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RESEARCH PAPER

Stimuli-Responsive Nano Hydrogels for Sustainable Water Pollution Reduction: A Comprehensive Review of Design, Performance, and Industrial Translation

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ABSTRACT

Water is getting polluted by variety of contaminants coming from both natural and man-made sources. Water shortage and pollution by variety of pollutants pose serious threat to 21st century challenges inadequately addressed by conventional treatment technologies. This review examines stimuli-responsive "smart" hydrogels as effective materials for water purification, offering unprecedented advantages through reversible physicochemical transitions triggered by environmental stimuli. Functionalized hydrogels revealed nearly 3-8 fold higher adsorption capacities when compared with traditional adsorbent as carbon along with reduction in regeneration energy use upto 10%. The review highlights removal efficiencies exceeding 95% for priority pollutants including heavy metals, dyes, pharmaceuticals, and microplastics. Critical engineering challenges are addressed-mechanical stability, fouling resistance, and scale-up complexities from laboratory to industrial scales. Techno-economic analyses reveal treatment costs of \$0.008-0.50/m^3, representing 30-60% cost reductions versus conventional methods when lifecycle considerations are incorporated. Life Cycle Assessment quantifies carbon footprints; biodegradability uses and novel end-of-life strategies.

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INTRODUCTION

In today's world, the primary concern is the availability of fresh and clean water. A study reported by the United Nations observed that more than 2 billion of people don't have the availability of clean drinking water. In general, 3.6 billion people face shortage of clean water for drinking purposes [1]. Several pollutants are there that result in water pollution and common sources include both natural and man-made. From the time of industrial progression, several kinds of pollutants are discharged to water system without any treatment

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[2, 3]. These include persistent organic pollutants such as per- and polyfluoroalkyl, pharmaceutical and personal care products (PPCPs). According to a study, there exist 83% of microplastics in water resulting in deteriorating both water quality and health [4-6]. Several traditional water treatment methods have limitations in terms of high cost, secondary pollution generation that led to developing other water treatment methods [7-12] through both performance limitations and sustainability concerns [13-16]. Activated carbon adsorption, long considered the gold standard for organic contaminant removal, suffers from limited selectivity resulting in rapid saturation in complex matrices [17, 18], relatively modest adsorption capacities typically ranging from 50-200 mg/g for most pollutants, energy-intensive regeneration requiring temperatures of 400-900°C and consuming 5-15 kWh per kg of adsorbent, and limited reusability with most systems degrading significantly after 2-3 regeneration cycles [19]. Chemical precipitation and coagulation methods, while effective for certain heavy metals, generate enormous volumes of toxic sludge-often 5-15% of the treated water volume-requiring complex and costly disposal, demonstrate poor efficiency for low-concentration contaminants typical of modern pollution (below 10-50 mg/L), and provide no solution whatsoever for organic micropollutants or microplastics [20]. Membrane-based technologies including reverse osmosis and nanofiltration, though capable of high rejection rates (95-99.9%),

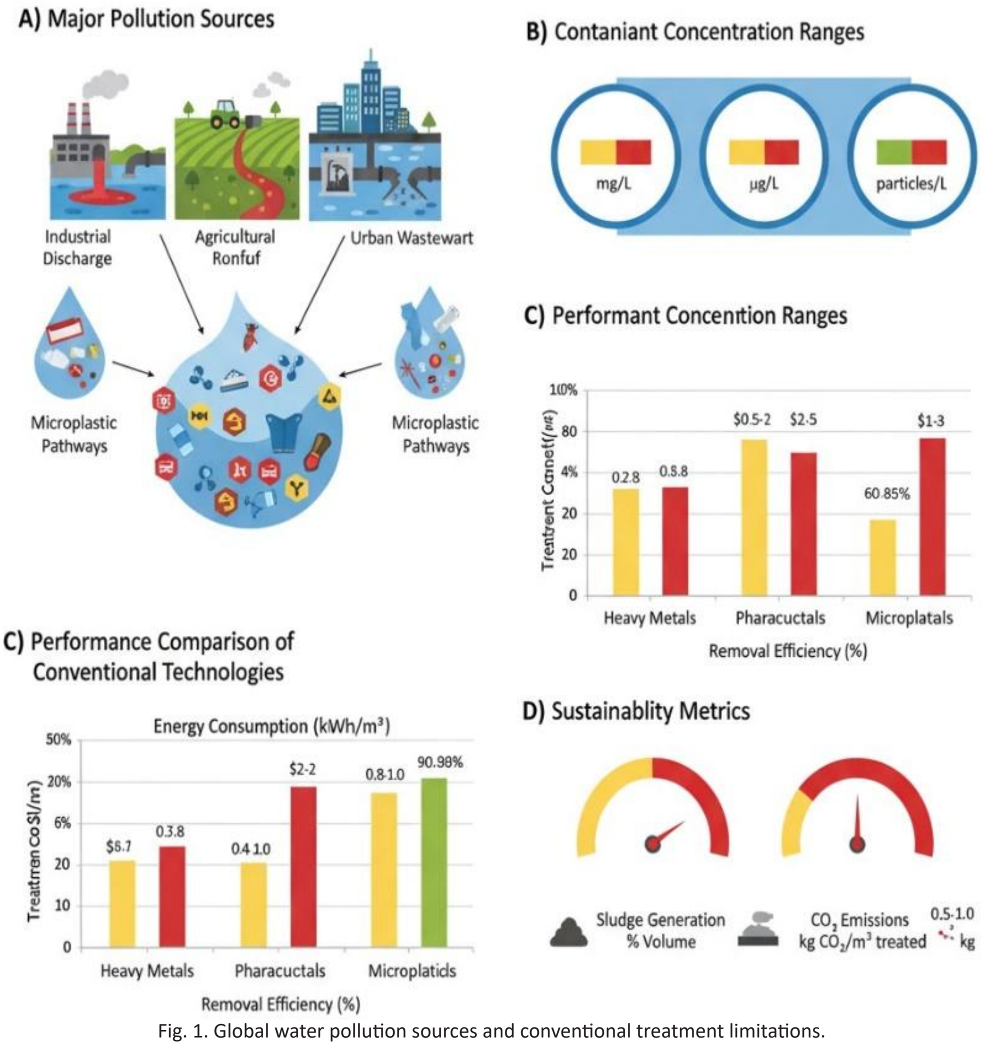

Fig. 1. Global water pollution sources and conventional treatment limitations.

suffer from prohibitive energy consumption of 3-10 kWh/m³ for reverse osmosis applications, severe fouling issues necessitating frequent chemical cleaning and membrane replacement, generation of concentrated reject streams requiring further treatment, and capital costs that remain inaccessible to many communities, with complete systems costing \$500-5000 per m³/day capacity (Fig. 1) [19, 21-24].

