**A Review of Hydrogels their Classifications, and Applications**

 **Deepti Chauhan, e-mail-** deeptichauhan2570@gmail.com

Department of Applied Chemistry, Delhi Technological University, Delhi, India

**Abstract**

A hydrogel is a three-dimensional network of polymers that can absorb biological fluids and is insoluble in water. A polymer network like that is created via physical crosslinking and chemical crosslinking mechanism. Whereas weak secondary forces make physical hydrogels, covalent forces form chemical hydrogels. There are numerous natural and synthetic polymers used to make hydrogels. The most significant characteristics of hydrogels are swelling, mechanical properties, and their biological properties, all of which have an impact on the hydrogel's morphology and structure. Hydrogel is used in wound dressings, tissue engineering, contact lenses, adsorbent, sensor and in medical applications, because of its water-absorbing properties and structural resemblance to the extracellular matrix (ECM). In this review hydrogels, types of hydrogels, their applications have discussed.

**1 Introduction**

**1.1 hydrogels**

Researchers, over the years, have given different definitions of hydrogels. Such as they are polymeric networks extensively swollen with water and hold onto a substantial amount of water within its structure, but insoluble in water. The hydrophilic functional groups attached to the polymeric network attributes to the absorbance and water retention property in a hydrogel. On the other hand, the cross-links between the polymeric chains attributes to their reluctance to dissolution. Hydrogels can be defined composed of two or more components having a 3-D network of polymeric chains. Hydrophilic gels are interpreted as networks of polymeric chains which are often colloidal gels having water as a medium of dispersion.1,2 Hydrogels are commonly stated as a cross-linked polymeric chains that undergoes swelling in presence of water, and are obtained through a simple reaction between one or more monomers. Its crosslinking allows it to retain its three-dimensional characteristics during its swollen phase.3 Over the past 50 years, hydrogels have drawn a lot of attention because of their extraordinary promise in a variety of applications.4 Hydrogels exhibit flexibility very similar to that of natural tissue due to their capability of carrying large water and fluid contents, such as biological fluids which may resemble biological tissues. Due to this property, a lot of interest has grown in designing the innovative devices through altering their tuneable physicochemical characteristics. Recently, synthetic hydrogels rapidly replaced natural hydrogels having distinct structures that can yield changeable functionality and degradable by additional modification. Relying upon the properties of the components utilized in polymeric network along with the density of the network joints, they can contain various amounts of water in equilibrium.5

The synthesis of hydrogels can be achieved by several chemical ways involving one-step methods like cross-linking of multifunctional monomers, polymerization, and multiple step methods which involves synthesis of polymeric chains containing highly reactive functional groups, which subsequently gets cross-linked with a suitable cross-linking agent. A polymer engineer can formulate polymeric networks possessing a molecular-scale control over structure including cross-linking density with modified features like, biodegradation, mechanical properties, biological and chemical response to stimuli.6

**1.2 Natural Gums based Hydrogels**

In the recent past, the prospected applications of natural gum polysaccharides in a range of fields of water, food, energy, environment, medicine, and biotechnology industries, have gained an eye of research fraternity, because of their accessibility, affordability, structural variety, and exceptional qualities. Natural gums or polysaccharides7 are obtainable from various tree groups, possessing extraordinary properties, including renewable, biodegradable, biocompatible, non-toxic nature and can be easily modified chemically.7 Natural gum-based hydrogels or polysaccharides provide numerous valuable properties compared to synthetic origin. In the recent years they have observed remarkable improvement as a novel alternative because of health, ecological problems and environmental contamination brought on by the unregulated usage of hydrogels made of synthetic polymers.8, 9 Hence, there is a great demand of the materials that don't damage the environment. These hydrophilic polymeric networks are insoluble in water, display higher strength and elasticity.1, 10 They are eminently responsive towards their environment, like any change in, pressure, electric field, solvent composition, pH and temperature.11,12,13 The practical importance of these hydrated polymeric network is greatly developing continuously and are valuable as biomimetic, intelligent, and intelligent materials. They have applications in sensors, actuators and frequently they are being studied as self-oscillating gels.14 Hydrogels termed as Smart networks exhibit a significant physicochemical response towards small changes in the surroundings. These alterations are reversible, and if the trigger is removed, they can go back to their original state.15

**1.3 Classification of Hydrogels**

*Based on source*: They can be of natural or synthetic origins. Natural polymers include polysaccharides like alginate and proteins like collagen and gelatine, starch, cellulose, glucomannan, pectin, hemicellulose, gums, and agarose forming hydrogels. Synthetic polymers including polyethylene glycol (PEG), polyvinyl alcohol (PVA), polyacrylic acid (PAA), polyacrylamide (PAM) that form hydrogels are conventionally synthesized using chemical polymerization methods.2

*Based on polymeric composition* or synthesis techniques:

1. Homopolymer hydrogels have basic structural and functional unit comprising of a single type of monomer in the polymeric network. Their skeletons may be cross-linked, based on the method used for polymerization as well as on the type of monomer.16
2. Copolymeric hydrogels are derived from a variety of monomeric units with at least one hydrophilic component. The polymeric network chains can be arranged in a random, block or alternating configuration. 17
3. Multipolymer interpenetrating polymeric network (IPN) can be synthesized using two separate, cross-linked components of natural or synthetic polymers, confined in a network form. In case of Semi-interpenetrating hydrogel, one polymer is a cross-linked and other polymeric component is a non-cross-linked.18 One straight polymeric chain enters another crosslinked network, and they interact without any chemical bonding.19

*Based on physical and chemical composition:* (I) Non-crystalline (Amorphous) (II) Semicrystalline, a composite of amorphous and crystalline phases. (III) Crystalline.2

*Based on cross-linked networks:* Chemically cross-linked networks have permanent bonding involving covalent interaction while physical networks have transient junctions involving entanglements of polymeric chain involving hydrogen bonds, polar or ionic, hydrophobic type of physical interactions.2

*Based on* *electrical charge*: (I) Neutral (non-ionic), (II) Ionic (including anionic or cationic), (III) Amphoteric having both acidic and basic groups, (IV) Zwitterionic (polybetaines) possess both cationic and anionic functionality in each repeating unit.2

**1.4 Preparation of hydrogels**

Hydrogels can be produced employing natural, synthetic, and composite of both natural and synthetic polymeric materials. Hydrogels have been created by cross-linking polymer chains through chemical alteration, external cross-linking agents, exposure to high energy radiation, and polymerization grafting. In the hydrogel formation chemical cross-linking involve the formation of new covalent bonds between polymeric chains in the hydrogel, where as physical cross-linking involves physical interactions between polymer chains.53 Both chemical and physical methods have their own advantages and disadvantages related with them. Conventional and controlled radical polymerization techniques results hydrogels with various morphologies, size and composition including hollow core-shell particles.54, 55 The most widely used mechanism is free radical polymerization to prepare hydrogels.56, 57 Usually in hydrogel preparation, the gel reactants react with crosslinker (s) to generate 3D-crosslinked networks in presence of radical initiators like potassium persulfate or ammonium persulfate. Free radical polymerization occurs in three main steps: initiation, propagation, and termination58. In the initiation step, free radicals (R●) are produced when an initiator dissociated and then react with other molecules (M) to produce the first radicals M●. In the propagation step highly, reactive free radicals rapidly react with molecules of monomer resulting formation of macroradicals. Usually, termination occurs by combination or disproportionation reaction of free radicals. Various shape of hydrogels like bulk, sphere, and films can be obtained by selecting the appropriate preparation process, raw material, and polymerization condition.47

*Bulk Hydrogels*: Usually, they are smoothly obtained by solution or homogeneous polymerization wherein all the reactants i.e., the monomer (or polymer), initiator, and cross- linker are soluble in the medium. The resultant hydrogel generally takes up the shape of the container in which it has been polymerized and yields a relatively homogeneous hydrogel.59 However, due to the slow diffusion of solute to the adsorption sites within hydrogel it will take long time to reach equilibrium during water treatment.60 Usually, bulk hydrogel is cut into small sized pieces manually or by using food blender to produce small size hydrogel beads for better adsorption efficiency. On the other hand, occasionally a cutting or grinding step could produce hydrogel particles with a fractured morphology and polydispersity.61, 62

*Spherical Hydrogels*: Spherical hydrogel does not require grinding or cutting and thus avoids further morphology destruction and energy consumption. Hydrogel bead is an example of spherical hydrogel with a millimetre diameter. Usually, synthesis of spherical hydrogels involves dropping the monomer or polymer suspension using syringe into a solution thus, the size of the resultant hydrogel bead typically depends on the syringe's diameter. Chitosan, a natural polysaccharide which is biodegradable, nontoxic, odourless, biocompatible and Hydrogel beads are often prepared using biopolymer. When it comes into contact with potassium and sodium cations, it can get crosslinked.63-67

*Hydrogel Films*: Hydrogel composite film appears to hold a lot of potential for practical use. They are simple to make and show robust and repeatable self-healing behaviour in the aqueous medium. Numerous hydrogels have been used as an effective ion-exchange film to purify water. Recently, the direct synthesis of nanofiber hydrogel film has been achieved using the electrospinning technology.38 Some extra components could be added to the hydrogel film either by grafting after polymerization or by combining additive with hydrogel precursor before polymerization to create a specific hydrogel composite with the required qualities.69 Hydrogel film is typically utilized as an active membrane in sensing applications, mainly to give a more hydrophilic surface that is less prone to contamination.65

**1.5 Characterization of Hydrogels**

Numerous characterisation approaches have been utilized for knowing the hydrogel’s physical and chemical properties. The physical properties of polymeric hydrogels determined by the volume fraction, effective molecular weight of the polymeric chain in between two crosslinking junction and on the density of the crosslinking.20 Hydrogels have many properties, such as absorption capacity, permeability, swelling behaviour, optical, surface, and mechanical properties. The nature of the polymer chains and the crosslinking present in the network structures play a significant function in the result of the properties of the hydrogel. All these properties are responsible for making hydrogel a promising material for a wide range of applications.21

*Fourier Transform Infrared Spectroscopy FTIR analysis*: This method provides reliable crosslinking data and gives a notion of the hydrogels' morphology.

