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CHAPTER 12

Polymer Based Nano Composite Hydrogels

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Abstract: Hydrogels are crosslinked polymer networks with a three-dimensional structure that can retain significant quantity of water because of their hydrophilic (water loving) groups, which makes them highly useful in fields such as medicine, drug delivery, and environmental science. They can be classified by source, crosslinking method, structure, or responsiveness, ranging from conventional to smart systems. Recent progress in nanocomposite hydrogels, achieved by incorporating nanoparticles such as silica, graphene oxide, carbon nanotubes, and magnetic or metallic nanofillers, has enhanced their mechanical strength, stability, and multifunctionality. These advanced systems enable applications in wound healing, drug delivery, wastewater treatment, biosensing, and energy storage, positioning them as next-generation multifunctional materials.

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Polymeric hydrogels are three dimensional self- sustaining, water-absorbed networks that exhibit viscoelastic behaviour [1, 2]. Due to the presence of functional groups such as hydroxyl, carboxyl, amino and amino on their polymer chains, they are able to swell enormously—absorbing water or biological fluids thousands of times their weight—while remaining insoluble. [3]. Hydrogels have been studied for many years, with their concept emerging long ago, when Wichterle and Lim, between 1954 and 1960, first described crosslinked poly-hydroxyethyl methacrylate (pHEMA)-based hydrogels with flexibility and structural integrity [4, 5]. Subsequently, hydrogel research has expanded significantly, with wide-ranging applications in biomedical sciences [6, 7]. The very term "hydrogel" reflects the inherent characteristics of these materials, combining water-swelling properties with structural stability and versatile functional applications. For this reason, hydrogels have long generate the interest of both material scientists and biomedical researchers, who have explored their formulation strategies and performance potential in detail [2, 8].

Hydrogel swelling characteristics are closely related to their high thermodynamic interaction tendency with solvents [9]. The use of diverse crosslinkers allows this trait to be tailored, through covalent bonding or physical interactions involving molecular forces [10]. It also display notable phenomena such as capillary rise, osmotic pressure difference and increased water mobility [11]. Those derived from natural polymers like chitosan, starch, guar gum, and alginate are especially valuable because of their degradability and biological compatibility [12, 14]. For example, A. Vashist and co-workers reported the development of biocompatible interpenetrating polymer networks using chitosan, methyl methacrylate (MMA), and oleo-based polyol for drug delivery systems [15]. In subsequent studies, the same researchers prepared hydrogel films reinforced with nanocomposites by combining a natural polysaccharide, a vinyl-based monomer, a polyol of plant origin, and carbon nanotube fillers, which exhibited improved mechanical strength, biodegradability, and biocompatibility [16]. S. Noori et al. reported the development of clay-based PVA–chitosan–honey hydrogels with antibacterial functionality, intended for use in wound dressings [17].

Smart hydrogels were conceived based on their capacity to react to diverse stimuli such as heat, pH shifts, ionic strength, illumination, magnetic or electric forces, and selected chemical agents [18, 19]. These unique behaviours open enormous opportunities for advanced applications, particularly in controlled drug delivery, which remains one of the most actively researched areas [7, 20–23]. To meet the rising pharmaceutical demands, diverse hydrogel drug delivery systems have been designed. Their classification is typically based on chemical makeup, structure, and polymer arrangement, including homopolymers, copolymers, blends, IPNs, and composites, with respective merits and limitations discussed later.

The classification of hydrogels may be carried out using several criteria including source, polymer composition, structural configuration, type of crosslink, and physical appearance [10]. From the perspective of origin, hydrogels may be grouped into natural forms, fully synthetic types, and semi-synthetic derivatives [24]. Synthetic hydrogels are generally prepared through the polymerization of vinyl-based monomers, whereas natural variants originate from biological building blocks such as nucleotides, peptides, or polysaccharides. Semi-synthetic forms arise from combining natural and synthetic polymers, thereby merging the advantages of both. In terms of polymer composition, homopolymeric hydrogels consist of networks derived from a single monomer type, which may or may not involve crosslinking depending on the chosen monomer and polymerization approach [25]. Unlike homopolymers, copolymeric hydrogels incorporate multiple monomers, including at least one hydrophilic unit, which can be distributed in random, block, or alternating patterns along the chain [26]. IPNs form a distinct hydrogel class, built from multiple crosslinked polymers, natural or synthetic, that intertwine on the molecular level. Such systems can also arise through polymer grafting, producing a durable 3D network [27].