Multi-panel infographic showing (A) Major pollution sources including industrial discharge, agricultural runoff, urban wastewater, and microplastic pathways; (B) Contaminant concentration ranges for emerging pollutants (heavy metals: mg/L, pharmaceuticals: µg/L, microplastics: particles/L); (C) Performance comparison chart of conventional technologies showing treatment costs (\$/m³), energy consumption (kWh/m³), and removal efficiencies (%) for different contaminant classes; (D) Sustainability metrics including sludge generation (% volume) and CO_2 emissions (kg CO_2/m³ treated). Use color coding: red for high impact/cost, yellow for moderate, green for low/sustainable. Economic studies revealed the restrictions about this as a study that involved 45 countries water treatment plan reported that for treating water, cost was nearly \$0.50-2.00 per cubic meter [25-28].

Smart hydrogels: Paradigm shifts in water treatment technology

Owing to the limitations of hydrogels under specific conditions, researchers are working on developing 3D crosslinked polymeric based hydrogels networks. These materials possess high water absorption potential and can absorb 90-99 % of water due to the presence of variety of hydrophilic polymer chains in its inner structure. These structures are linked with each other by different forces including weak physical or strong chemical forces (Fig. 2) [29-33].

Stimuli-responsive hydrogels are designed at

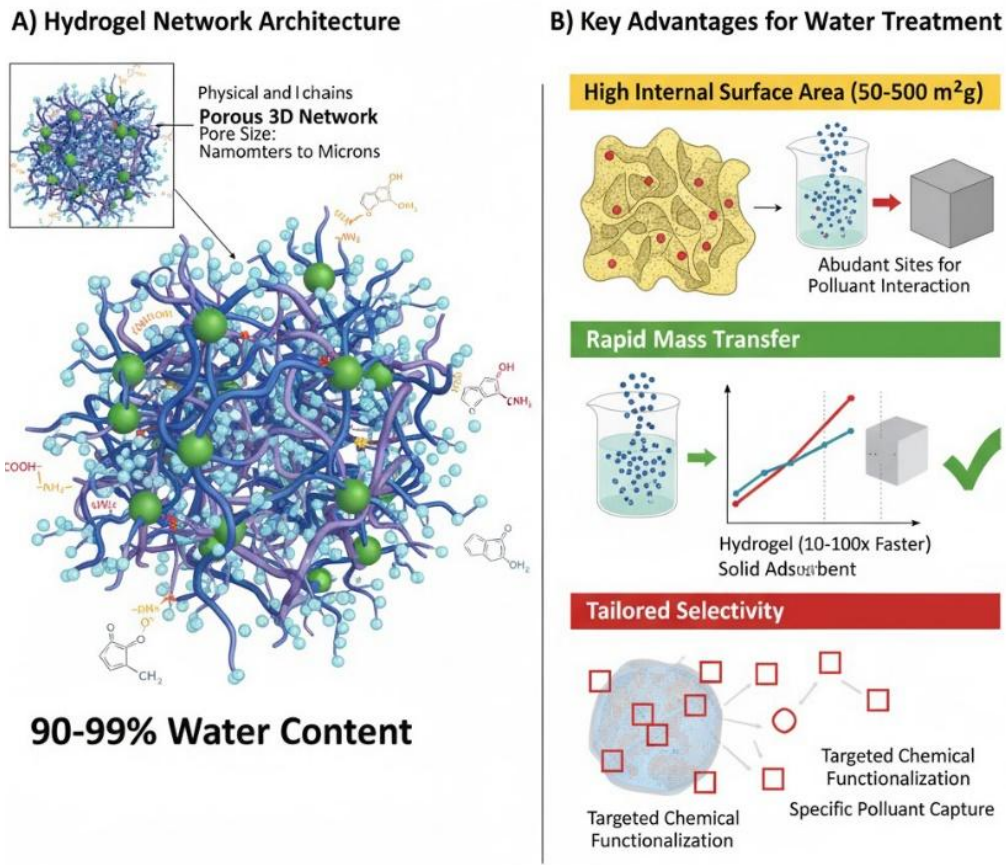

Fig. 2. Fundamental structure and advantages of hydrogels for water treatment.

Table 1. Comparative performance metrics [36-42].

Technology	Adsorption Capacity (mg/g)	Regeneration Efficiency (%)	Regeneration Energy (kWh/kg)	Operational Lifespan	Treatment Cost ($\$/\text{m}^3$)	Sludge Generation	Selectivity
Activated Carbon	50-200	60-75	5-15	6-12 months (2-3 cycles)	0.40-0.80	Low (spent carbon)	Low
Ion Exchange Resins	100-300 (eq basis)	80-95	2-8	12-24 months (50-200 cycles)	0.30-0.60	Low (brine)	Moderate
Chemical Precipitation	N/A (bulk removal)	N/A (single use)	N/A	N/A	0.20-0.60	Very high (5-15% vol)	Very low
Membrane Filtration	N/A (physical separation)	N/A (fouling issue)	3-10 (per m^3 permeate)	18-36 months	0.50-1.20	Moderate (concentrate)	Size-dependent
Synthetic Smart Hydrogels	200-500	85-95	0.5-3	12-36 months (10-20 cycles)	0.15-0.45	Very low	High
Bio-based Hydrogels	100-300	70-85	0.2-2	6-18 months (3-8 cycles)	0.10-0.35	Very low (biodegradable)	Moderate-High
Hybrid Hydrogel Systems	300-800	85-98	0.5-3	12-36 months (8-15 cycles)	0.15-0.50	Very low	Very high

the molecular level to undergo dramatic, often reversible changes in their physicochemical properties when exposed to specific environmental triggers. In these hydrogels, even a minor change in pH as ±1 unit can cause dramatic swelling or collapse. Temperature variations of just ±5−10 °C can also trigger phase transitions in polymers that exhibit a lower or upper critical solution temperature (LCST or UCST). Additionally, the addition or chelation of specific ions like Ca2+ or Mg2+ can modify ionic strength and alter crosslink density (Table 1). Electromagnetic radiation, as UV, visible, or near-IR light induce changes in polymers, and in remote, non-contact actuation via electric or magnetic fields [34, 35].

Stimuli-responsive materials transform water treatment by enabling low-energy regeneration (Fig. 3). While materials as activated carbon (AC) needs extreme heat (400−900 °C) or ion exchange resins require harsh, smart hydrogels achieve gentle, reversible release of pollutants. A pH-responsive hydrogel captures heavy metals at neutral pH (i.e., 7) and releases them when pH is acidic (i.e., 2−3) [43]. Crucially, this process is entirely reversible: neutralizing the pH returns the hydrogel to its original state, ready for reuse. Similarly, temperature-responsive hydrogels can capture organic pollutants in an expanded, hydrophilic state at room temperature, then release them in a collapsed, hydrophobic state at elevated temperature (often just 40-50 °C), with cooling returning the material to its original configuration. These mild regeneration conditions typically consume 5-10 times less energy than conventional thermal regeneration while producing minimal secondary waste [44, 45].

Multi-stimulus responsive systems can provide even greater control, with pH-temperature dual-responsive materials demonstrating synergistic effects where combined stimuli produce regeneration efficiencies unattainable with either stimulus alone (Figs. 4 and 5) [46]. The selectivity by molecular-level design allows these materials to target specific priority pollutants even in complex matrices as a thiol-functionalized hydrogel will bind Hg^{2+} with selectivity ratios exceeding 100:1 over competing ions as calcium or sodium, enabling effective treatment even in seawater or high-salinity wastewaters. Economic projections based on pilot-scale demonstrations suggest that smart hydrogel systems can achieve 30-60% reductions in total treatment costs over their operational lifetime compared to conventional technologies [46-48].

