" Kerbala Journal of Veterinary Medical Sciences, Vol. 1, Supplement I, 2025 "
"Proceedings of the 6th Scientific Conference, College of Veterinary Medicine, University of Karbala"

Hydrogel-based composites reinforced with multi-walled carbon nanotubes : a review of applications in wastewater treatment and drug delivery

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Received: 4/5/2025 **Accepted:**25/5/2025 **Published:** 3/7/2025

***Abstract*— Multi-walled carbon nanotube (MWCNT)-containing nanocomposite hydrogels have become extremely adaptable platforms with promising results in a range of environmental and medicinal applications. The use of MWCNTs improves adsorption capacity, electrical conductivity, mechanical robustness, and thermal stability—elements crucial for wastewater cleanup and drug delivery systems. Because of their improved mechanical stability, simplicity of production, and higher cost-effectiveness, MWCNTs are frequently chosen over single-walled carbon nanotubes (SWCNTs). In addition to allowing for controlled medication release in response to physiological cues, such hybrid materials have demonstrated efficacious performance in the adsorption of organic dyes and heavy metals from contaminated water. Future clinical and environmental uses are made possible by functionalization, which also increases biocompatibility and therapeutic efficacy. However, challenges such as dispersion uniformity, long-term toxicity, and scale-up production persist. Addressing these limitations through interdisciplinary research and green engineering strategies will be vital to realizing the full potential of hydrogel-MWCNT nanocomposites. Continued interdisciplinary research, supported by advances in green synthesis and computational design, is critical to overcome these limitations and unlock the full potential of hydrogel-MWCNT composites in addressing pressing medical and environmental challenges.**

***.Keywords* — hydrogel-MWCNT composites ; Environmental Applications ; pH-Responsive Systems; Drug Delivery**

INTRODUCTION

THE continuous increase in worldwide health and sustainability problems has driven the development of advanced functional materials with multifunctional capabilities (1). Among these because of their hydrophilicity which allows them to absorb and hold onto large volumes of aqueous or biological fluids without dissolving, hydrogels are three-dimensional networks of polymers (2).Their networks of chemically or physically crosslinked polymers are responsible for this unusual property, which enables them to keep their structure even when enlarged. Hydrogels have attracted a lot of interest in a variety of fields, including biomedical engineering, pharmaceutical formulations, and environmental remediation, because of their biocompatibility, tunable porosity, biodegradability, and sensitivity to external stimuli like pH, ionic strength, and temperature.(3). Despite these advantageous qualities, typical hydrogels frequently have limited multifunctionality, low electrical conductivity, and insufficient mechanical toughness (4). The creation of nanocomposite hydrogels, particularly those supplemented with carbon-based nanomaterials like multi-walled carbon nanotubes (MWCNTs), has been spurred by these limitations. MWCNTs work as efficient nano-reinforcements (5), greatly improving the mechanical and functional performance of hydrogel matrices because of their remarkable mechanical strength, electrical conductivity, thermal resilience, and high specific surface area.(6) In this context fig(1), a comparative analysis between single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs) becomes particularly relevant. SWCNTs consist of a single rolled graphene sheet forming a seamless cylindrical nanostructure with diameters typically below 2 nm. MWCNTs, by contrast, are composed of multiple concentric graphene cylinders, resulting in a larger diameter range between 5 and 50 nm.(7) This multilayered structure provides greater mechanical durability and enhanced load-bearing capacity, making MWCNTs particularly advantageous in structural reinforcement. While SWCNTs are known for their