Hydrogels are grouped into crystalline, semi-crystalline, and crystalline amorphous types according to their composition and structure [24]. They may also be distinguished by the type of crosslinking involved: chemically crosslinked hydrogels possess permanent covalent bonds, physically crosslinked hydrogels, on the other hand, are stabilized by reversible interactions, including polymer chain entanglement, ionic bonds, hydrogen bonding, or hydrophobic interactions [9]. Finally, hydrogels can vary in physical form, being produced as matrices, films, gels, or microspheres, depending on the polymerization technique used in their synthesis.

Hydrogels may also be grouped by the charge on their polymer networks. This includes non-ionic types, ionic hydrogels that are either cationic or anionic, amphoteric varieties with acidic and basic groups, and zwitterionic (polybetainic) hydrogels in which every repeat unit contains both charges. [1]. All hydrogel types show significant flexibility due to their strong water retention, allowing them to mimic the properties of biological tissues [12]. They exhibit maximum toughness and rigidity both during swelling in aqueous media and under storage conditions [28]. Furthermore, these systems are effective in regulating the release of therapeutic agents or nutrients at the desired time [29], while maintaining biocompatibility, biodegradability, and desirable mechanical strength. Many of them are designed to be introduced into the human body through injection [16, 30]. Additional favourable characteristics include their colourless, odourless, and non-toxic nature [31], In addition, these materials can sense and react to external cues—including electrical stimulation, pH or temperature changes, enzymatic reactions, and ionic environments—leading to transformations in their texture or structure [32]. Hydrogels are also known for their good transport properties and their ease of modification for specific applications [33].

Despite their advantages, hydrogels face constraints in biomedical use, such as weak mechanical properties, fast burst release of water-soluble drugs, and inadequate loading of hydrophobic compounds, affecting sustained therapeutic delivery [6, 34–36]. The market still offers a limited number of hydrogel-based products for drug delivery and tissue engineering purposes [37], highlighting the need for further advancements in these fields. To overcome such drawbacks, Researchers have investigated modifications such as copolymer hydrogels, interpenetrating polymer networks, and nanocomposite hydrogels (NCHs) [29, 38–40]. These changes strengthen hydrogel properties and extend their use to diverse fields, such as electronics [41], applied in farming as moisture-holding hydrogel beads for crops [14], personal care products and aesthetic surgery [9], ecosystem restoration and contaminant removal [42], Microbial cultivation [43], protein separation and analysis techniques [44], Immune-based therapies and vaccine development [45], Frameworks for promoting bone tissue regeneration [46], restoration of heart tissue [47], ophthalmology [48], dentistry, healing of wounds and controlled drug administration [49, 50]. Nanocomposite hydrogels have attracted significant interest because they combine the inherent benefits of hydrogels with the added functionalities provided by incorporated nanomaterials.

Nanocomposite hydrogels (NCHs) are crosslinked biopolymer networks that incorporate nanoparticles or nanostructures ranging from 10 to 100 nm, enabling them to absorb water. Compared to conventional hydrogels, NCHs demonstrate enhanced properties, especially in terms of elasticity and mechanical strength [29, 35, 51]. In these systems, hard nanoparticles act as reinforcing segments that strengthen the soft organic polymer matrix, producing a synergistic combination of properties [52]. Numerous studies have shown that incorporating nanofillers derived from carbon, ceramics, ceramics, or metals markedly enhances the biofunctional and mechanical performance of hydrogels [7, 16, 53]. The earliest nanocomposite hydrogels were developed by Haraguchi and colleagues, who utilized poly-N-isopropylacrylamide (PNIPAAm) with montmorillonite nanoclay. These materials exhibited enhanced mechanical strength, swelling behavior, ocular accuracy, and responsiveness to external stimuli [54]. More recently, the development of novel NCH films with star and dendrimer morphologies has demonstrated exceptional swelling and mechanical properties, indicating their potential for biomedical applications. Current research underscores the use of biopolymer-based NCHs owing to their compatibility with biological systems and applicability in therapeutic delivery, tissue regeneration, and wound management [12, 35]. For hydrogel fabrication in biomaterials applications, researchers often use biocompatible natural polymers like polysaccharides, carbohydrate derivatives, modified cellulose, and poly(α-amino acids) [55].