Scope And Objectives of Review

This comprehensive review aims to provide the water treatment research community, environmental engineers, and materials scientists with a critical, holistic assessment of stimuli-responsive hydrogel technology spanning fundamental science, engineering challenges, and pathways to industrial implementation. Herein, firstly, the key focus is on investigating the key functionalities and characteristics of smart hydrogels. The emphasis is on the understanding of interactions that exist between polymeric chains, the stability of these chains and the key features that make them effective to use in variety of uses ranging from medical to water treatment. The mechanistic insight was also investigated for better analysis of variation in swelling characteristics of polymer and gel formation [48-50]. Secondly, various explored different methods of the smart hydrogel synthesis that include crosslinking chemical as well as radiation-based methods along with the discussion of their pros and cons. Thirdly, the key mechanism of the pollutant removal by hydrogels was also studied along with the involvement of ionic strength effects and Debye screening lengths, H-bonding as well as π-π stacking in adsorption method. Advanced oxidation processes enabled by catalytic hydrogels are thoroughly examined, including photocatalytic mechanisms with detailed electron-hole pair generation and radical formation pathways, Fenton and Fenton-like reactions with transition metal catalysts, persulfate activation generating sulfate radicals, and enzymatic degradation for highly selective biotransformation. Each mechanism is evaluated quantitatively in terms of degradation kinetics, energy requirements, operational pH and temperature windows, and reusability limitations (Fig. 6) [51].

Fourth, we survey the application landscape for smart hydrogels across the most pressing water treatment challenges. Heavy metal removal receives detailed attention given its widespread industrial importance, with performance data presented for lead, mercury, arsenic, cadmium, chromium, and copper spanning adsorption capacities (100-850 mg/g depending on system), kinetics (equilibrium times 30-180 minutes), selectivity ratios in mixed-metal solutions (10-100:1 for optimized systems), regeneration protocols (acidic, basic, or complexing agent-

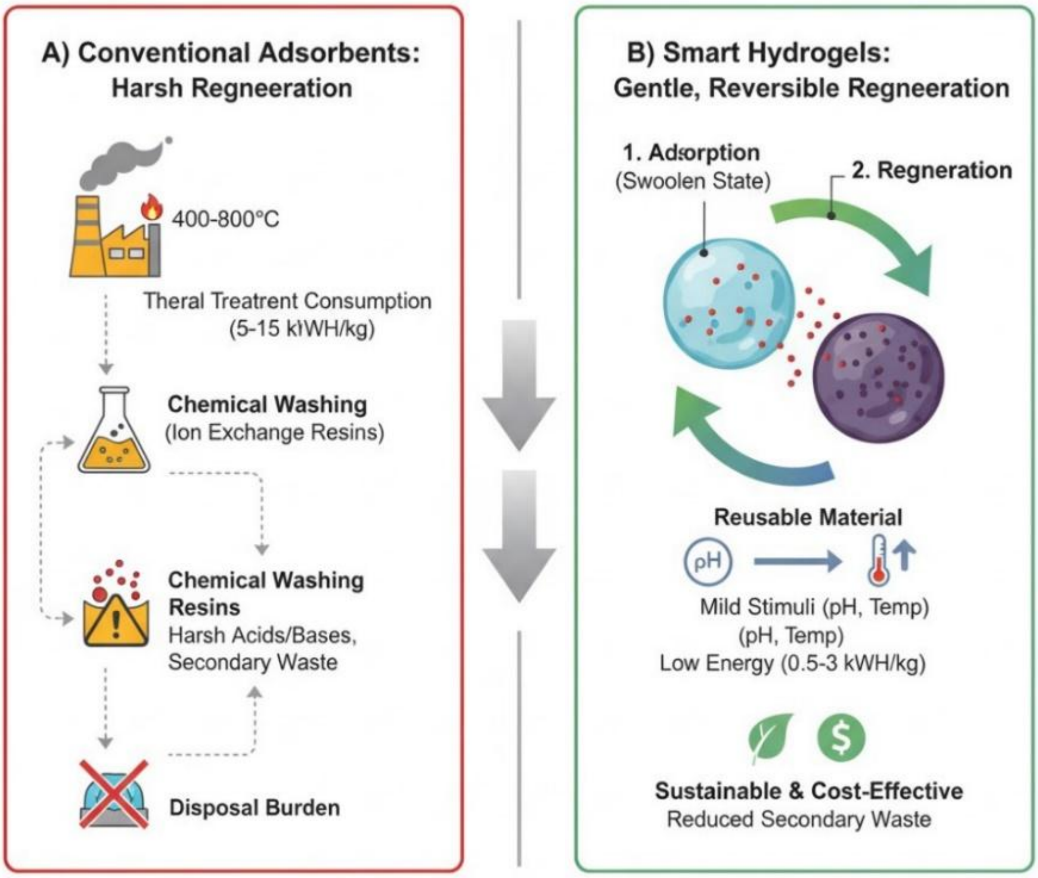

Fig. 3. Low-energy regeneration: Smart hydrogel advantages in water treatment.

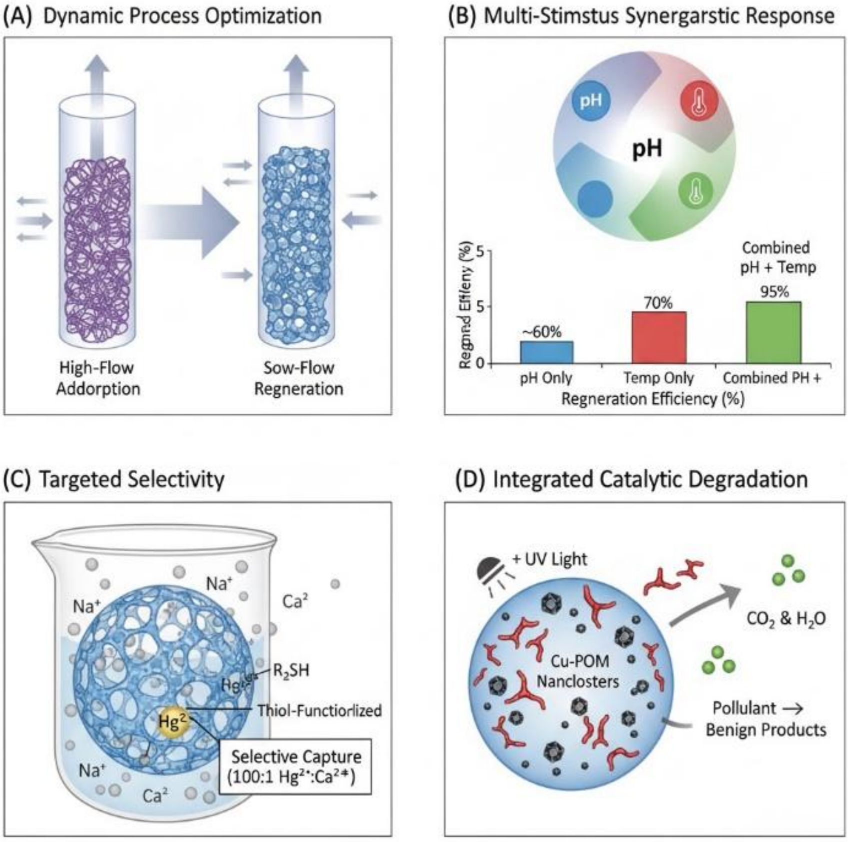

Fig. 4. Advanced advantages of smart hydrogels in water treatment.