unique quantum confinement effects, which contribute to their superior electron transport and tunable conductivity (metallic or semiconducting based on chirality), MWCNTs typically display metallic characteristics and higher structural integrity due to inter-wall interactions.(8) Furthermore, SWCNTs offer a higher specific surface area, which is valuable for sensor and catalytic applications. However, MWCNTs tend to be more cost-effective, thermally stable, and easier to process, particularly in aqueous or polymeric systems. Mechanically, both types of carbon nanotubes outperform conventional fillers. However, MWCNTs exhibit superior tensile strength and stiffness,(9) primarily due to their multi-wall configuration which enables better stress absorption. This makes them highly effective for reinforcing polymeric matrices in hydrogel composites, especially in fields requiring structural resilience such as drug delivery systems and pollutant adsorption platforms. The state-of-the-art in hydrogel-MWCNT nanocomposites is critically assessed in this study, which covers their dual-role applications in drug administration and wastewater treatment as well as their synthesis methodologies and structural and functional characterization methods. Furthermore, it highlights important research issues such as scale-up constraints, biocompatibility difficulties and dispersion stability and offers suggestions for developing this exciting class of smart materials in the biomedical and environmental fields (10)

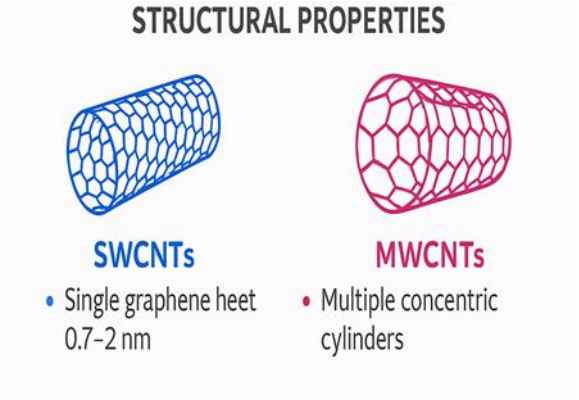

Figure 1. Comparison Between Single-Walled and Multi-Walled Carbon Nanotubes in Nanocomposite Applications.

2. Synthesis Strategies of Hydrogel-MWCNT Composites

The integration of multi-walled carbon nanotubes (MWCNTs) into hydrogel matrices has been extensively explored to overcome the intrinsic limitations of conventional hydrogels, such as low mechanical strength, limited conductivity, and poor responsiveness. Various synthesis strategies have been developed to fabricate hydrogel-MWCNT nanocomposites, each offering distinct advantages in terms of interaction strength, dispersion stability, and functional performance (11). The two primary approaches include physical blending m covalent grafting, In-situ Polymerization and Click Chemistry and Hybrid Crosslinking at Fig(2)illustrates various synthesis approaches for MWCNT-based hydrogel composites.2.1 Physical Blending

Physical blending remains one of the most accessible and commonly used methods for embedding multi-walled carbon nanotubes (MWCNTs) within hydrogel structures. In this technique, MWCNTs are introduced into the hydrogel precursor solution—which includes monomers, crosslinking agents, and polymerization (12) initiators—prior to the formation of the three-dimensional polymer network. Its primary advantages include procedural simplicity, ease of scale-up, and the lack of a need for intricate chemical alterations. Nonetheless, this method presents a notable obstacle: ensuring an even distribution of the nanotubes throughout the hydrogel matrix.(13). Due to the hydrophobic nature of unmodified MWCNTs and the presence of strong van der Waals forces, these nanomaterials have a tendency to cluster, forming bundles that hinder uniform dispersion and reduce the overall performance of the composite. To mitigate this issue, surfactants—whether ionic (e.g., sodium dodecyl sulfate, SDS), cationic (e.g., cetyltrimethylammonium bromide, CTAB), or non-ionic (e.g., polyethylene glycol, PEG)—are commonly used to improve dispersion stability. Additionally, sonication techniques are often employed to physically disrupt agglomerates. Although this blending approach does not create covalent bonding between the nanotubes and the polymer network, it still imparts notable improvements in the mechanical and electrical properties of the hydrogel, making it suitable for various mid-range engineering and biomedical applications. (14).