*Atomic Force Microscopy (AFM)*: This technique helps to examine the hydrogels' surface morphology. It uses multimode atomic force microscope.

*Network Pore Size:* Various techniques, for instance, mercury porosimetry, Quasi-elastic laser light scattering, equilibrium swelling, electron microscopy, and rubber elasticity measurements experiments are employed to find out the network pore size of hydrogel. This is an important technique for hydrogel characterization.

 *X-ray Diffraction*: X-ray diffraction analysis enables one to understand the crystalline and amorphous nature of hydrogel, whether the crystallinity is maintained or was distorted while synthesizing.

*Swelling Behaviour*: To study the potential use as a hydrogel, the specific swelling data studies are employed and it has been successfully studied by numerous researchers.

*Crosslinking and Mechanical Strength*: The crosslinking density inside the network structure of hydrogel determines its mechanical strength. Generally, with increasing crosslinker concentration mechanical strength of the hydrogel also increases.

*Rheology*: It depends on the kind of interactions (entanglement, association, and crosslinks) present in the polymeric network among polymer chains.

All these characterization methods provide important information about the desired crosslinking results, formation of hydrogel. Which can be useful further for various applications.3

**2 Applications of Hydrogel**

The salient features of hydrogels, they are biodegradable, hydrophilic character, biocompatible, less toxic, highly flexible like tissues and easily modifiable. They have good transport properties and the capacity to adapt to changes in the environment, such as those in pH, temperature, or metabolite concentration. Owing to their extraordinary properties, hydrogels are said to have novel applications in a number of fields like drug delivery, wound dressing, agriculture, tissue engineering, water purification, hygiene applications, etc.3,7

Because hydrogels exhibit characteristics that are comparable to those of human soft tissue, they are widely used in biomedical fields, including drug delivery.22-25, gene vectors, tissue engineering26, 27, and biosensors28, 29. Hydrogels meet both material and biological requirements because they have unique characteristics like desired functionality, reversibility, and biocompatibility. They are frequently employed for cell-laden, tissue regeneration, drug delivery, and biosensor.

*Soft Contact Lenses*: It remains one of the most popular uses for hydrogels because of their biocompatibility and mechanical properties. By dissolving the lens's water, hydrogels can be adjusted to match the curvature of the entire eye, allowing atmospheric oxygen to reach the cornea.30 Polyhydroxyethylmethacrylate (PHEMA) was the first ever established synthetic hydrogel as a favourable and great candidate for manufacture of contact lens by Wichterle and Lim (1960).3

*Tissue Regeneration and Tissue Engineering*: The loss or chronic failure of any organ function due to some severe disease or accident necessitates the demand of tissue and organ transplantations. It has becoming more difficult because there are fewer donors available and because of societal, legal, and other norms.31 Tissue engineering has raised hopes for creating a perfect live replacement that mimics the ways in which living tissues perform in the human body.3 Scaffolds act as 3-D artificial templates in which the rebuilding of targeted tissue is cultured to grow. The extremely porosity of hydrogel enables the diffusion of cells during migration, transfer of nutrients and excludes the unwanted products outside of cellular membranes.32 Hydrogels, both natural and synthetic, are utilized as scaffolds in numerous tissue engineering applications, such as the restoration of blood arteries, skin, heart valves, cartilage, and tendons.33 They have been used in a number of biomedical applications, including fillers for scar cosmetic repair7, bladder34, cartilage35, orthopaedic applications36, skin37 and bone38. Polysaccharides based hydrogels that exhibit biocompatibility with tissues which increases their significance in tissue engineering and biomedical applications.

*Wound healing*: Injured skin is covered to avoid bleeding and to protect the wound from environmental infections. Wound dressings are non-toxic, antiseptic, permeable to oxygen, preserve wound moisture, cause minimum damage, eliminates excess exudates and thus fasten the healing process while direct interacting with the wound. A great advantage of gum based hydrogel in wound dressings is that they can easily be applied or removed without interfering with the wound beds.39, 40 Compared to traditional bandages, pads, or gauzes, the mechanical characteristics of hydrogels increase their elasticity and flexibility to adapt with wounds and provide patients with immediate pain relief. They act as a coolant to localized wound in case of burn also reduces the pain and recovers from resultant damage.41, 42 Non-adhesive nature and hydrophilic surface of hydrogels do not allow it to attach with cells therefore causes less pain and discomfort to patient. Hydrogel transparency has a benefit over traditional bandages as it causes less discomfort during peeling it off. Various hydrogels for wound dressings are available, like amorphous gels, gel-impregnated gauzes, plasters or sheets. The development of hydrogel formulations to address different aspects of wound healing and management such as easy dressing, reduction in infection is attaining new heights.43, 3

*Drug Delivery*: Hydrogels' porous structure can act as a matrix for the loading or distribution of pharmaceuticals while also shielding them from harsh environments. Hydrogel targets specific sites like colon as a drug delivery agent and release drug or other nutrients timely. In addition to this hydrogel interacts very less with the drug and other loaded solute hence sustained and prolonged release occurs in the larger fraction comparative to conventional drug delivery systems.7 Because of their special ability to retain large volumes of water, hydrogels are valuable in drug delivery applications that regulate the release of solute over a predetermined length of time. This trait is known as hydrophilicity. Many biomaterials that function through two mechanisms have been investigated for this aim. (1) By adjusting the crosslinker dosage and keeping an eye on the proportion of hydrophilic to hydrophobic monomers, a controlled release of the medication can be accomplished. (2) Hydrogel release large fraction of active drug molecules (protein and peptides) because its interaction with drug is very less. Drug delivery that is targeted and controlled would help with healing and lessen unwanted side effects. Drug release from hydrogel is expressed by a number of processes, including diffusion, chemical control, deswelling, and environmentally responsive release. 3

*Agricultural Applications:* One significant step in achieving sustainable development and growth in agriculture is water management44. Superabsorbent polymeric hydrogels (SPH) derived from natural polysaccharides have gained significance in agriculture due to their remarkable capacity to hold and retain large amounts of water. In dry and semi-arid regions, SPH can be added to the soil to prolong longer moisture retention, enabling crops to tolerate arid weather. In dry and semi-arid soil, hydrogels act as "mini liquid tanks," releasing water into the soil along with the targeted amount of loaded nutrients. Modification in hydrogel properties as required give fertile physical properties of soil.45 The usage natural polysaccharides based SPH is flourishing owing to their biodegradability, durability, high water holding ability, avoid loss of nutrients, nontoxic, and their sustainability compared to synthetic polymer based hydrogels.46 Hydrogels have been used for the prevention of soil erosion over a decade by reduction in soil erosion, increasing water holding capacity, enhancing permeability of finely textured soils, enhance water infiltration among fine-textured agricultural soils. The water-soluble polyacrylamide (PAM) hydrogels form a thin film covering soil surface and are very efficient in preventing soil erosion. This film protect soil surface from washing away during irrigation and retains the optimum water content within the soil system, so that irrigation water can permeate easily.3

*Hydrogel as adsorbent:*  As we all know emerging contaminantsincluding pharmaceuticals, pesticides, industrial chemicals, metal ions, surfactants, and personal care products have elevated worldwide concern for their noteworthy hazard to marine ecosystem and human health. Many of them have no regulatory standards on the effects of chronic exposure due to the lack of information.70 These contaminants are stable under variety of circumstances such as aerobic digestion, heat and light thus they have the potential to build up and harm ecosystems. Therefore, adsorption method has been greatly adopted to treat emerging contaminates as it is really efficient and affordable.71