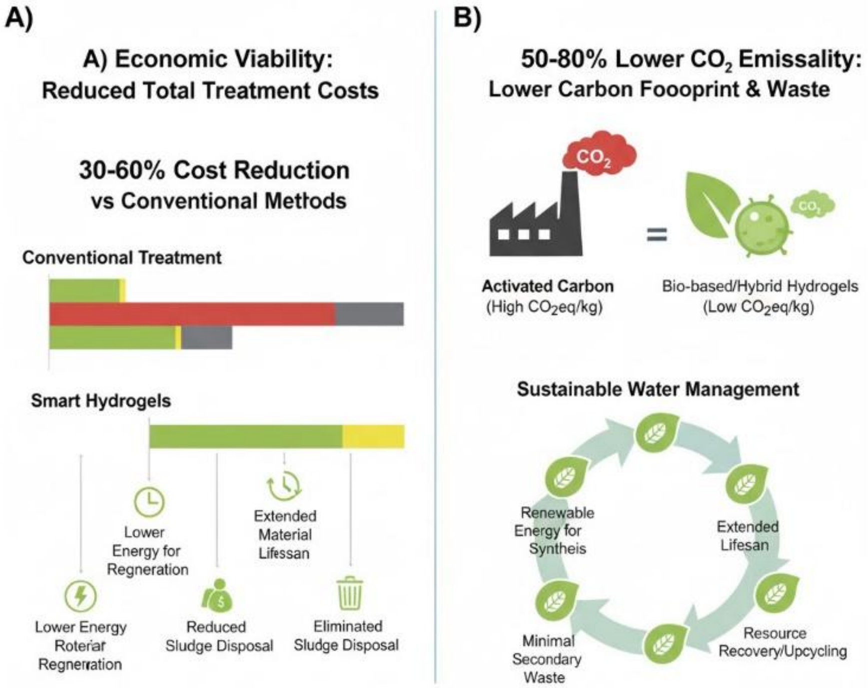

Fig. 5. Economic and environmental sustainability of smart hydrogels.

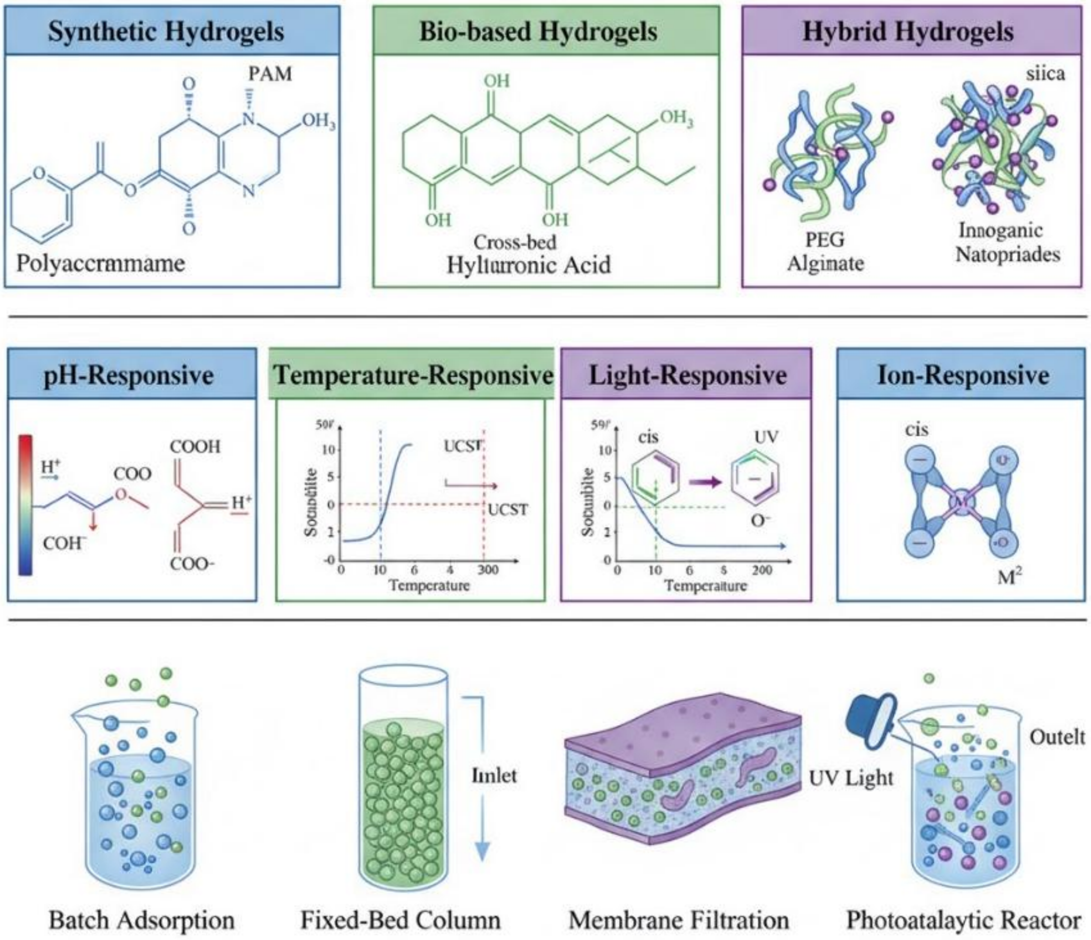

Fig. 6. Classification and functionality of smart hydrogel systems.

based), and real wastewater treatment case studies from electroplating, mining, and electronics industries. Fifth, we confront the engineering challenges that historically prevented hydrogel translation from laboratory to industry. Mechanical stability under realistic operational stresses-including compression from bed weight in packed columns, transmembrane pressure in membrane configurations (1-10 bar), and cyclic loading from repeated swelling/deswelling -is analyzed. Sixth, we provide techno-economic assessments and environmental sustainability analyses that determine commercial viability. Life Cycle Assessment (LCA) frameworks are applied rigorously, quantifying environmental impacts across the entire value chain: synthesis phase impacts including raw material extraction, energy-intensive polymerization and crosslinking, solvent consumption and waste generation. Finally, we examine regulatory considerations for drinking and wastewater applications as outlined in Table 2 [52].

CHEMISTRY AND PHYSICS OF SMART HYDROGELS

Structural foundations

The defining characteristic of a hydrogel is its ability to absorb and retain enormous quantities of water within a three-dimensional crosslinked polymer network while maintaining structural integrity [55]. The swelling equilibrium is achieved when the chemical potential of water in the gel equals that of pure water, which can be expressed as the balance between the osmotic pressure driving water into the network and the elastic retraction force of the stretched polymer chains. The mixing contribution arises from the entropy

Table 2. Research gaps and future directions-priority matrix [40, 47, 53, 54].