Based on chemical structure, natural polymers are divided into three primary groups. Polysaccharides—including chitosan, guar gum, agar, starch, gum tragacanth, aloe vera gel, hyaluronic acid, alginate, and agarose—form the first group, while polyamides or polypeptides like collagen, gelatin, fibroin, wheat proteins, soy proteins, and fibrin make up the second. The third class includes polyesters, most notably poly(3-hydroxyalkanoates) [47]. Numerous studies have described the creation of biopolymer-based nanocomposite hydrogels (NCHs) with improved properties and innovative applications. For example, Barkhordari and colleagues engineered hydrogel nanocomposites incorporating double-layered hydroxides (LDH) and carboxymethyl cellulose (CMC) for the controlled delivery of ibuprofen [56]. Nanocomposite hydrogel films were fabricated by Tanpichai and co-workers through the incorporation of cellulose nanocrystals into poly(vinyl alcohol), resulting in enhanced structural robustness and heat resistance. [57]. Peng et al. prepared clay-reinforced cellulose NCHs with remarkable mechanical and superabsorbent properties, effective for removing methylene blue. Collectively, such studies demonstrate the adaptability of NCHs and the diversity of materials and methods applied in their development.

Chitosan-based nanocomposite hydrogels represent a particularly significant subclass. Chitosan, formed by glucosamine and N-acetylglucosamine units joined through β (1–4) glycosidic bonds, is usually derived from chitin via an acid-mediated deacetylation process [27]. Chemical modification of chitosan is possible thanks to its amino and hydroxyl groups, which can enhance solubility in water or organic solvents; inherently, it dissolves in glacial acetic acid as the amino groups become protonated [15]. Chitosan's outstanding biological and physicochemical characteristics are suitable for biomedical uses, although hydrogels composed solely of chitosan tend to have limited mechanical strength [59]. This drawback has been addressed through the dispersion of nanofillers, which markedly enhance thermal, electrical, and mechanical performance [60–62]. For example, Sharad et al. described the development of hybrid materials and nanocomposite ionogels using agarose–chitosan systems integrated with ionic liquids through dissolution, regeneration, and sol–gel processes. Embedding silver nanoparticles within chitosan matrices yielded nanocomposites with enhanced thermal and mechanical characteristics, making them applicable in food preservation, actuators, sensing devices, wound management, and therapeutic delivery [63].

Starch-based nanocomposite hydrogels constitute another significant category. Starch, a plant-derived polysaccharide, consists mainly of linear amylose and amylopectin, a polysaccharide with an extensively branched structure [64]. Starch is generated via enzymatic pathways in plants and is commonly extracted from organs like seeds, tubers, stems and roots. Its natural abundance, biodegradability, and structural versatility make it an ideal candidate for developing functional nanocomposite hydrogels with diverse applications.

Over the past few years, starch has been widely explored for the preparation of hydrogels aimed at biomedical applications. While promising, it is hindered by inherent shortcomings, including difficulty in processing, brittleness, limited moisture content, insufficient mechanical strength, and weak oxygen barrier capacity. To address these drawbacks, various nanofillers—such as hydroxyapatite, multi-walled carbon nanotubes (MWCNTs), nanoclays, and metal oxides— By integrating nanomaterials into starch-derived polymer matrices, researchers have developed nanocomposite hydrogels with superior physicochemical and mechanical attributes, which widens their potential in biomedical areas such as drug delivery, tissue regeneration, and personal care. For instance, Spagnol and colleagues synthesized superabsorbent hydrogels from starch-g-poly(sodium acrylate) enhanced with cellulose nanowhiskers (CNWs), demonstrating that dispersions up to 10 wt% improved swelling and structural strength. In a similar vein, Fama et al. created starch-based nanocomposite hydrogels reinforced with low concentrations of MWCNTs. These composites displayed nearly a 100% increase in elastic modulus, while their water vapour permeability was reduced by 43% compared to unmodified starch hydrogels, highlighting the beneficial influence of nanofillers.

Nanocomposite hydrogels derived from cellulose are widely studied because cellulose is an abundant and renewable natural polymer. It is composed of β-1,4-linked glucose units with the formula (C6H10O5)n (n ≈ 10,000–15,000), occurring in plants, trees, tunicates, and bacteria. While cellulose-based hydrogels are biocompatible and hydrophilic, strong intermolecular forces restrict their solubility in water. This limitation is typically overcome by chemical modification, yielding derivatives such as MC, HPC, HPMC, and CMC, which expand their applications in packaging, medicine, and wound healing.