2.2 Covalent Grafting

Covalent grafting refers to the chemical modification of MWCNT surfaces to introduce functional moieties—such as carboxylic acid (-COOH), hydroxyl (-OH), or amino ($-NH_2$) groups—which enable the formation of strong covalent bonds with reactive sites on polymer chains or hydrogel precursors.(15) This technique provides enhanced compatibility between the nanotubes and the hydrogel matrix, resulting in a well-integrated, homogeneously dispersed composite material that surpasses the structural stability achieved through physical blending. (16) Functionalization is typically performed using oxidative treatments, such as exposure to nitric or sulfuric acid mixtures, or via plasma activation, which increases the hydrophilicity and chemical reactivity of the nanotubes. The modified MWCNTs can subsequently participate in covalent interactions with acrylate- or methacrylate-based monomers through mechanisms such as free-radical polymerization or condensation reactions.(17) The resulting covalently bonded network leads to improved load transfer across the interface and significantly enhances the mechanical resilience of the hydrogel. Furthermore, this method positively impacts other material properties, including swelling dynamics, thermal stability, and electrical conductivity.(18) Such enhancements make covalently functionalized MWCNT-hydrogel systems ideal candidates for use in advanced biomedical fields, including targeted drug

delivery, biosensor fabrication, and wastewater treatment technologies.(18, 19)

2.3 In-situ Polymerization

In this approach, the polymerization of monomers—such as acrylamide (AAm), acrylic acid (AAc), or N-isopropylacrylamide (NIPAM)—is carried out in the presence of functionalized MWCNTs,(20)enabling the formation of an interpenetrating network wherein the hydrogel matrix develops around the nanotube surfaces. This method promotes strong interfacial contact between the polymer chains and the carbon nanotubes, effectively anchoring the nanofillers within the gel structure. The intimate embedding of MWCNTs during in situ polymerization not only facilitates uniform dispersion but also contributes to efficient load transfer,(21) significantly enhancing the mechanical strength, elasticity, and resilience of the hydrogel. Furthermore, the presence of reactive functional groups on the MWCNT surface enables site-specific covalent bonding, which stabilizes the composite and prevents phase separation over time.[22] This tailored interaction results in a reinforced hydrogel matrix with superior performance in a range of applications. For instance, the increased mechanical durability is crucial for tissue scaffolds and wearable biosensors, while the improved conductivity and responsiveness are highly beneficial in stimuli-sensitive drug delivery systems and electrochemical water purification platforms.(23) Moreover, by carefully selecting the monomer type and functional group compatibility, researchers can fine-tune the swelling kinetics, release profiles, and pH/temperature sensitivity of the hydrogel, making this synthesis route highly versatile and adaptable to both biomedical and environmental engineering needs.(24)

2.4 Click Chemistry and Hybrid Crosslinking

New techniques like dual ionic-covalent crosslinking, Michael addition, and click chemistry have been used to create extremely robust and multipurpose hydrogel-MWCNT systems.(25)

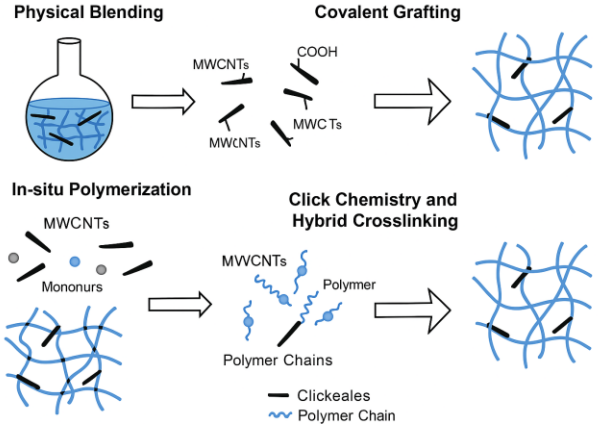

Figure 2. illustrates various synthesis approaches for MWCNT-based hydrogel composites