Challenge Domain	Current Status	Critical Gaps	Required Advances	Expected Timeline	Impact Potential
Fundamental Understanding	Empirical optimization dominates	Molecular mechanisms of selective binding	Computational modeling, advanced spectroscopy	2-5 years	High (enables rational design)
Mechanical Robustness	Lab-scale stability adequate	Industrial-scale durability insufficient	Biomimetic designs, nanocomposites	3-7 years	Very High (enables deployment)
Scale-up Manufacturing	Batch synthesis, kg scale	Continuous production, ton scale	Process engineering, quality control	5-10 years	Critical (commercial viability)
Cost Reduction	\$20-60/kg for advanced systems	Target <\$10/kg for commodity use	Cheaper precursors, simplified synthesis		Critical (market penetration)
Regeneration Efficiency	5-20 cycles demonstrated	>50 cycles needed for economics	Enhanced reversibility, fouling control	2-5 years	High (operational costs)
Standardization	No industry standards	Testing protocols, performance metrics	Collaborative standard development	3-5 years	Moderate (facilitates adoption)
LCA Validation	Limited studies, small scale	Comprehensive cradle-to-grave data	Field trials, long-term monitoring	5-10 years	High (sustainability claims)
Nanoplastic Removal	Early research stage	Effective sub-micron capture	Ultra-small pores, strong interactions		Very High (emerging threat)

of mixing polymer and water, described by the Flory-Huggins interaction parameter χ, which characterizes the polymer-solvent interaction strength. The elastic contribution originates from the conformational entropy decrease when polymer chains are extended during swelling. Quantitatively, the equilibrium swelling ratio (Q = Vswollen/Vdry) scales approximately as Q ∝ ve^(-1/3), indicating that higher crosslink densities produce lower swelling and stiffer gels, while lower crosslink densities yield higher swelling and softer gels [56-61]. The molecular architecture of the polymer network profoundly influences both equilibrium properties and dynamic behavior. Homogeneous networks with uniform crosslink distribution exhibit predictable swelling and mechanical responses described well by classical theories. However, most practical hydrogels contain structural heterogeneities arising from non-uniform crosslinking during synthesis, resulting in regions of dense crosslinking coexisting with loosely crosslinked or even uncrosslinked domains. Advanced synthesis techniques aim to control this heterogeneity: cryogelation conducted at sub-zero temperatures yield macroporous structures through ice crystal templating, dramatically enhancing flow-through applications by reducing hydraulic resistance (Fig. 7) [61-64].

Neutral polymers interact primarily through weak van der Waals forces and hydrogen bonding. Polyelectrolyte hydrogels containing ionizable groups exhibit dramatically enhanced capabilities through electrostatic interactions. Polyanionic systems such as poly(acrylic acid) (PAA) with pKa ≈ 4.5 or poly(methacrylic acid) (PMAA) with pKa ≈ 5.5 become negatively charged at pH > pKa through deprotonation of carboxyl groups ($R\text{-}COOH \rightarrow R\text{-}COO^- + H^+$), enabling strong attraction of cationic species including most heavy metal ions and cationic organic dyes [65-67]. Conversely, polycationic systems such as chitosan with pKa ≈ 6.5 or poly(4-vinylpyridine) become positively charged at pH < pKa through protonation of amine or pyridine groups ($R\text{-}NH_2 + H^+ \rightarrow R\text{-}NH_3^+$), facilitating capture of anionic pollutants including chromate (CrO_4^{2-}), arsenate (AsO_4^{3-}), and anionic dyes [56, 65, 68, 69].

Amphoteric or zwitterionic hydrogels incorporating both acidic and basic groups exhibit even more sophisticated behavior. Sulfobetaine or carboxybetaine polymers possess both positive and negative charges on the same monomer unit, creating an overall neutral but highly polar surface [70-72]. Nuclear magnetic resonance (NMR) relaxometry studies reveal that water relaxation

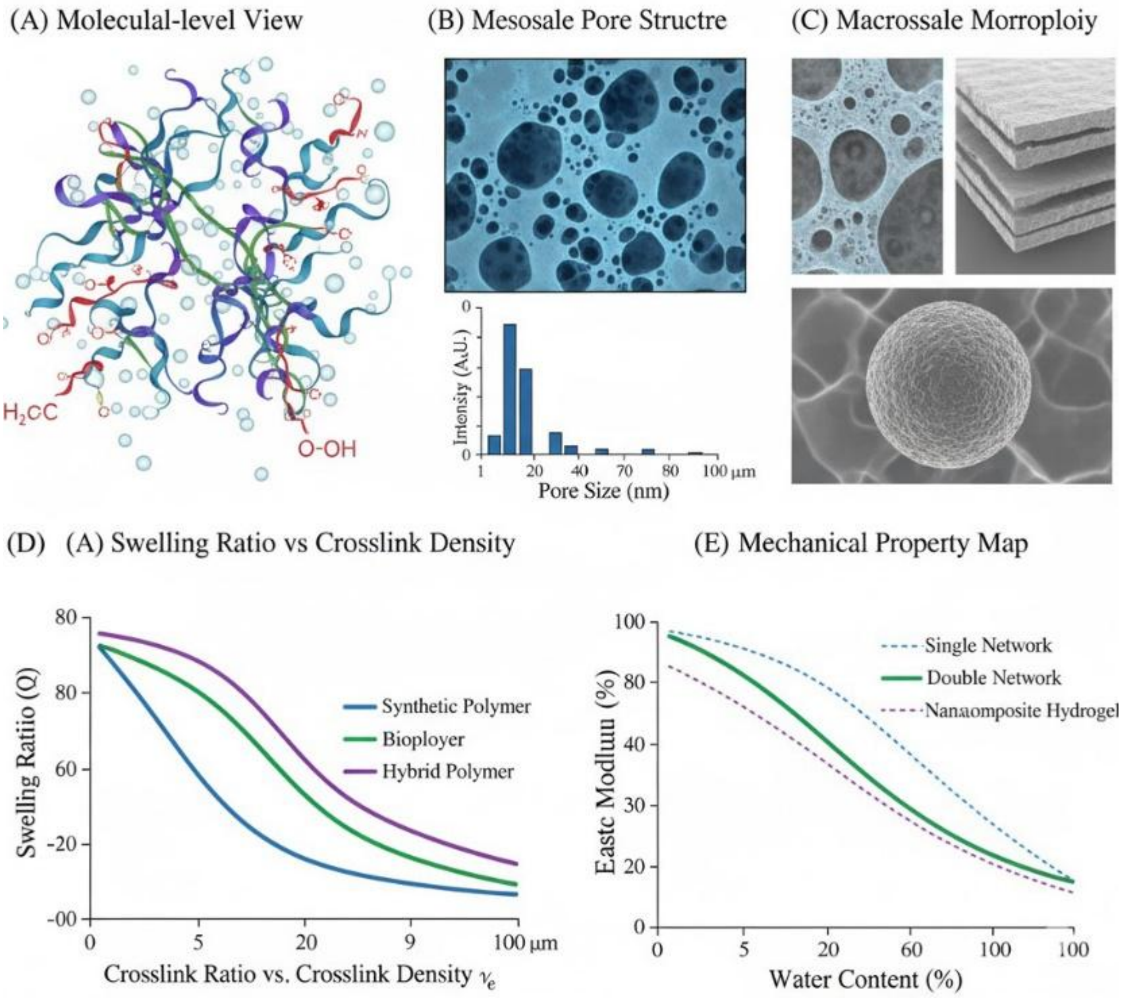

Fig. 7. Hydrogel's structure-property relationships.