The use of hydrogel as an adsorbent in pollution management applications is becoming more and more popular. Both the hydrogel adsorbents and the type of adsorbate have a significant impact on the adsorption process. The Freundlich and Langmuir models provide a good interpretation for the adsorption data of emerging contaminants on hydrogels; the kinetic model is often pseudo-second-order. Because of the several interactions that occur between the adsorbate and the adsorbent, such as hydrophobic interaction, hydrogen bonding, ionic or electrostatic interaction, and π–π interaction, hydrogel adsorbents have a great affinity for pollutants. This fluctuates depending on several factors, including pH, the ionic strength of the solution, the chemical makeup of the adsorbent and adsorbate, and more. The surface of the adsorbent will have an ionic charge when the pH of the solution differs from the hydrogel adsorbents' isoelectric point. Ionic adsorbate undergoes simultaneous protonation and deprotonation at varying pH levels, leading to electrostatic interactions between them. Hence, pH is an important factor responsible for adsorption mechanism.47, 3 Many solid and liquid phase removal trials remained tracked for the elimination of pollutants from liquid such as coagulation, biochemical precipitation, adsorption, photodegradation, ion exchange, flocculation, electrochemical treatment, and membrane percolation.48-51 Of all these many methods, adsorption is seen to be superior due to its high efficiency, low effort, and ease of use. Hydrogels are thought to be special for adsorption-based water refining because of their high absorption capacity, low crystallinity, abundance of functional groups, and porous structure. Due to the several significant functional groups that polysaccharides (Gum) include in their structure, hydrogels based on them and graft copolymers have been thoroughly investigated as adsorbents for the removal of contaminants from aqueous environments, including heavy metal ions and organic dyes. The principle advantage of using natural gum-based hydrogels as adsorbents is their biocompatibility, their structure can be easily tailored according to the nature of the pollutant.52 Although hydrogels are found to be superior candidate for the elimination of several aqueous contaminants, including heavy metals, dyes and other emerging contaminates but selective adsorption of contaminates is hardly explored. Therefore, research attempts are required to prepare hydrogels with desired properties, sensitivity, and selectivity toward a specific contaminant. Many hydrogels have been developed with desirable strength and adsorption capacity, but their chemical and biological stability always ignored which needs to be considered for the sustainability and economic viability of wastewater treatment.47

*Hydrogel as sensor of heavy metal ions in environmental and biological sample*: Nonbiodegradable heavy metal ions widespread existence in water are potentially threatening to the ecosystem and living organisms. Hydrogels have been functionalized with many biomolecules, including DNA, to form stimuli-responsive sensors and materials72,73 However, for sensing application most of them rely on hydrogel phase transition or volume change. Because of their high sensor loading capacity, excellent biocompatibility, and extremely low optical background, hydrogels are perfect for optical sensor immobilization. Moreover , hydrogel backbone property such as charge and hydrophobicity can be modified by mixing with different monomers, allowing further control of sensor performance.73 As a transducer material, the stimuli-responsive hydrogel can be utilized to convert a recognition unit's reaction into a physical signal that can be detected by, e.g., quantifying the change of optical length with an optical fibre, observing the resulting change in swelling pressure under isochoric conditions or by measuring the diffracted wavelength of a polymerized crystalline colloidal array. The host-guest interactions in sensing applications have been proven to be a powerful tool. Usually, macrocyclic polyethers, i.e., crown ethers have been proved to be promising candidates in combination with hydrogel facilitated by the generation of highly selective and reversible host-guest complexes with specific alkali and heavy metal cations. Notably, the colorimetric sensing approach has garnered a lot of interest due to its direct visual perception, affordability, speed, and ease of use. Most colorimetric sensors are dispersed in sample solution for full contact with the target chemical to increase sensitivity; however, an uneven and unstable dispersion of the sensors might occasionally result in unsteady detection findings. Chemo sensors can be constructed on solid substrates to circumvent this issue. The choice of solid substrate is crucial since it has a significant impact on the sensor's sensitivity. In the sensor studies, a colorimetric chemo sensor can be formed by the design of molecules that change their colour in sample solution due to an alteration in their molecular structure in the presence of target ions.74 In aqueous conditions, the designed sensor molecule's solubility is crucial. The fact that the sensor cannot dissolve directly in water, although pollutant species, such as anion or cation, are soluble in water, is one of the most significant problems in this research. Additionally, the soluble sensor is meant to be used just once. To deal with such issues, researchers have opted to polymerize molecules that have sensing properties. According to this perspective, the sensor must be easily extracted from the sample solution and insoluble to be utilized again. Hydrogel is the best illustration of a solid support or polymer that is readily extracted from the sample solution through filtration. They are important for various sensing applications as they can be synthesized with good yield, have swelling in water, are reusable and stimuli responsive.74,75

Among other sophisticated technique such as atomic absorption (AAS) spectroscopy, inductively coupled plasma (ICP) spectroscopy which needed additives that are time consuming and complicated. Hence formulation of a new sensing methods for simple, fast, and portable on-site detection of multiple metal ions is considerable research interest. A colorimetric hydrogel sensor can act as an indicator which can produce visual changes in the presence of metal ions. The colorimetric probe has many binding sites like -OH, -NH and -SH functional groups that can form water-insoluble and stable complexes with various metal ions under ambient conditions. The colour change mechanism involved chemisorption process. Which implies the electron transfer mechanism occurring between adsorbent (sensor) and adsorbate (metal ions).76

Stimulus-sensitive hydrogels give response to slight changes in their environment such as physical stimuli including temperature, pressure, electric field, light, ionic strength, and magnetic field, chemical stimuli for example pH or ions change, or biological stimuli by changing volume in antigen, glucose, and enzyme. The hydrogels in the presence of these stimuli experience phase transition by sensing target substrate and simultaneously transform this sense into a macroscopic event. Such hydrogels may act as active sensing material and their response time depends on the shape, size and composition of hydrogel and can be improved by increasing both the number of ionic groups, and pore size and by reducing the size and cross-linking density.77 Polysaccharide-based natural polymers, including cellulose, starch, protein, chitosan and their derivatives, have also been explored in hydrogels synthesis for sensing applications, because, moreover to their ample functional groups and special chemical or physical properties, they are more interesting than their synthetic analogues which make them suitable for sensing. Hydrogels embedded with ion sensitive component can provide a great way of sensing ions, their concentration, and pH. Hydrogels based on polyacrylamide because of excellent biocompatibility and well-defined synthesis protocols with desirable physiological and mechanical functions are widely used in biosensors.78

Hou formulated an injectable hydrogel based on polysaccharide/polyacrylamide system for high-performance strain sensors.79 Hydrogels based on PAM and photonic crystals have also been explored as glucose or pH sensors by tracking the ionic strength. In addition to photonic crystal sensors, PAM hydrogels were immobilized with protein, enzymes, peptides, or antibodies for molecular recognition. They have been used humidity sensing, in the form of composites, because of their super absorbency.78

Amine-functionalized polyacrylamide hydrogels cross-linked with 5,6-dicarboxylic fluorescein are more selective for Cu2+ in presence of other metal ions and can be used to detect and quantify cupric ions.80 Toxic heavy-metal ions (Hg2+) may be identified by polyethylene glycol diacrylate (PEGDA) hydrogels by judicious exploitation of optical waveguides. The material allows to modify smooth surface with minimal light scattering at the surfaces. The fluorescence of embedded carbon dots (CDs) can be used to detect absorbed metal ions.81 Other mechanisms including fluorescence red shifts upon Hg2+ ions binding can be used through exploitation of thymine rich DNA-polyacrylamide hydrogels.82

The colloidal photonic crystal hydrogel (CPCH) films functionalized with aptamer were employed for the visual recognition of heavy metal ions (Hg2+ and Pb2+). The CPCHs were obtained from a colloidal crystal arrangement of monodisperse silica nanoparticles, polymerized inside the polyacrylamide hydrogel and aptamers were then cross-linked within hydrogel network. The specific binding of target ions and single-stranded aptamers cross-linked in the hydrogel network caused the hydrogel to shrink during detection. Which was identified as a corresponding blue shift in the Bragg diffraction peak position of the CPCHs and used to estimate the amount of the target ion.83

Diehl et. al. discussed the rapid mechanical actuation and sensing performance of plasmonic nanostructures combined with responsive polymeric network.84 Stimuli-responsive DNA-based nucleic acid hydrogel system and their novel applications have been reported.85 Recent developments about enzyme-responsive polymeric assemblies, nanoparticles, hydrogels and discussed their promising applications in biocatalysis, drug controlled release, sensing, imaging, and diagnostics.86 The molecular recognition properties of analyte-responsive hydrogels, the physicochemical changes occurs upon analyte binding can be used to generate a detectable signal for sensing applications and how these materials have been incorporated into sensors and drug delivery systems have been reported.87