3-CHARACTERIZATION TECHNIQUES FOR MWCNT-REINFORCED HYDROGELS

Comprehensive characterization of MWCNT-reinforced hydrogels is essential to understand the interplay between their structure and functional performance in various applications such as environmental remediation and biomedical delivery systems.[26] The integration of MWCNTs into hydrogel matrices significantly alters their physicochemical properties, and thus, a multi-technique analytical approach is required to capture the complete structural, thermal, mechanical, and functional profiles of the composites Fig(3)illustrates Characterization Techniques for Hydrogel-Based Nanocomposites Reinforced with Multi-Walled Carbon Nanotubes (MWCNTs). The major characterization tools used include Fourier Transform Infrared Spectroscopy (FTIR) and Raman Spectroscopy to elucidate the chemical bonding, detect characteristic functional groups, and assess the degree of MWCNT functionalization within the hydrogel,(27) also another technique Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) To visualize the surface topography, pore structure, and nano structural dispersion of MWCNTs throughout the hydrogel matrix, X-ray Diffraction (XRD) also commonly used to characterize the crystallinity and phase composition of MWCNTs.(26, 27) Typical features include Main Peak: $2\theta \approx 26°$: This corresponds to the (002) plane of graphitic carbon, indicating the interlayer spacing in MWCNTs (about 0.34 nm), similar to graphite. Additionally Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC) to measures the mass loss of a sample as it is heated. It's useful for determining thermal stability, Assessing purity Evaluating oxidation resistance ,DSC detects glass transition (Tg), crystallization, and melting temperatures. While Mechanical Testing To assess the reinforcement effect of MWCNTs on the mechanical integrity of hydrogels The mechanical and viscoelastic enhancements—including stronger tensile and compressive performance, greater elasticity, and optimized storage and loss moduli—demonstrate that the nanotubes have been successfully embedded into the material matrix.[28] Moreover Swelling Behavior and Porosity Analysis To determine the water uptake capacity and porous architecture of the hydrogel composite, critical for adsorption and drug loading by Swelling ratio studies under different pH conditions simulate environmental or physiological conditions,(29, 30) while porosity analysis supports data on internal network structure, Combined, these methods provide an in-depth understanding of MWCNT-hydrogel composites across scales—from microstructure to overall performance—enabling their tailored development for targeted applications in Fig (3) Characterization Techniques for Hydrogel-Based Nanocomposites Reinforced with Multi-Walled Carbon Nanotubes (MWCNTs).

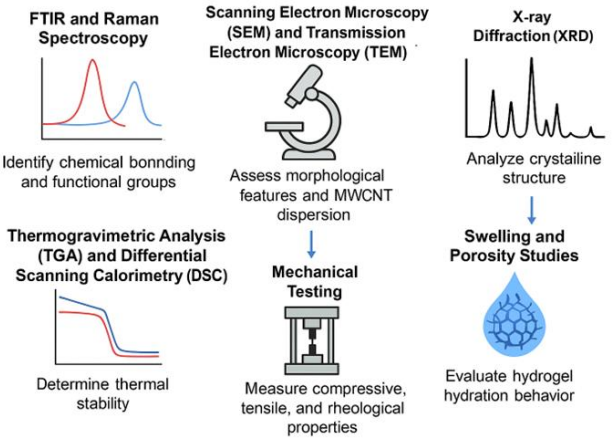

Figure 3.Characterization Techniques for Hydrogel-Based Nanocomposites Reinforced with Multi-Walled Carbon Nanotubes (MWCNTs).