times (T_1, T_2) decrease substantially in hydrogels versus bulk water, providing quantitative measures of water-polymer interactions. These differences in water structure have practical implications: bound water does not contribute to solute transport and effectively reduces available water content for pollutant dissolution; this "excluded volume" effect can paradoxically enhance selectivity by providing a pre-concentration mechanism where contaminant-to-water ratio in accessible pore space exceeds that in the bulk solution [73-75].

Stimuli-responsive mechanisms: Molecular origins and quantitative models

pH-responsive systems: Polyelectrolyte theory and applications

pH-responsive hydrogels undergo reversible volume transitions in response to changes in solution pH through ionization or deionization of acidic or basic pendant groups on the polymer backbone. The theoretical framework for understanding these transitions combines polyelectrolyte theory, which describes the distribution of mobile ions around charged polymers, with network elasticity theory. For a weak polyacrylic acid gel in aqueous solution, the degree of ionization (α) of carboxyl groups depends on pH according to the Henderson-Hasselbalch equation: $pH = pKa + \log[\alpha/(1-\alpha)]$, where pKa is the acid dissociation constant (typically 4.5-5.5 for PAA depending on local environment). With an increase in solution pH, there is an increment in deprotonation i.e., α. This helps in developing negative charge on polymer chain and thereby causing ionic interactions between chains of polymer finally leading to swelling of gel [76-78] that can be better understandable by Donnan equilibrium theory. For polyanionic gels at high pH, the fixed negative charges on the polymer exclude mobile anions (Cl^-) from the gel phase while attracting excess cations (Na^+), creating a measurable Donnan potential typically in the range of 10-50 mV. The resulting osmotic pressure drives swelling, with the swelling ratio increasing approximately as $Q \propto \alpha^2/ve$ when ionic strength is low, indicating that higher ionization (higher pH) produces dramatically enhanced swelling. However, addition of neutral salt (NaCl) screens the electrostatic interactions through Debye-Hückel shielding with a characteristic Debye length $\lambda D = [\varepsilon\varepsilon_0 kT/(2NAe^2I)]^{(1/2)}$, where ε is the dielectric constant, ε_0 is permittivity of free space, k is Boltzmann's constant, NA is Avogadro's number, e is elementary charge, and I is ionic strength. At physiological ionic strength ($I \approx 0.15$ M), $\lambda D \approx 0.8$ nm, substantially reducing swelling compared to pure water. This ionic strength dependence is considered when designing systems for water containing dissolved salts (Fig. 8) [79-86].

The kinetics of pH-triggered swelling and deswelling exhibit characteristic time scales determined by polymer diffusion and network relaxation. For small pH changes near the pKa, swelling kinetics typically follow second-order behavior with time constants ranging from minutes for thin films (<100 µm thickness) to hours for bulk gels (>1 mm). For large pH jumps crossing the pKa, the response can be accelerated through incorporation of porous structures enabling convective flow rather than purely diffusive transport. The practical utility of pH-responsive systems for water treatment stems from their ability to capture pollutants at one pH and release them at another. For example, a carboxyl-

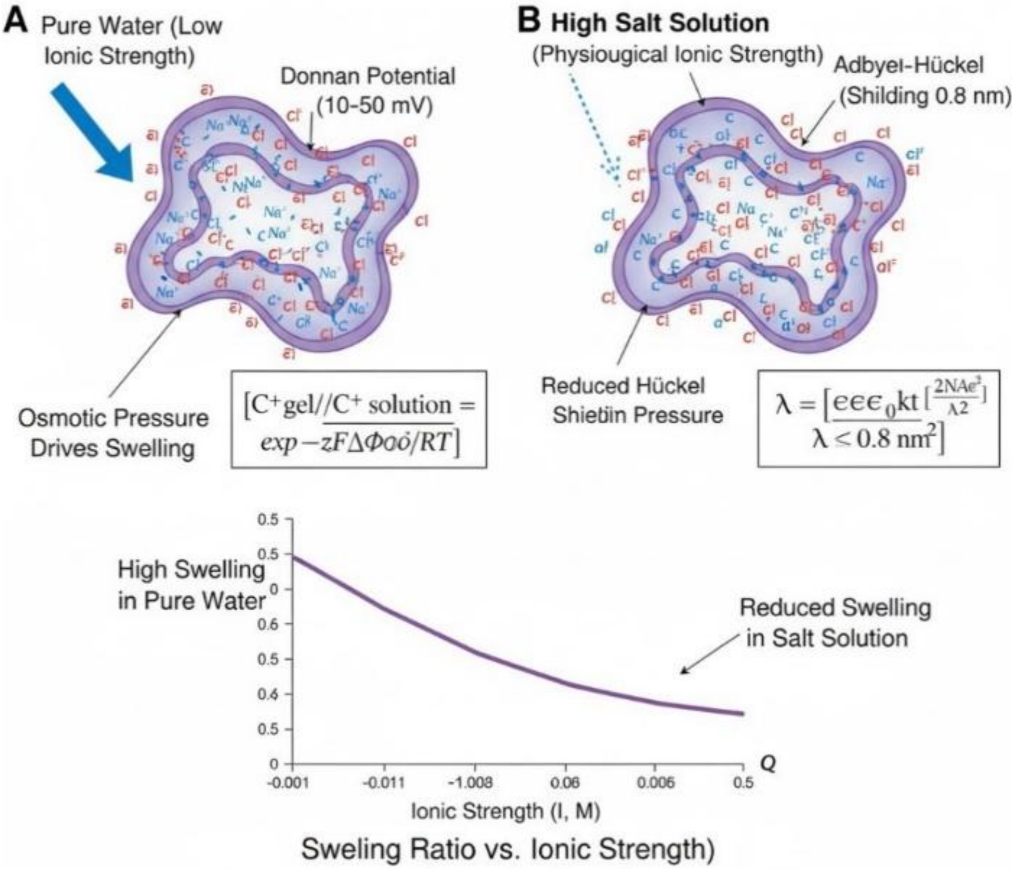

Fig. 8. Donnan equilibrium and ionic strength effects on hydrogel swelling.

Table 3. pH-responsive polymers for water treatment applications [89-93].