**2.1 Heavy Metals and Toxicity**

The heavy metals are toxic bio-accumulative, non-biodegradable pollutants of the environment that pose a risk to human health. Heavy metals, such as arsenic, mercury, cadmium, lead, etc., are well-known bio accumulative, highly toxic, non-biodegradable pollutants of the environment. Increased urbanization, industrialization, and natural calamities such as volcanic activity, erosion of minerals and leaching of deposited ores are responsible for an increased level of heavy metals in our environment.88 Living organisms require small quantities of heavy metals such as manganese, iron, cobalt, copper, and zinc. These are nutritionally essential for the regulation of human metabolism. While all metals are hazardous in greater concentrations, heavy metals like lead, mercury, and cadmium are hazardous even in smaller amounts.89 Heavy metals such as lead, mercury and plutonium have no known vital role in organisms but can cause serious illness due to their accumulation over time in the bodies of animals.90 These metal ions aggregate in the human and animal bodies through the food chain, ecological system induces irreversible pollution and causes some serious health issues such as cancer, organ damage, nervous system damage and sometimes death.91 Though, metal ions play vital roles in biology, but even nectar is a poison if taken to excess. Thus, surplus levels of metal ions in living bodies can lead to malfunctioning in respiration, growth, gene transcriptions, enzymatic reactions, and immune functions.92 Therefore, routine detection of heavy metal ions is important for the environment. Current techniques, such as AAS, ICPMS, X-ray fluorescence, etc., require expensive equipment, complicated and time-consuming methods, and high levels of operator skills. The cost-effective, simple, fast, facile toxic metal ion detection method that allows real time on spot detection of heavy metal ions is an important goal.93

Heavy metals are among the most commonly found pollutants in wastewater. Because they pose a serious threat to the environment, it is imperative that these pollutants be removed from water during the water treatment process, and this involves study.94 The discharge of harmful heavy metal-contaminated wastewater, whether pre-treated, straight into aquatic environments.95 Without any obvious symptoms, these metal ions may compile up to extremely high hazardous levels. The safe and sensible use of agricultural soils is hampered by long-term irrigation with wastewater contaminated with heavy metal ions. Food quality suffers when heavy metals such as Cd, Cr, Cu, Zn, Pb, Hg, and Mn aggregate excessively in agricultural soil. Vegetables and plants grown close to industrial zones have higher concentrations of heavy metals. Both humans and animals who consume these goods may have health issues due to the compilation of heavy metal ions in both edible and non-edible materials. For living organism to survive, early detection, identification, and removal of heavy metal ions from effluents are crucial.96,97

**2.2 Elimination of heavy metals**

C.-H. Hung, G.-F. Chang, A. Kumar, G.-F. Lin, L.-Y. Luo, W.-M. Ching, E. Wei-guangdiau, chem. Commun., (**2007) 978–980.**

Conventional methods such as coagulation/flocculation, biological treatment, reverse osmosis, electrochemical operation, complexation/sequestration, ion exchange, membrane filtration, chemical precipitation, zeolites, adsorption, and carbon-based sorbent are typically used to physically and chemically remove heavy metal ions from wastewater. At lower quantities of heavy metals, the aforementioned procedure loses economic viability and may result in secondary pollution.98-100 Many methods have been developed to remove heavy metal ions from wastewater, but they all have drawbacks. For example, when using a solvent extraction method, the eluent needs to be treated to prevent pollution from spreading. Adsorption of contaminants on solid sorbents seems to be an effective technology, but chemical precipitation of toxic sediments is not an economically viable method. Among all of these adsorption methods, is well known for being a simple, efficient, and adaptable way to remove heavy metals from aqueous solutions. Ions can enter the cross-linked framework of hydrogel more quickly due to its high-water retention capacity.101 They experience reversible volume changes in response to temperature and pH changes in the environment. Because of this characteristic, hydrogels are used as sensors, absorbents, and molecular detectors. Water molecules and ions can readily diffuse into and interact with functional groups (-COOH, -NH2, -OH) in a polymeric network thanks to the hydrogel's highly porous structure. Hydrogels can form complexes with metal ions, which makes them effective metal absorbents.102 Depending on the type of the polymers used, as well as on the properties, nature and density of the network junctions, such structures are in an equilibrium with aqueous medium can contain different amounts of water with a low optical background, high loading capacity, and good biocompatibility. Hydrogels which can swell up to thousands of times of their dry mass in aqueous media in response to external stimuli are called smart materials. This is due to the presence of hydrophilic functional groups like -NH2, –OH, -COOH, and -SO3H in the three dimensional structures, these groups can interact with pollutant species through both electrostatic and secondary interactions in aqueous media.103 Hydrogels are perfect for optical sensor immobilization owing good biocompatibility, better sensor loading capacity, and very low optical background.104 Further, by mixing with different monomers hydrogel backbone property such as charge and hydrophobicity can be modified, allowing control of sensor performance.

A number of alternative techniques have been reported for the elimination of harmful metal ions from water. For example, the Cerium phosphate polypyrrole flower-like nanocomposite material (CePO4-PPY) has been identified as a potentially effective adsorbent for the removal of Cr (VI) from wastewater. Adsorption and simultaneous in situ chemical reduction of Cr (VI) and Cr (III) were both used in the removal procedure.105 A promising nanocomposite based on lanthanum phosphate polyaniline (LaPO4-PANI) has been discovered for the removal of Cr (VI). The combined effects of reduction and adsorption were implicated in the adsorption mechanism.105 The core-shell nanocomposite based on polyaniline (PANI) and thorium dioxide (ThO2) was used to remove Cr (VI) from water. In the adsorption experiment, the ThO2-PANI nanocomposite was able to partially convert Cr (VI) to Cr (III).106 It was discovered that an adsorbent based on poly o-toluidine (POT) and lanthanum phosphate (LaP) was an effective adsorbent with a better regeneration capability and the potential to remove fluoride from ground-contaminated water.101–107

There have been reported methods for removing Zn2+, Cd2+, and Hg2+ from water. For example, polyacrylamide hydrogels functionalized with DNA are used to remove Hg2+ from water. 108 An optical nanocomposite material based on highly ordered mesoporous silica impregnated with ligand N, N-disalicylidene-4,5-dimethyl-phenylenedene is utilized for the sensitive and targeted removal of Hg2+ from wastewater.109 The diacryloyl derivative of cysteine cross-linked with poly(N-isopropylacrylamide) hydrogel is used to remove Pb2+ and Cd2+.101 A sensitive fluorescent sensor for the detection and elimination of harmful metal ions such as Cd2+, Hg2+, and Pb2+ from aqueous samples is based on the immobilization of 2,2-dipicolylamine modified naphthalimide fluorophore on the surface of silica microsphere.110 Red mud, a byproduct of the aluminum industry, has been made into an effective and affordable adsorbent for Zn2+, Cd2+ .111 carbon aerogel a novel kind of activated carbon for adsorption Pb2+, Cd2+ and Hg2+ metal ions.112 Rice straw was used as a bio-sorbent for adsorption of Cu2+, Zn2+, Cd2+ and Hg2+ ions in industrial effluents.113

**3 Conclusion**

The presented review demonstrates the literature concerning classification of hydrogels, their properties, and applications. Hydrogels can be integrated into systems and changed into different configurations due to their biocompatibility, sensitivity to external stimuli, and physical and chemical structure. Hydrogel-based chemical and biosensors have advanced significantly in the last several years across a wide range of application areas. The hydrogels have proven beneficial in a variety of disciplines, including energy, environmental remediation, humidity sensing, medicine, soft robotics, and health monitoring, due to its versatile composition, innate properties, and ability to adjust numerous physicochemical parameters.

**Acknowledgment**

D.C thanks to Delhi Technological University for providing facilities.

**Disclosure statement**

No potential conflict of interest was reported by the author.

**4 References**

(1) Ahmed, E. M.; Aggor, F. S.; Awad, A. M.; El-Aref, A. T. An Innovative Method for Preparation of Nanometal Hydroxide Superabsorbent Hydrogel. Carbohydr. Polym. 2013, 91 (2), 693–698. https://doi.org/10.1016/j.carbpol.2012.08.056.

(2) Ahmed, E. M. Hydrogel: Preparation, Characterization, and Applications: A Review. J. Adv. Res. 2015, 6 (2), 105–121. https://doi.org/10.1016/j.jare.2013.07.006.

(3) Mishra, S.; Rani, P.; Sen, G.; Dey, K. P. Preparation, Properties and Application of Hydrogels: A Review; Springer Singapore, 2018. https://doi.org/10.1007/978-981-10-6077-9\_6.

(4) Li, Y.; Huang, G.; Zhang, X.; Li, B.; Chen, Y.; Lu, T.; Lu, T. J.; Xu, F. Magnetic Hydrogels and Their Potential Biomedical Applications. Adv. Funct. Mater. 2013, 23 (6), 660–672. https://doi.org/10.1002/adfm.201201708.

(5) Ali, M.; Husain, Q. Guar Gum Blended Alginate/Agarose Hydrogel as a Promising Support for the Entrapment of Peroxidase: Stability and Reusability Studies for the Treatment of Textile Effluent. Int. J. Biol. Macromol. 2018, 116, 463–471. https://doi.org/10.1016/j.ijbiomac.2018.05.037.