Early research on cellulose-based nanocomposite hydrogels focused on bacterial cellulose (BC) combined with gelatin, resulting in materials with excellent mechanical strength, swelling capacity, and crystallinity. Nevertheless, the high cost and limited production of BC constrained its broader applications. Consequently, cellulose nanocrystals (CNCs) derived from plants emerged as a cost-effective alternative. CNCs exhibit high solubility in water and have demonstrated significant potential in nanocomposite hydrogel development. For example, pH-responsive superabsorbent nanocomposite hydrogels were synthesized using cellulose nanocrystals (CNCs) Using free radical copolymerization, researchers synthesized poly(acrylamide-co-acrylate) (PAM-AA) hydrogels that exhibited higher swelling capacity. Along similar lines, A. C. Babu and colleagues prepared nanocomposite hydrogels composed of carboxymethyl cellulose (CMC), poly(acrylamide-co-2-acrylamido-2-ethylpropanesulfonic acid), and silver nanoparticles, which provided strong antibacterial properties. Additionally, Zhang's team reported graphene oxide-enriched CMC–polyacrylamide nanocomposite hydrogels with superior mechanical integrity and swelling performance compared to unmodified hydrogels, highlighting their potential in drug delivery and tissue engineering.

Another prominent group of hydrogels is based on poly(vinyl alcohol) (PVA). Despite its insolubility in water due to high hydroxyl content and polymerization degree, PVA can be rendered stable in aqueous and biological environments when supported by chemical or physical crosslinking methods. Hydrogels derived from PVA are extensively applied in medical tools, paper manufacturing, and food-related sectors due to their notable hydrophilicity, compatibility with biological systems, and superior film-forming ability. However, their limited mechanical strength restricts broader biomedical applications. To overcome this challenge, incorporating nanofillers into PVA matrices has emerged as an effective strategy to improve both functional and mechanical performance, thereby expanding their potential applications across various fields.

Characteristic Properties of Nano composite Hydrogels

Literature reports emphasize that nanocomposite hydrogels (NCHs) exhibit superior biocompatibility, degradability, mechanical robustness, swelling ability, and stimulus responsiveness. Such advantages expand their application in drug delivery, tissue repair, wound management, and bone regeneration. For instance, Wang et al. designed NCHs from elastin-like polypeptides and graphene oxide, achieving highly flexible structures that could bend, stretch, and coil with temperature changes. In related work, M. Yadav and co-workers fabricated hydrogel films composed of graphene oxide (GO), carboxymethylcellulose (CMC), and alginate using solution mixing followed by evaporation. Remarkably, the incorporation of as little as 1 wt% GO led to substantial improvements in tensile strength and Young's modulus, with enhancements varying between 40% and more than 1100%. The uniform dispersion of GO within the CMC system was particularly important in improving mechanical and thermal stability, as observed in Young's modulus enhancements from 103 ± 6 MPa to 173 ± 6 MPa and thermal stability improvements from 32.65 ± 5 GPa to 81.12 ± 5 GPa.

Several investigations have highlighted the role of nanocomposite hydrogels in site-specific drug delivery. For example, Q. Pan and colleagues engineered a system based on carboxymethyl chitosan, modified graphene oxide, fluorescein isothiocyanate, and lactobionic acid (LA). Using doxorubicin as a model therapeutic, they observed pH-sensitive release behaviour, where the LA-functionalized composites were biocompatible with liver cancer cells in the unloaded state but promoted cytotoxicity after drug incorporation and release. Similarly, J. Zang et al. created nanocomposite hydrogels from sodium alginate, hydroxyapatite (HAp), and halloysite nanotubes (HNTs), achieving encapsulation efficiencies up to 75% and improved drug loading and controlled release capabilities. S.A. Poursamar et al. further reported polyvinyl alcohol (PVA)-HAp nanocomposite hydrogels fabricated via freeze-drying, which showed excellent biocompatibility, bioactivity, and mechanical performance. These scaffolds supported effective cell penetration and proliferation during in-vitro studies, establishing their potential in bone tissue engineering.

Alongside GO and hydroxyapatite, nanofillers such as CNTs, silica nanoparticles, and clays are also employed to optimize hydrogel properties. For instance, A. Giri et al. designed carboxymethyl guar gum–MWCNT systems that improved stability, swelling, and transdermal delivery of diclofenac sodium. Likewise, CNT-reinforced PVA and polyvinylpyridine hydrogels displayed superior mechanical strength and biological response in osteochondral repair models. A.A. Rodrigues et al. further confirmed that CNT-based PVA hydrogels accelerated bone growth without inflammatory side effects. MWCNT-alginate scaffolds prepared by Jodder et al. also exhibited good stability, improved mechanical strength, and promoted cellular growth, thereby supporting their use in tissue engineering.