Polymer System	Functional Group	pKa	pH Transition Range	Swelling Ratio (Q)	Target Pollutants	Adsorption Capacity (mg/g)	Regeneration Method	Typical Cost ($/kg)
Poly(acrylic acid) (PAA)	-COOH	4.5-5.0	pH 3-7	2-50	Heavy metals (Cu^{2+}, Pb^{2+}, Cd^{2+}), cationic dyes	200-450	Acid wash (pH 2)	10-25
Poly(methacrylic acid) (PMAA)	-COOH	5.0-5.5	pH 4-8	2-30	Heavy metals, cationic dyes	180-400	Acid wash (pH 2)	15-30
Chitosan	$-NH_2$	6.5	pH 3-7	2-20	Anionic dyes, Cr(VI), As(V), metals	100-350	Base wash (pH 10)	20-40
Poly(4-vinylpyridine)	Pyridine-N	5.0	pH 3-7	3-40	Anionic pollutants, metal complexes	150-320	Base wash (pH 10)	40-80
Alginate	-COOH	3.5-4.0	pH 2-6	5-100	Heavy metals (selective Ca^{2+}/Pb^{2+})	150-600	Acid + EDTA	25-50
Poly(acrylamide-co-acrylic acid)	-COOH/-$CONH_2$	4.5-5.0	pH 3-7	10-80	Metals, organic pollutants	250-500	Acid wash (pH 2)	12-28
Carboxymethyl cellulose	-COOH	4.0-4.5	pH 3-7	5-35	Heavy metals, dyes	120-280	Acid wash (pH 2)	15-35

functionalized gel at pH 6 ($\alpha \approx 0.9$, highly charged) efficiently binds Cu^{2+} through formation of copper-carboxylate complexes with stability constants $K \approx 10^8\ M^{-2}$, achieving adsorption capacities of 200-400 mg/g. Subsequent acidification to pH 2 ($\alpha \approx 0.01$, nearly neutral) protonates the carboxyl groups, eliminating electrostatic binding and reducing the complex stability constant by orders of magnitude, releasing the copper ions into a small volume of acidic regeneration solution where they are concentrated 10-50 fold. Neutralization of the gel then restores its original state for reuse, completing a regeneration cycle that consumes only dilute acid and base (typical cost $0.10-0.30 per kg of gel per cycle) rather than energy-intensive thermal treatment (Table 3) [87-89].

Temperature-responsive systems: Phase transition thermodynamics

Temperature-responsive hydrogels exploit polymers that undergo phase transitions at specific temperatures, exhibiting discontinuous changes in solubility and therefore swelling behavior. The most extensively studied class contains polymers with a Lower Critical Solution Temperature (LCST), below which the polymer-water system exists as a homogeneous single phase (polymer dissolved or gel swollen), and above which phase separation occurs (polymer precipitates or gel collapses). Poly(N-isopropylacrylamide) (PNIPAAm) represents the archetypal LCST polymer with a transition temperature of approximately 32°C in pure water-conveniently near physiological temperature for biomedical applications and readily accessible for water treatment processes. The molecular origin of the LCST phenomenon involves a delicate balance between polymer-water hydrogen bonding, which is enthalpically favorable and promotes dissolution, and hydrophobic association of polymer segments, which is entropically favorable at higher temperatures due to release of ordered water structures surrounding non-polar groups. At temperatures below the LCST, hydrogen bonding dominates and polymer chains are extended and hydrated; as temperature increases, thermal energy disrupts hydrogen bonds, allowing hydrophobic interactions to dominate, causing chain collapse and aggregation (Fig. 9) [94-97].

The thermodynamics of the LCST transition can be described through the temperature-dependent Flory-Huggins interaction parameter $\chi(T)$, which for LCST systems increases with temperature rather than remaining constant. Empirically, χ often follows a relationship: $\chi = A + B/T$, where A and B are constants depending on the specific polymer-solvent pair. Phase separation occurs when χ exceeds a critical value (typically $\chi > 0.5$ for high molecular weight polymers), which for PNIPAAm in water corresponds to approximately 32°C. The sharpness of the transition-critically important for applications requiring precise temperature control-can be characterized by the transition width, typically 2-5°C for PNIPAAm homopolymers but tunable through copolymerization. Incorporation

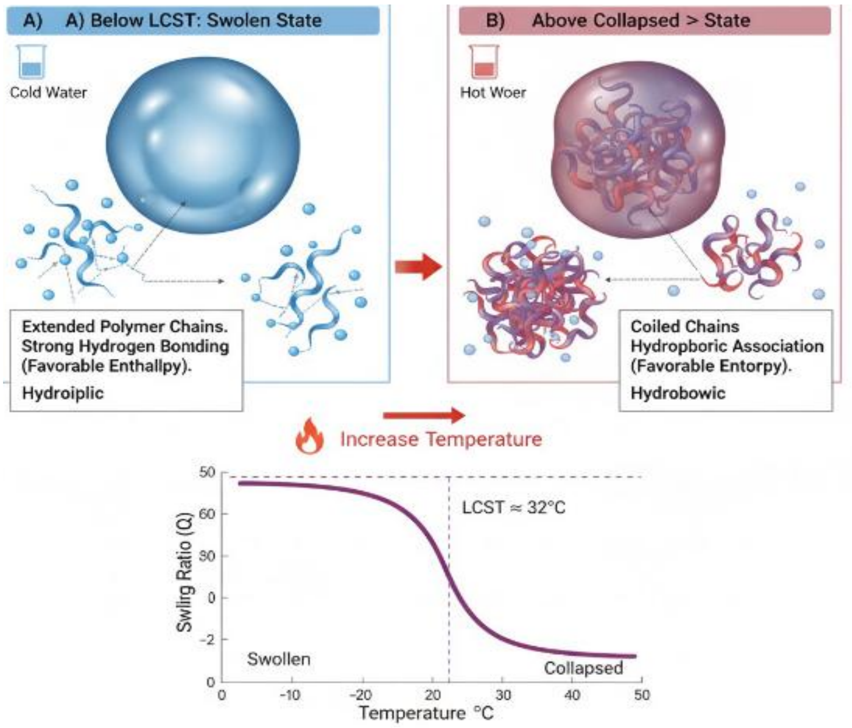

Fig. 9. Temperature-responsive hydrogels: The LCST phenomenon.