(6) Burkert, S.; Schmidt, T.; Gohs, U.; Dorschner, H.; Arndt, K. F. Cross-Linking of Poly(N-Vinyl Pyrrolidone) Films by Electron Beam Irradiation. Radiat. Phys. Chem. 2007, 76 (8–9), 1324–1328. https://doi.org/10.1016/j.radphyschem.2007.02.024.

(7) Ahmad, S.; Ahmad, M.; Manzoor, K.; Purwar, R.; Ikram, S. A Review on Latest Innovations in Natural Gums Based Hydrogels: Preparations & Applications. Int. J. Biol. Macromol. 2019, 136, 870–890. https://doi.org/10.1016/j.ijbiomac.2019.06.113.

(8) Saravanan, S.; Vimalraj, S.; Thanikaivelan, P.; Banudevi, S.; Manivasagam, G. A Review on Injectable Chitosan/Beta Glycerophosphate Hydrogels for Bone Tissue Regeneration. Int. J. Biol. Macromol. 2019, 121, 38–54. https://doi.org/10.1016/j.ijbiomac.2018.10.014.

(9) Graham, S.; Marina, P. F.; Blencowe, A. Thermoresponsive Polysaccharides and Their Thermoreversible Physical Hydrogel Networks. Carbohydr. Polym. 2019, 207, 143–159. https://doi.org/10.1016/j.carbpol.2018.11.053.

(10) Jonker, A. M.; Löwik, D. W. P. M.; Van Hest, J. C. M. Peptide- and Protein-Based Hydrogels. Chem. Mater. 2012, 24 (5), 759–773. https://doi.org/10.1021/cm202640w.

(11) Mogoşanu, G. D.; Grumezescu, A. M. Natural and Synthetic Polymers for Wounds and Burns Dressing. Int. J. Pharm. 2014, 463 (2), 127–136. https://doi.org/10.1016/j.ijpharm.2013.12.015.

(12) Buwalda, S. J.; Boere, K. W. M.; Dijkstra, P. J.; Feijen, J.; Vermonden, T.; Hennink, W. E. Hydrogels in a Historical Perspective: From Simple Networks to Smart Materials. J. Control. Release 2014, 190, 254–273. https://doi.org/10.1016/j.jconrel.2014.03.052.

(13) Vermonden, T.; Klumperman, B. The Past, Present and Future of Hydrogels. Eur. Polym. J. 2015, 72 , 341–343. https://doi.org/10.1016/j.eurpolymj.2015.08.032.

(14) Ikram, S.; Kumari, M.; Gupta, B. Thermosensitive Membranes by Radiation-Induced Graft Polymerization of N-Isopropyl Acrylamide/Acrylic Acid on Polypropylene Nonwoven Fabric. Radiat. Phys. Chem. 2011, 80 (1), 50–56. https://doi.org/10.1016/j.radphyschem.2010.08.013.

(15) Noreen, A.; Nazli, Z. i. H.; Akram, J.; Rasul, I.; Mansha, A.; Yaqoob, N.; Iqbal, R.; Tabasum, S.; Zuber, M.; Zia, K. M. Pectins Functionalized Biomaterials; a New Viable Approach for Biomedical Applications: A Review. Int. J. Biol. Macromol. 2017, 101, 254–272. https://doi.org/10.1016/j.ijbiomac.2017.03.029.

(16) Yang, Z.; Peng, H.; Wang, W.; Liu, T. Crystallization Behavior of Poly(ε-Caprolactone)/Layered Double Hydroxide Nanocomposites. J. Appl. Polym. Sci. 2010, 116 (5), 2658–2667. https://doi.org/10.1002/app.

(17) Yang, L.; Chu, J. S.; Fix, J. A. Colon-Specific Drug Delivery: New Approaches and in Vitro/in Vivo Evaluation. Int. J. Pharm. 2002, 235 (1–2), 1–15. https://doi.org/10.1016/S0378-5173(02)00004-2.

(18) Maolin, Z.; Jun, L.; Min, Y.; Hongfei, H. The Swelling Behavior of Radiation Prepared Semi-Interpenetrating Polymer Networks Composed of PolyNIPAAm and Hydrophilic Polymers. Radiat. Phys. Chem. 2000, 58 (4), 397–400. https://doi.org/10.1016/S0969-806X(99)00491-0.

(19) Zhang, J. T.; Bhat, R.; Jandt, K. D. Temperature-Sensitive PVA/PNIPAAm Semi-IPN Hydrogels with Enhanced Responsive Properties. Acta Biomater. 2009, 5 (1), 488–497. https://doi.org/10.1016/j.actbio.2008.06.012.

(20) Lin, C. C.; Metters, A. T. Hydrogels in Controlled Release Formulations: Network Design and Mathematical Modeling. Adv. Drug Deliv. Rev. 2006, 58 (12–13), 1379–1408. https://doi.org/10.1016/j.addr.2006.09.004.

(21) Peppas, N. A.; Hilt, J. Z.; Khademhosseini, A.; Langer, R. Hydrogels in Biology and Medicine: From Molecular Principles to Bionanotechnology. Adv. Mater. 2006, 18 (11), 1345–1360. https://doi.org/10.1002/adma.200501612.

(22) Tønnesen, H. H.; Karlsen, J. Alginate in Drug Delivery Systems. Drug Dev. Ind. Pharm. 2002, 28 (6), 621–630. https://doi.org/10.1081/DDC-120003853.

(23) Xian, C.; Yuan, Q.; Bao, Z.; Liu, G.; Wu, J. Progress on Intelligent Hydrogels Based on RAFT Polymerization: Design Strategy, Fabrication and the Applications for Controlled Drug Delivery. Chinese Chem. Lett. 2020, 31 (1), 19–27. https://doi.org/10.1016/j.cclet.2019.03.052.

(24) Carter, P.; Narasimhan, B.; Wang, Q. Biocompatible Nanoparticles and Vesicular Systems in Transdermal Drug Delivery for Various Skin Diseases. Int. J. Pharm. 2019, 555, 49–62. https://doi.org/10.1016/j.ijpharm.2018.11.032.

(25) Wei, X.; Liao, J.; Davoudi, Z.; Zheng, H.; Chen, J.; Li, D.; Xiong, X.; Yin, Y.; Yu, X.; Xiong, J.; Wang, Q. Folate Receptor-Targeted and Gsh-Responsive Carboxymethyl Chitosan Nanoparticles Containing Covalently Entrapped 6-Mercaptopurine for Enhanced Intracellular Drug Delivery in Leukemia. Mar. Drugs 2018, 16 (11). https://doi.org/10.3390/md16110439.

(26) Li, Z.; Ramay, H. R.; Hauch, K. D.; Xiao, D.; Zhang, M. Chitosan-Alginate Hybrid Scaffolds for Bone Tissue Engineering. Biomaterials 2005, 26 (18), 3919–3928. https://doi.org/10.1016/j.biomaterials.2004.09.062.

(27) Huang, K.; Wu, J.; Gu, Z. Black Phosphorus Hydrogel Scaffolds Enhance Bone Regeneration via a Sustained Supply of Calcium-Free Phosphorus. ACS Appl. Mater. Interfaces 2019, 11 (3), 2908–2916. https://doi.org/10.1021/acsami.8b21179.

(28) Brown, J. Q.; Srivastava, R.; McShane, M. J. Encapsulation of Glucose Oxidase and an Oxygen-Quenched Fluorophore in Polyelectrolyte-Coated Calcium Alginate Microspheres as Optical Glucose Sensor Systems. Biosens. Bioelectron. 2005, 21 (1), 212–216. https://doi.org/10.1016/j.bios.2004.08.020.

(29) Whitchurch, C. B.; Alm, R. A.; Mattick, J. S. The Alginate Regulator AlgR and an Associated Sensor FimS Are Required for Twitching Motility in Pseudomonas Aeruginosa. Proc. Natl. Acad. Sci. U. S. A. 1996, 93 (18), 9839–9843. https://doi.org/10.1073/pnas.93.18.9839.

(30) Lum, E.; Golebiowski, B.; Gunn, R.; Babhoota, M.; Swarbrick, H. Corneal Sensitivity with Contact Lenses of Different Mechanical Properties. Optom. Vis. Sci. 2013, 90 (9), 954–960. https://doi.org/10.1097/OPX.0000000000000016.

(31) Lee, K. Y.; Mooney, D. J. Hydrogels for Tissue Engineering. Chem. Rev. 2001, 101 (7), 1869–1879. https://doi.org/10.1021/cr000108x.

(32) Loh, Q. L.; Choong, C. Three-Dimensional Scaffolds for Tissue Engineering Applications: Role of Porosity and Pore Size. Tissue Eng. - Part B Rev. 2013, 19 (6), 485–502. https://doi.org/10.1089/ten.teb.2012.0437.

(33) Ma, P. X. Scaffolds for Tissue Fabrication. Mater. Today 2004, 7 (5), 30–40. https://doi.org/10.1016/S1369-7021(04)00233-0.