Mesoporous silica nanoparticles (MSNs) represent another class of fillers that expand the biomedical applicability of nanocomposite hydrogels. Popet et al. investigated pH-responsive chitosan-MSN systems, showing highly tunable drug release rates, where ibuprofen release increased from 20% at physiological pH 7.4 to 90% at acidic pH 5.0 after eight hours. Similarly, M. Zhu et al. developed chitosan-MSN composites for cartilage regeneration, which exhibited faster gelation rates, higher elastic moduli, and sustained release of gentamicin and bovine serum albumin. Chondrocyte culture tests confirmed superior performance compared to pure chitosan hydrogels. Furthermore, G. Gao et al. reported stretchable, tough, and self-healing nanocomposite hydrogels synthesized from acrylamide and Na-montmorillonite via free radical polymerization. These hydrogels exhibited extremely high fracture elongation (11,800%) and toughness (10.1 MJ/m^3), with full recovery after deformation, positioning them as promising candidates for artificial muscle and actuator applications.

Biomedical Applications of Nano composite Hydrogels

The unique characteristics of nanocomposite hydrogels make them attractive candidates for diverse biomedical uses, particularly in drug delivery, wound repair, tissue engineering, and bone regeneration. In tissue engineering, the goal is to restore damaged tissues using scaffolds that mimic natural extracellular environments. Nanocomposite hydrogels, with their three-dimensional porous networks, hydrophilicity, elasticity, and mechanical robustness, provide excellent platforms for cell proliferation, attachment, and differentiation. For instance, Sinha et al. employed PVA-hydroxyapatite hydrogels for cartilage restoration, while A.K. Gaharwar et al. developed nanoclay-enriched electrospun poly(ε-caprolactone) scaffolds that enhanced surface roughness, biodegradability, and mechanical properties, thereby promoting stem cell differentiation.

In wound healing, nanocomposite hydrogels offer significant advantages over conventional dressings by maintaining appropriate humidity, preventing infection, and reducing pain while providing strong mechanical support. PVA-clay nanocomposite hydrogels synthesized via freeze-thawing demonstrated improved swelling and mechanical strength suitable for wound dressing. Chitosan-based hydrogels loaded with silver and gold nanoparticles further exhibited antibacterial activity and biocompatibility, confirming their utility in advanced wound care.

Drug delivery represents another critical application area, where nanocomposite hydrogels enable sustained, controlled, and stimuli-responsive release of therapeutic agents. These systems combine hydrophilic polymeric networks with embedded nanoparticles to regulate drug loading and release via mechanisms such as diffusion, swelling, or environmental triggers like temperature, pH, or magnetic fields. W. Zhu and co-workers designed an injectable supramolecular hydrogel system for the controlled delivery of cisplatin in cancer treatment, which demonstrated potent cytotoxicity against bladder carcinoma cells. Other systems based on chitosan, starch, cellulose, and carboxymethyl cellulose reinforced with fillers such as silver, ZnO, montmorillonite, and carbon nanostructures have shown additional antibacterial, thermal, and mechanical advantages, extending their applications across biomedical, pharmaceutical, and even food packaging fields.

Cellulose-Based Nano composite Hydrogels and Objective of the Work

Latest developments in cellulose-based nanocomposite hydrogels have demonstrated significant improvements in their mechanical and thermal properties, expanding their applicability in both biological and energy-related fields. For instance, cellulose–graphene hydrogels display superior strength and stability, while cellulose–clay hydrogels exhibit remarkable mechanical robustness and enhanced dye removal efficiency, making them valuable for wastewater treatment through effective absorption of methyl blue. Carboxymethyl cellulose (CMC)-based hydrogels reinforced with zinc oxide nanoparticles are particularly promising for wound dressing applications due to their high swelling capacity, antibacterial properties, and biocompatibility. Likewise, CMC-montmorillonite nanocomposites show pH- and magnetic-sensitive behaviour with reduced swelling ratios, enabling their use in colon-targeted drug delivery systems. Furthermore, CMC-graphene and CMC-reduced graphene oxide composites demonstrate high swelling, drug loading capacity, and thermal stability, along with biodegradability and porosity, making them potential candidates for anticancer drug delivery and tissue engineering scaffolds.

