring and human–machine interfaces. The electromechanical performance and sensing capability can be also improved through the integration of conductive polymers, carbon-based materials, metal nanoparticles or other functional nanomaterials (López-Díaz et al., 2024).

5.7 Emerging and Advanced Applications

Recent advances in polymer chemistry, nanotechnology, 3D printing, fabrication and computational materials science are enabling hydrogels to reach more application spaces. Hydrogel bioinks are designed for three-dimensional bioprinting in addition to this, the incorporation of hydrogel-based matrices into organ-on-chip and microfluidic systems.

Responsive polymers, nanomaterials, sensors and computational approaches are enabling the development of responsive superstructures (smart hydrogel platforms) that can sense, respond to and adapt their behavior in response to biological or environmental stimuli. These advances point to the transition of hydrogels from a traditional polymeric material toward smart and intelligent material systems that are multifunctional (Lanzalaco et al., 2023).

6. Challenges and Limitations

Hydrogels are multifunctional, but there are several barriers preventing their large-scale and clinical or even industrial translation. One big limitation is still mechanical weakness, especially for extremely wetted networks submitted to repetitive loading. Depending on the material used sterilization can affect the polymer structure, crosslinking, swelling or bioactive components. Similarly, the long-term stability and degradation pattern is always difficult to prediction under complex combination of physiological, environmental or soil parameters. Despite advances, reproducible crosslinking, pore architecture, composition and batch to batch performance remains a challenge in industrial scale. Moreover, advanced polymers, nanomaterials and fabrication technologies can also contribute to production cost. High standards for toxicity, degradation products, sterility and manufacturing reproducibility apply to the use of sensitive biomedical hydrogels. In environmental and agricultural applications, the widely varying fates of their hydrogel residues after disposal, such as polymer degradation, nanoparticle release, and potential ecological effects have received little attention.

7. Conclusion

Historically, hydrogels have been a very simple class of materials, principally seen as water absorbing polymers; however, this has grown into an easily tunable platform usable in diverse applications in biomedicine, environmental remediation, agriculture and food technology, electronics & robotics, and energy storage. This functionality is achieved by tuning the swelling, porosity, mechanical properties, degradation, conductivity, bioactivity and responsiveness of the ULs by means of molecular design or structural design. Nevertheless, other major issues such as mechanical durability, reproducibility, cost and scale-up technology, regulatory approval and environmental safety people still remain unresolved. This contextually improves the future of hydrogel technology via merging advanced fabrication, sustainable raw materials, functionalities, sensing intelligences and computational design. These advancements could further enable the movement of the field of hydrogels from laboratory scale materials towards viable, large-scale and sustainable technologies with immediate biomedical, environmental and industrial implications.

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