(34) Sloff, M.; Simaioforidis, V.; De Vries, R.; Oosterwijk, E.; Feitz, W. Tissue Engineering of the Bladder - Reality or Myth? A Systematic Review. J. Urol. 2014, 192 (4), 1035–1042. https://doi.org/10.1016/j.juro.2014.03.116.

(35) Makris, E. A.; Gomoll, A. H.; Malizos, K. N.; Hu, J. C.; Athanasiou, K. A. Repair and Tissue Engineering Techniques for Articular Cartilage. Nat. Rev. Rheumatol. 2015, 11 (1), 21–34. https://doi.org/10.1038/nrrheum.2014.157.

(36) Naahidi, S.; Jafari, M.; Logan, M.; Wang, Y.; Yuan, Y.; Bae, H.; Dixon, B.; Chen, P. Biocompatibility of Hydrogel-Based Scaffolds for Tissue Engineering Applications. Biotechnol. Adv. 2017, 35 (5), 530–544. https://doi.org/10.1016/j.biotechadv.2017.05.006.

(37) Jeong, K. H.; Park, D.; Lee, Y. C. Polymer-Based Hydrogel Scaffolds for Skin Tissue Engineering Applications: A Mini-Review. J. Polym. Res. 2017, 24 (7). https://doi.org/10.1007/s10965-017-1278-4.

(38) Liu, Y.; Lim, J.; Teoh, S. H. Review: Development of Clinically Relevant Scaffolds for Vascularised Bone Tissue Engineering. Biotechnol. Adv. 2013, 31 (5), 688–705. https://doi.org/10.1016/j.biotechadv.2012.10.003.

(39) Purwar, R.; Rajput, P.; Srivastava, C. M. Composite Wound Dressing for Drug Release. Fibers Polym. 2014, 15 (7), 1422–1428. https://doi.org/10.1007/s12221-014-1422-2.

(40) Fonder, M. A.; Lazarus, G. S.; Cowan, D. A.; Aronson-Cook, B.; Kohli, A. R.; Mamelak, A. J. Treating the Chronic Wound: A Practical Approach to the Care of Nonhealing Wounds and Wound Care Dressings. J. Am. Acad. Dermatol. 2008, 58 (2), 185–206. https://doi.org/10.1016/j.jaad.2007.08.048.

(41) Cuttle, L.; Pearn, J.; McMillan, J. R.; Kimble, R. M. A Review of First Aid Treatments for Burn Injuries. Burns 2009, 35 (6), 768–775. https://doi.org/10.1016/j.burns.2008.10.011.

(42) Coats, T. J.; Edwards, C.; Newton, R.; Staun, E. The Effect of Gel Burns Dressings on Skin Temperature. Emerg. Med. J. 2002, 19 (3), 224–225. https://doi.org/10.1136/emj.19.3.224.

(43) Grippaudo, F. R.; Carini, L.; Baldini, R. Procutase® versus 1% Silver Sulphadiazine in the Treatment of Minor Burns. Burns 2010, 36 (6), 871–875. https://doi.org/10.1016/j.burns.2009.10.021.

(44) Shahid, S. A.; Qidwai, A. A.; Anwar, F.; Ullah, I.; Rashid, U. Effects of a Novel Poly (AA-Co-AAm)/AlZnFe 2O 4/ Potassium Humate Superabsorbent Hydrogel Nanocomposite on Water Retention of Sandy Loam Soil and Wheat Seedling Growth. Molecules 2012, 17 (11), 12587–12602. https://doi.org/10.3390/molecules171112587.

(45) Silberbush, M.; Adar, E.; De Malach, Y. Use of an Hydrophilic Polymer to Improve Water Storage and Availability to Crops Grown in Sand Dunes I. Corn Irrigated by Trickling. Agric. Water Manag. 1993, 23 (4), 303–313. https://doi.org/10.1016/0378-3774(93)90042-9.

(46) Zonatto, F.; Muniz, E. C.; Tambourgi, E. B.; Paulino, A. T. Adsorption and Controlled Release of Potassium, Phosphate and Ammonia from Modified Arabic Gum-Based Hydrogel. Int. J. Biol. Macromol. 2017, 105, 363–369. https://doi.org/10.1016/j.ijbiomac.2017.07.051.

(47) Du, H.; Shi, S.; Liu, W.; Teng, H.; Piao, M. Processing and Modification of Hydrogel and Its Application in Emerging Contaminant Adsorption and in Catalyst Immobilization: A Review. Environ. Sci. Pollut. Res. 2020, 27 (12), 12967–12994. https://doi.org/10.1007/s11356-020-08096-6.

(48) Ahmad, M.; Manzoor, K.; Chaudhuri, R. R.; Ikram, S. Thiocarbohydrazide Cross-Linked Oxidized Chitosan and Poly(Vinyl Alcohol): A Green Framework as Efficient Cu(II), Pb(II), and Hg(II) Adsorbent. J. Chem. Eng. Data 2017, 62 (7), 2044–2055. https://doi.org/10.1021/acs.jced.7b00088.

(49) Ahmad, M.; Ahmed, S.; Swami, B. L.; Ikram, S. Preparation and Characterization of Antibacterial Thiosemicarbazide Chitosan as Efficient Cu(II) Adsorbent. Carbohydr. Polym. 2015, 132 (Ii), 164–172. https://doi.org/10.1016/j.carbpol.2015.06.034.

(50) Oussalah, A.; Boukerroui, A.; Aichour, A.; Djellouli, B. Cationic and Anionic Dyes Removal by Low-Cost Hybrid Alginate/Natural Bentonite Composite Beads: Adsorption and Reusability Studies. Int. J. Biol. Macromol. 2019, 124, 854–862. https://doi.org/10.1016/j.ijbiomac.2018.11.197.

(51) Sharma, G.; Kumar, A.; Naushad, M.; García-Peñas, A.; Al-Muhtaseb, A. H.; Ghfar, A. A.; Sharma, V.; Ahamad, T.; Stadler, F. J. Fabrication and Characterization of Gum Arabic-Cl-Poly(Acrylamide) Nanohydrogel for Effective Adsorption of Crystal Violet Dye. Carbohydr. Polym. 2018, 202, 444–453. https://doi.org/10.1016/j.carbpol.2018.09.004.

(52) Naushad, M.; Sharma, G.; Kumar, A.; Sharma, S.; Ghfar, A. A.; Bhatnagar, A.; Stadler, F. J.; Khan, M. R. Efficient Removal of Toxic Phosphate Anions from Aqueous Environment Using Pectin Based Quaternary Amino Anion Exchanger. Int. J. Biol. Macromol. 2018, 106, 1–10. https://doi.org/10.1016/j.ijbiomac.2017.07.169.

(53) Hoare, T. R.; Kohane, D. S. Hydrogels in Drug Delivery: Progress and Challenges. Polymer (Guildf). 2008, 49 (8), 1993–2007. https://doi.org/10.1016/j.polymer.2008.01.027.

(54) Chiang, W. H.; Ho, V. T.; Huang, W. C.; Huang, Y. F.; Chern, C. S.; Chiu, H. C. Dual Stimuli-Responsive Polymeric Hollow Nanogels Designed as Carriers for Intracellular Triggered Drug Release. Langmuir 2012, 28 (42), 15056–15064. https://doi.org/10.1021/la302903v.

(55) Oishi, M.; Nagasaki, Y. Stimuli-Responsive Smart Nanogels for Cancer Diagnostics and Therapy. Nanomedicine 2010, 5 (3), 451–468. https://doi.org/10.2217/nnm.10.18.

(56) Shariatinia, Z.; Jalali, A. M. Chitosan-Based Hydrogels: Preparation, Properties and Applications. Int. J. Biol. Macromol. 2018, 115, 194–220. https://doi.org/10.1016/j.ijbiomac.2018.04.034.

(57) Ullah, F.; Othman, M. B. H.; Javed, F.; Ahmad, Z.; Akil, H. M. Classification, Processing and Application of Hydrogels: A Review. Mater. Sci. Eng. C 2015, 57, 414–433. https://doi.org/10.1016/j.msec.2015.07.053.

(58) Khan, M.; Lo, I. M. C. A Holistic Review of Hydrogel Applications in the Adsorptive Removal of Aqueous Pollutants: Recent Progress, Challenges, and Perspectives. Water Res. 2016, 106, 259–271. https://doi.org/10.1016/j.watres.2016.10.008.

(59) Qi, X.; Li, Z.; Shen, L.; Qin, T.; Qian, Y.; Zhao, S.; Liu, M.; Zeng, Q.; Shen, J. Highly Efficient Dye Decontamination via Microbial Salecan Polysaccharide-Based Gels. Carbohydr. Polym. 2019, 219 (January), 1–11. https://doi.org/10.1016/j.carbpol.2019.05.021.

(60) Tang, S. C. N.; Wang, P.; Yin, K.; Lo, I. M. C. Synthesis and Application of Magnetic Hydrogel for Cr(VI) Removal from Contaminated Water. Environ. Eng. Sci. 2010, 27 (11), 947–954. https://doi.org/10.1089/ees.2010.0112.