This review aims to survey and analyze recent strategies for the design and fabrication of nanocomposite hydrogels. Their notable water uptake capacity, biodegradability, compatibility with biological systems, and mechanical robustness render them highly suitable for diverse applications, including wound care materials, tissue engineering frameworks, contact lenses, biosensing devices, and carriers for therapeutic agents. Injectable and orally deliverable nanocomposite hydrogels have attracted considerable interest, particularly for chemotherapy applications, where conventional drugs often suffer from poor distribution and significant side effects. To overcome these limitations, studies have been carried for the fabrication of nanocomposite hydrogels in both gel and film forms, utilizing chitosan, carboxymethyl cellulose (CMC), hydroxyethyl cellulose (HEC), and polyvinyl alcohol (PVA) as polymeric matrices, linseed oil-based polyol as a crosslinking agent, and carbon nanotubes (CNTs), sodium montmorillonite (NaMMT), and fumed silica as reinforcing nanofillers. The hydrogels are synthesized through solution blending combined with free radical polymerization and are subsequently assessed for their efficacy in the controlled delivery of the anticancer drug cisplatin. Comprehensive studies are conducted on their physico-mechanical, spectral, and morphological properties, along with assessments of swelling behavior, biodegradability, and biocompatibility

The plan of the work encompasses the systematic development and characterization of nanocomposite hydrogels, followed by the assessment of how polyol and nanofillers influence their properties. These hydrogels are analyzed for their mechanical strength, swelling behaviour, drug release efficiency, cytotoxicity, and overall biocompatibility, thereby establishing their suitability for biomedical use.

Facile Formulation of Chitosan–Polyvinyl Alcohol–Polyol–Fumed Silica Hydrogels

One part of this research is devoted to the formulation of biocompatible chitosan–PVA–polyol–fumed silica nanocomposite hydrogels. The main objective of this chapter is to examine the swelling behaviour, biodegradability, and cytotoxicity of these systems under physiological conditions, with a view to evaluating their potential for therapeutic drug delivery. Biodegradability was studied through soil burial and hydrolytic degradation tests, while cytotoxicity and biocompatibility were assessed using HEK-293 and HCT116 colon cancer cell lines. The hydrogels were also tested for cisplatin loading and release behaviour, confirming their ability to sustain drug delivery in a controlled manner.

Na-Montmorillonite Dispersed CMC–HEC–Polyol Hydrogels

Another formulation involved Na-montmorillonite dispersed nanocomposite hydrogels prepared from CMC, HEC, acrylonitrile, and linseed oil-based polyol using solution-blending methods. These systems were structurally, morphologically, and mechanically characterized, with swelling properties also evaluated in detail. The synergistic incorporation of polyol and nanofillers enhanced the mechanical robustness and sustained drug release performance of the hydrogel films. Biocompatibility and cytotoxicity evaluations using MTT assays on HEK-293 and MCF-7 cells demonstrated their suitability for biomedical applications.

MWCNT-Reinforced Chitosan–Polyvinyl Alcohol–Polyol Hydrogels

The final section of this review examines the literature concerning the fabrication of pH-responsive, mechanically robust nanocomposite hydrogels. These hydrogels have been prepared via free radical polymerization using chitosan, PVA, and a polyol crosslinker and structurally characterized through FT-IR, optical microscopy, SEM, and TEM analyses. Their swelling behaviour has been evaluated at pH levels of 1.0, 4.0, 7.0, and 7.4, while biodegradability and cytotoxicity have been examined using MTT assays on HEK-293 and HCT116 cells. The findings demonstrated that the inclusion of MWCNTs enhanced mechanical stability and stimulus responsiveness, making these hydrogels highly promising for tissue engineering applications.

Conclusion

This review has emphasized that the successful design and evaluation of nanocomposite hydrogels. The resulting systems demonstrated considerable promise for applications in controlled drug release, wound repair, tissue engineering, and cancer treatment, due to their biodegradability, porous structure, and compatibility with cells. The incorporation of nanomaterials such as fumed silica, NaMMT, graphene derivatives, and CNTs notably enhanced their stability and functional responsiveness. Overall, these hydrogels present versatile platforms for biomedical and pharmaceutical applications. The findings emphasize their potential as next-generation materials, paving the way for further exploration in targeted and efficient therapeutic delivery systems.

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