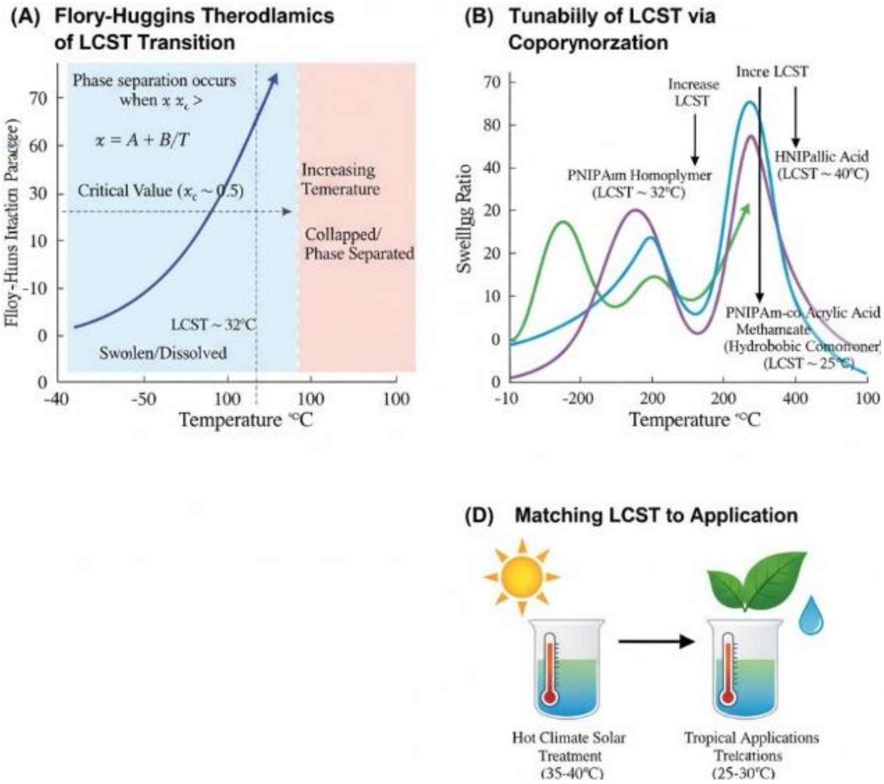

Fig. 10. Thermodynamics along with tunability of LCST hydrogels.

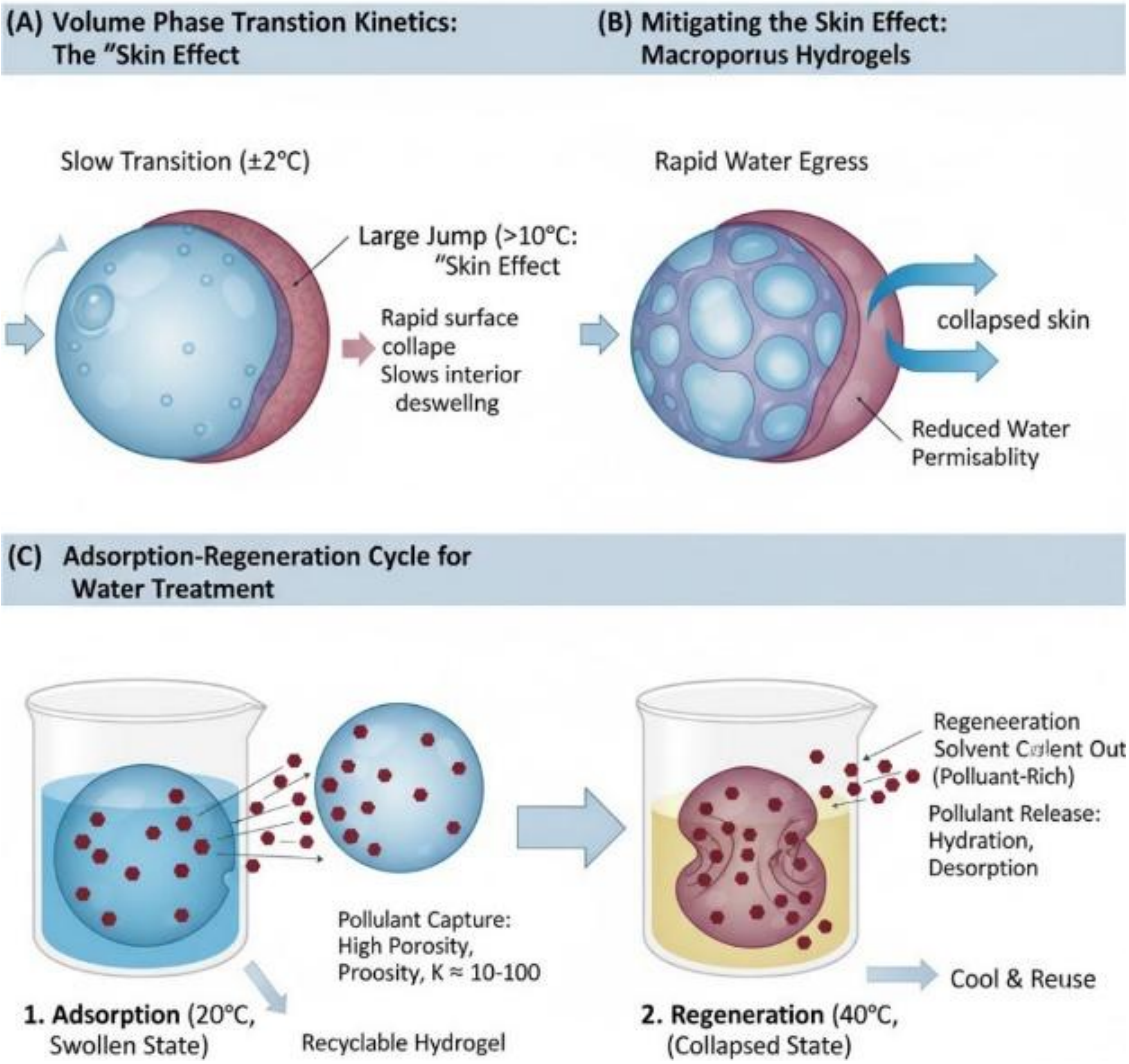

Fig. 11. Kinetics and applications of temperature-responsive hydrogels for water treatment.

of hydrophilic comonomers such as acrylic acid or acrylamide increases the LCST (making the gel more water-compatible), while hydrophobic comonomers such as butyl methacrylate decrease the LCST (Fig. 10) [98-101].

The practical utility of temperature-responsive systems for water treatment involves capturing pollutants in a swollen state at low temperature (where high porosity and surface area promote rapid adsorption) and releasing them in a collapsed state at elevated temperature (where reduced hydration and enhanced hydrophobic interactions destabilize pollutant binding). For example, a PNIPAAm-based gel at 20°C (swollen) adsorbs non-polar organic contaminants such as phenol or chlorinated pesticides through partitioning into the hydrated polymer network with partition coefficients K ≈ 10-100; heating to 40°C (collapsed) expels water and concentrates the organic pollutants in a much smaller volume while simultaneously shifting the partition equilibrium to favor release into an organic-rich regeneration solvent. Cooling returns the gel to its swollen state for the next adsorption cycle (Fig. 11) [102-105].

CONCLUSION

Stimuli-responsive hydrogels represent a transformative paradigm shift in water treatment technology, offering unprecedented advantages over conventional methods through their ability to undergo reversible physicochemical transitions triggered by environmental stimuli. Current study delves to study smart hydrogels that obtain 3-8 fold higher adsorption capacities compared to carbon, along with 5-10 fold reductions in regeneration energy uses. These substances deliver >95% removal for pollutants while enabling 30-60% lifecycle cost reductions. Despite these compelling advantages, critical challenges remain before widespread industrial deployment: mechanical stability under operational stress, scale-up from laboratory to ton-scale production, long-term fouling resistance in complex matrices, and batch-to-batch manufacturing consistency. By systematically addressing these engineering challenges through interdisciplinary collaboration, smart hydrogels can fulfill their transformative potential as sustainable, energy-efficient, and economically viable solutions for global water security in 21st century.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript.

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