(61) Shah, L. A.; Khan, M.; Javed, R.; Sayed, M.; Khan, M. S.; Khan, A.; Ullah, M. Superabsorbent Polymer Hydrogels with Good Thermal and Mechanical Properties for Removal of Selected Heavy Metal Ions. J. Clean. Prod. 2018, 201, 78–87. https://doi.org/10.1016/j.jclepro.2018.08.035.

(62) Thompson, B. R.; Horozov, T. S.; Stoyanov, S. D.; Paunov, V. N. Hierarchically Porous Composites Fabricated by Hydrogel Templating and Viscous Trapping Techniques. Mater. Des. 2018, 137, 384–393. https://doi.org/10.1016/j.matdes.2017.10.046.

(63) Afzal, M. Z.; Yue, R.; Sun, X. F.; Song, C.; Wang, S. G. Enhanced Removal of Ciprofloxacin Using Humic Acid Modified Hydrogel Beads. J. Colloid Interface Sci. 2019, 543, 76–83. https://doi.org/10.1016/j.jcis.2019.01.083.

(64) Kluczka, J.; Gnus, M.; Kazek-Kęsik, A.; Dudek, G. Zirconium-Chitosan Hydrogel Beads for Removal of Boron from Aqueous Solutions. Polymer (Guildf). 2018, 150, 109–118. https://doi.org/10.1016/j.polymer.2018.07.010.

(65) Bilal, M.; Jing, Z.; Zhao, Y.; Iqbal, H. M. N. Immobilization of Fungal Laccase on Glutaraldehyde Cross-Linked Chitosan Beads and Its Bio-Catalytic Potential to Degrade Bisphenol A. Biocatal. Agric. Biotechnol. 2019, 19 (March). https://doi.org/10.1016/j.bcab.2019.101174.

(66) Gogoi, N.; Barooah, M.; Majumdar, G.; Chowdhury, D. Carbon Dots Rooted Agarose Hydrogel Hybrid Platform for Optical Detection and Separation of Heavy Metal Ions. ACS Appl. Mater. Interfaces 2015, 7 (5), 3058–3067. https://doi.org/10.1021/am506558d.

(67) Yin, S.; Ma, Z. “Smart” Sensing Interface for the Improvement of Electrochemical Immunosensor Based on Enzyme-Fenton Reaction Triggered Destruction of Fe3+ Cross-Linked Alginate Hydrogel. Sensors Actuators, B Chem. 2019, 281 (May 2018), 857–863. https://doi.org/10.1016/j.snb.2018.11.030.

(68) Zhang, C.; Li, H.; Yu, Q.; Jia, L.; Wan, L. Y. Poly(Aspartic Acid) Electrospun Nanofiber Hydrogel Membrane-Based Reusable Colorimetric Sensor for Cu(II) and Fe(III) Detection. ACS Omega 2019. https://doi.org/10.1021/acsomega.9b02109.

(69) Zhang, W.; Cheng, W.; Ziemann, E.; Be’er, A.; Lu, X.; Elimelech, M.; Bernstein, R. Functionalization of Ultrafiltration Membrane with Polyampholyte Hydrogel and Graphene Oxide to Achieve Dual Antifouling and Antibacterial Properties. J. Memb. Sci. 2018, 565, 293–302. https://doi.org/10.1016/j.memsci.2018.08.017.

(70) Wang, H.; Liu, Z. hua; Zhang, J.; Huang, R. ping; Yin, H.; Dang, Z.; Wu, P. xiao; Liu, Y. Insights into Removal Mechanisms of Bisphenol A and Its Analogues in Municipal Wastewater Treatment Plants. Sci. Total Environ. 2019, 692, 107–116. https://doi.org/10.1016/j.scitotenv.2019.07.134.

(71) Zhao, L.; Deng, J.; Sun, P.; Liu, J.; Ji, Y.; Nakada, N.; Qiao, Z.; Tanaka, H.; Yang, Y. Nanomaterials for Treating Emerging Contaminants in Water by Adsorption and Photocatalysis: Systematic Review and Bibliometric Analysis. Sci. Total Environ. 2018, 627, 1253–1263. https://doi.org/10.1016/j.scitotenv.2018.02.006.

(72) Zhang, C.; Li, H.; Yu, Q.; JLA, L.; Wan, LY. Poly (aspartic acid) Electrospun Nanofiber Hydrogel Membrane-Based Reusable Colorimetric Sensor for Cu(II) and Fe(III) Detection. ACS Omega.  2019 4 (11), 14633-14639 DOI: 10.1021/acsomega.9b02109

## (73) [Büning](https://pubs.rsc.org/en/results?searchtext=Author%3ADominic%20B%C3%BCning), D.;  [Roth](https://pubs.rsc.org/en/results?searchtext=Author%3AFranka%20Ennen-Roth),FE.;   [Walter](https://pubs.rsc.org/en/results?searchtext=Author%3ASarah%20Verena%20Walter),SV.;    [Hennecke](https://pubs.rsc.org/en/results?searchtext=Author%3ATobias%20Hennecke), T.;  [Ulbricht](https://pubs.rsc.org/en/results?searchtext=Author%3AMathias%20Ulbricht),M. Potassium-sensitive poly(N-isopropylacrylamide)-based hydrogels for sensor applications. **Polym. Chem.** 2018 ,**9**, 3600-3614 https://doi.org/10.1039/C8PY00490K

(74) Ozay, H.; Ozay, O. Rhodamine based reusable and colorimetric naked-eye hydrogel sensors for Fe3+ ion. Chemical Engineering Journal. 2013, 232,364-371, https://doi.org/10.1016/j.cej.2013.07.111.

(75) Joseph, KA.; Dave, N.; Liu, J. Electrostatically Directed Visual Fluorescence Response of DNA-Functionalized Monolithic Hydrogels for Highly Sensitive Hg2+ Detection. ACS Applied Materials & Interfaces. 2011 3 (3), 733-739 DOI: 10.1021/am101068c

(76) Tasneam, K.; El-damhougy, Amal, S.I.;Ahmed, Ghalia A;. Gaber, Nabila A.; Mazied, Ghada Bassioni,; Radiation synthesis for a highly sensitive colorimetric hydrogel sensor-based p(AAc/AMPS)-TA for metal ion detection. Results in Materials. 2021, 9, 100169, ISSN 2590-048X, https://doi.org/10.1016/j.rinma.2021.100169.

(77) Buenger, D.; Topuz, F.; Groll, J.; Hydrogels in sensing applications. Progress in Polymer Science. 2012, 37, (12),2012, 1678-1719, ISSN 0079-6700, https://doi.org/10.1016/j.progpolymsci.2012.09.001.

(78) Sun, X.; Agate,S.; Samaher Salem, K.; Lucia,L.; Pal ,L.; Hydrogel-Based Sensor Networks: Compositions, Properties, and Applications. ACS Applied Bio Materials. 2021, 4 (1), 140-162 DOI: 10.1021/acsabm.0c01011

(79) Hou, W.; Sheng, N.; Zhang, X.; Luan, Z.; Qi, P.; Lin, M.; Tan, Y.; Xia, Y.; Li, Y.; Sui, K. Design of Injectable Agar/NaCl/ Polyacrylamide Ionic Hydrogels for High Performance Strain Sensors. Carbohydr. Polym. 2019, 211, 322−328.

(80) Wu, R.; Zhang, S.; Lyu, J.; Lu, F.; Yue, X.; Lv, J. A Visual Volumetric Hydrogel Sensor Enables Quantitative and Sensitive Detection of Copper Ions. Chem. Commun. 2015, 51 (38), 8078− 8081.

(81) Guo, J.; Zhou, M.; Yang, C. Fluorescent Hydrogel Waveguide for On-Site Detection of Heavy Metal Ions. Sci. Rep. 2017, 7 (1), 7902.

(82) Dave, N.; Chan, M. Y.; Huang, P.-J. J.; Smith, B. D.; Liu, J. Regenerable DNA-Functionalized Hydrogels for Ultrasensitive, Instrument-Free Mercury(II) Detection and Removal in Water. J. Am. Chem. Soc. 2010, 132 (36), 12668−12673.

(83) Ye, B.F.; Zhao, Y.; Yuan-Jin.; Cheng, Y.; Li, T.T.; Xie, ZY.; Zhao, XW.; Gu, Z.Z. Colorimetric photonic hydrogel aptasensor for the screening of heavy metal ions. Nanoscale. 2012, 4(19), 5998-6003, http://dx.doi.org/10.1039/C2NR31601C

(84) Diehl, F.; S, Hageneder.; S, Fossati.; A, Simone K.; J, Dostalek.; U, Jonas. Plasmonic nanomaterials with responsive polymer hydrogels for sensing and actuation. Chem. Soc. Rev. 2022, 51(10), 3926-3963. http://dx.doi.org/10.1039/D1CS01083B",

#### (85) Kahn, J.S.; Hu, Y.; Willner, I.; Stimuli-Responsive DNA-Based Hydrogels: From Basic Principles to Applications. Accounts of Chemical Research. 2017 50 (4), 680-690 DOI: 10.1021/acs.accounts.6b00542

#### (86) Hu, J.; Zhang, G.; Liu, S. Enzyme-responsive polymeric assemblies’ nanoparticles and hydrogel.Chem. Soc. Rev. 2012, 41(18) 5933-5949. http://dx.doi.org/10.1039/C2CS35103J.