4. Environmental Applications of MWCNT-Hydrogel Composites in Wastewater Treatment

The rising global demand for clean water necessitates the development of advanced materials that offer high efficiency, cost-effectiveness, and sustainability in wastewater purification (31). MWCNT-reinforced hydrogels have emerged as hybrid nanomaterials that combine the adsorption capacity, porosity, and water-swelling nature of hydrogels with the unique surface characteristics and functionality of multi-walled carbon nanotubes (MWCNTs) (32). These composites offer multifunctional advantages across several pollutant categories: fig (4) Environmental applications of MWCNT-Hydrogel Composites

4.1 Heavy Metal Ion Removal
Heavy metal ions such as lead (Pb^{2+}), cadmium (Cd^{2+}), chromium (Cr^{6+}), and mercury (Hg^{2+}) pose significant threats to aquatic ecosystems and human health due to their toxicity, endurance, and bioaccumulation capability. MWCNTs embedded in hydrogel matrix are high-affinity adsorbents due to the following characteristics. [33] highly surface area and lots of functional groups (like -OH and -COOH) Interactions between metal species and π–π electron donors and acceptors Both the polymeric and nanotube components enhance ion exchange and omplexation mechanisms. Furthermore, the swelling nature of the hydrogel improves removal kinetics by increasing the diffusion of metal ions into interior adsorption sites. (34)

4.2 Adsorption of Organic Dyes
Synthetic dyes such as methylene blue (MB), malachite green (MG), and Congo red are widely used in textile, leather, and paper industries, often discharged into waterways without adequate treatment.(19) MWCNT-based hydrogels serve as highly effective sorbents due to: π–π stacking interactions between aromatic dye molecules and graphitic surfaces of MWCNTs , Electrostatic attraction between negatively charged functional groups in the hydrogel and cationic dye molecules , Micro- and mesoporous structures that promote entrapment and physical adsorption These synergistic mechanisms enable rapid and efficient dye uptake, with some composites showing adsorption capacities exceeding 100 mg/g for specific dyes.(35)

4.3 Antimicrobial Activity and Photocatalytic Degradation
To expand their utility beyond adsorption, MWCNT-hydrogel systems can be doped with photocatalytic agents such as titanium dioxide (TiO_2), zinc oxide (ZnO), or silver nanoparticles (AgNPs).(36) These modifications introduce additional water purification functionalities, Antimicrobial Activity: Disrupts bacterial cell membranes and inhibits microbial proliferation through reactive oxygen species (ROS) or direct contact damage.[36]
- Photocatalysis: Under UV or visible light, the incorporated metal oxides generate electron–hole pairs that degrade organic contaminants into harmless end products (CO_2 and H_2O). - Multi-cycle regeneration: These systems retain high performance over multiple uses, promoting sustainability.[36] Together, these features make MWCNT-hydrogel composites a powerful tool for integrated water treatment strategies that address chemical, dye, and microbial pollutants.[37] AlsoThe results of some research have shown that the MWCNT–chitosan composite exhibited a stronger influence on fibrosis development and collagen accumulation when compared to the SWCNT–chitosan counterpart. (38) The presence of inflammatory responses further supported its role in promoting wound healing. Inflammation is a critical early phase in the healing process, during which neutrophils become activated and release lysosomal enzymes that help degrade and remove damaged extracellular matrix proteins (39). Additionally, the inflammatory response recruits more macrophages to the wound site, where they release signaling molecules and contribute to clearing cellular debris and pathogens (40).

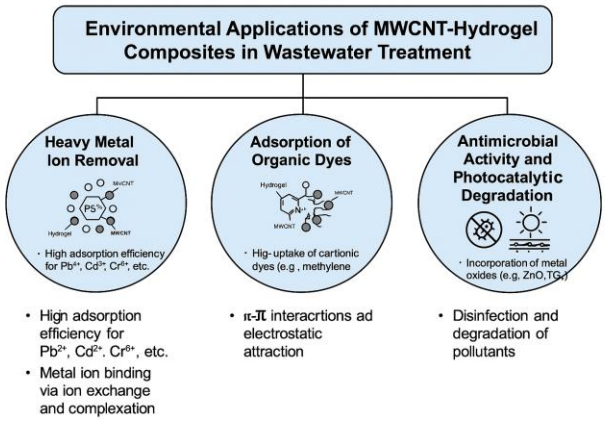

Figure 4. Environmental Applications of MWCNT-Hydrogel Composites .