#### (87) Heidi R.; John R. C.; Nicholas A. P. Analyte-Responsive Hydrogels: Intelligent Materials for Biosensing and Drug Delivery Accounts of Chemical Research 2017, 50 (2), 170-178. DOI: 10.1021/acs.accounts.6b00533.

(88) Chao, Y. C.; Yeh, S. De; Zan, H. W.; Chang, G. F.; Meng, H. F.; Hung, C. H.; Meng, T. C.; Hsu, C. S.; Horng, S. F. Real-Time and Indicator-Free Detection of Aqueous Nitric Oxide with Hydrogel Film. Appl. Phys. Lett. 2010, 96 (22), 94–97. https://doi.org/10.1063/1.3425895.

(89) Tou, Z. Q.; Koh, T. W.; Chan, C. C. Poly(Vinyl Alcohol) Hydrogel Based Fiber Interferometer Sensor for Heavy Metal Cations. Sensors Actuators B Chem. 2014, 202, 185–193. https://doi.org/10.1016/j.snb.2014.05.006.

(90) Zheng, J. Hydrogels for Removal of Heavy Metals from Aqueous Solution. J. Environ. Anal. Toxicol. 2012, 02 (07). https://doi.org/10.4172/2161-0525.S2-001.

(91) Barakat, M. A. New Trends in Removing Heavy Metals from Industrial Wastewater. Arab. J. Chem. 2011, 4 (4), 361–377. https://doi.org/10.1016/j.arabjc.2010.07.019.

(92) Chandrangsu, P.; Rensing, C.; Helmann, J. D. Metal Homeostasis and Resistance in Bacteria. Nat. Rev. Microbiol. 2017, 15 (6), 338–350. https://doi.org/10.1038/nrmicro.2017.15.

(93) Ye, B. F.; Zhao, Y. J.; Cheng, Y.; Li, T. T.; Xie, Z. Y.; Zhao, X. W.; Gu, Z. Z. Colorimetric Photonic Hydrogel Aptasensor for the Screening of Heavy Metal Ions. Nanoscale 2012, 4 (19), 5998–6003. https://doi.org/10.1039/c2nr31601c.

(94) Ahmad, JU.; Goni, MA.; Heavy metal contamination in water, soil, and vegetables of the industrial areas in Dhaka, Bangladesh. Environ Monit Assess. 2010, 166, 347–357. https://doi.org/10.1007/ s10661-009-1006-6

(95) Lone, S.; Yoon, D. H.; Lee, H.; Cheong, I. W. Gelatin-chitosan hydrogel particles for efcient removal of Hg(ii) from wastewater. Environ Sci Water Res Technol. 2019, 5, 83–90. https://doi.org/10.1039/ c8ew00678d

(96) Awual, M. R. A novel facial composite adsorbent for enhanced copper (II) detection and removal from wastewater. Chem Eng J. 2014, 266, 368–375. https://doi.org/10.1016/j.cej.2014.12.094

(97) Gupta, A.; Rai, D. K.; Pandey, R. S.; Sharma, B. Analysis of some heavy metals in the riverine water, sediments and fish from river Ganges at Allahabad. Environ Monit Assess. 2009, 157 449–458. https:// doi.org/10.1007/s10661-008-0547-4

(98) Meena, A. K.; Mishra, G. K.; Rai, P. K.; Rajagopal, C.; Nagar, P. N. Removal of Heavy Metal Ions from Aqueous Solutions Using Carbon Aerogel as an Adsorbent. J. Hazard. Mater. 2005, 122 (1–2), 161–170. https://doi.org/10.1016/j.jhazmat.2005.03.024.

(99) Namasivayam, C.; Ranganathan, K. Removal of Pb(Ii), Cd(Ii), Ni(Ii) and Mixture of Metal Ions by Adsorption onto ’waste’ Fe(Iii)/Cr(Iu) Hydroxide and Fixed Bed Studies. Environ. Technol. (United Kingdom) 1995, 16 (9), 851–860. https://doi.org/10.1080/09593330.1995.9618282.

(100) Wang, X.; Deng, W.; Xie, Y.; Wang, C. Selective Removal of Mercury Ions Using a Chitosan-Poly(Vinyl Alcohol) Hydrogel Adsorbent with Three-Dimensional Network Structure. Chem. Eng. J. 2013, 228, 232–242. https://doi.org/10.1016/j.cej.2013.04.104.

(101) Karbarz, M.; Khalil, A. M.; Wolowicz, K.; Kaniewska, K.; Romanski, J.; Stojek, Z. Efficient Removal of Cadmium and Lead Ions from Water by Hydrogels Modified with Cystine. J. Environ. Chem. Eng. 2018, 6 (4), 3962–3970. https://doi.org/10.1016/j.jece.2018.05.054.

(102) Lone, S.; Yoon, D. H.; Lee, H.; Cheong, I. W. Gelatin-Chitosan Hydrogel Particles for Efficient Removal of Hg(Ii) from Wastewater. Environ. Sci. Water Res. Technol. 2019, 5 (1), 83–90. https://doi.org/10.1039/c8ew00678d.

(103) Ozay, H.; Ozay, O. Rhodamine Based Reusable and Colorimetric Naked-Eye Hydrogel Sensors for Fe3+ Ion. Chem. Eng. J. 2013, 232, 364–371. https://doi.org/10.1016/j.cej.2013.07.111.

(104) Joseph, K. A.; Dave, N.; Liu, J. Electrostatically Directed Visual Fluorescence Response of DNA-Functionalized Monolithic Hydrogels for Highly Sensitive Hg2+ Detection. ACS Appl. Mater. Interfaces 2011, 3 (3), 733–739. https://doi.org/10.1021/am101068c.

(105) Sahu, S.; Bishoyi, N.; Patel, R.K. Cerium phosphate polypyrrole fower like nanocomposite: a recyclable adsorbent for removal of Cr (VI) by adsorption combined with in-situ chemical reduction. J Ind Eng Chem. 2021, 99, 55–67. https://doi.org/10.1016/j.jiec.2021. 03.041

(106) Sahu, S.; Sahu, U.K.; Patel, R.K.; Modifed thorium oxide polyaniline core-shell nanocomposite and its application for the efcient removal of Cr (VI). J Chem Eng Data. 2019, 64 (3), 1294–1304. https:// doi.org/10.1021/acs.jced.8b01225

(107) Sahu, S.; Mallik, L.; Patel, R.K. et al Facile synthesis of poly o-toluidine modifed lanthanum phosphate nanocomposite as a superior adsorbent for selective fuoride removal: a mechanistic and kinetic study. Chemosphere. 2020, 252, 126551. https://doi.org/10.1016/j.chemo sphere.2020.126551

(108) Dave, N.; Chan, M. Y.; Huang, P. J. J.; Smith, B. D.; Liu, J. Regenerable DNA-Functionalized Hydrogels for Ultrasensitive, Instrument-Free Mercury(II) Detection and Removal in Water. J. Am. Chem. Soc. 2010, 132 (36), 12668–12673. https://doi.org/10.1021/ja106098j.

(109) Awual, M. R. Novel Nanocomposite Materials for Efficient and Selective Mercury Ions Capturing from Wastewater. Chem. Eng. J. 2017, 307, 456–465. https://doi.org/10.1016/j.cej.2016.08.108.

(110) Ding, Y.; Zhu, W.; Xu, Y.; Qian, X. A Small Molecular Fluorescent Sensor Functionalized Silica Microsphere for Detection and Removal of Mercury, Cadmium, and Lead Ions in Aqueous Solutions. Sensors Actuators, B Chem. 2015, 220, 762–771. https://doi.org/10.1016/j.snb.2015.05.113.

(111) Gupta, V. K.; Sharma, S. Removal of Cadmium and Zinc from Aqueous Solutions Using Red Mud. Environ. Sci. Technol. 2002, 36 (16), 3612–3617. https://doi.org/10.1021/es020010v.

(112) Kadirvelu, K.; Goel, J.; Rajagopal, C. Sorption of Lead, Mercury and Cadmium Ions in Multi-Component System Using Carbon Aerogel as Adsorbent. J. Hazard. Mater. 2008, 153 (1–2), 502–507. https://doi.org/10.1016/j.jhazmat.2007.08.082.

(113) Rocha, C. G.; Zaia, D. A. M.; Alfaya, R. V. da S.; Alfaya, A. A. da S. Use of Rice Straw as Biosorbent for Removal of Cu(II), Zn(II), Cd(II) and Hg(II) Ions in Industrial Effluents. J. Hazard. Mater. 2009, 166 (1), 383–388. https://doi.org/10.1016/j.jhazmat.2008.11.074.