5.Biomedical Applications of MWCNT-Hydrogel Composites: Drug Delivery Systems

In the realm of modern medicine, the pursuit of intelligent drug delivery systems (DDS) that can precisely control the release of therapeutic agents has become a priority. MWCNT-reinforced hydrogel composites have emerged as promising candidates for such tasks due to their structural versatility, responsiveness to biological stimuli, and capacity for high drug loading. These hybrid systems combine the water-retaining and biocompatible nature of hydrogels with the exceptional drug-carrying and protective capabilities of multi-walled carbon nanotubes (MWCNTs)(41)

5.1 Dual-Controlled and Targeted Drug Release

MWCNTs act as effective nanocarriers capable of loading drugs via surface adsorption, encapsulation within their hollow cores, or covalent attachment (42) When embedded in a hydrogel matrix, this combination offers a dual-controlled drug release mechanism:

- **Initial burst release** is regulated by diffusion through the swollen hydrogel matrix.
- **Sustained and controlled release** follows via gradual desorption or degradation of MWCNTs, influenced by physiological stimuli.

This two-stage delivery mechanism enhances drug bioavailability, reduces dosing frequency, and enables site-specific delivery, particularly beneficial in cancer therapy, wound healing, and localized infections.(43).

5.2 Stimuli-Responsive Behavior: pH and Temperature Sensitivity

Advanced hydrogel-MWCNT systems can be engineered to respond to specific physiological triggers:

- **pH-Responsive Systems**: Functionalized MWCNTs or hydrogel matrices (e.g., containing poly(acrylic acid)) respond to the acidic microenvironment of tumors or inflamed tissues by expanding or degrading to release drugs selectively at the site of pathology.(44)
- **Thermo-Responsive Systems**: Polymers like PNIPAM (poly(N-isopropylacrylamide)) exhibit phase transitions near body temperature, allowing temperature-dependent drug release, useful in hyperthermia-assisted therapies(45)

These "smart" systems ensure spatial and temporal control over therapeutic delivery, significantly enhancing treatment outcomes while minimizing systemic toxicity.

5.3 Biocompatibility, Bioavailability, and Safety Considerations

Although pristine MWCNTs may pose cytotoxic risks due to oxidative stress or cellular membrane damage, these effects are significantly mitigated through:

- Surface functionalization with biocompatible groups (e.g., PEGylation or carboxylation).
- Encapsulation within soft, hydrophilic hydrogel matrices, which act as protective barriers(44).

These modifications not only reduce immunogenic responses and improve circulation time but also support enhanced solubility, drug retention, and cellular uptake, thereby boosting overall bioavailability (46) In preclinical models, such composites have shown promising therapeutic indices and minimal inflammatory responses, indicating their potential for future clinical applications. Fig (5) MWCNT-Embedded Hydrogels: Enhancing Drug Release, Responsiveness, and Biocompatibility.

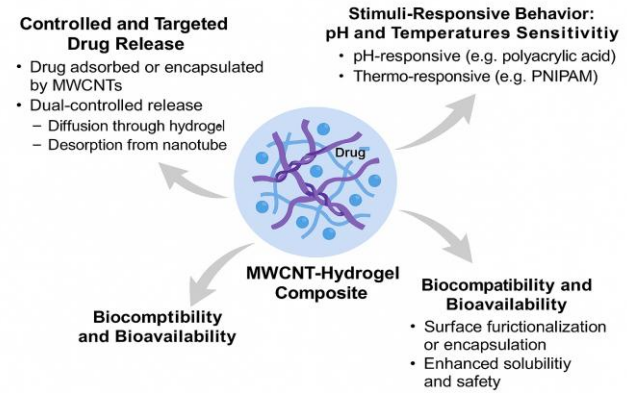

Figure 5. MWCNT-Embedded Hydrogels: Enhancing Drug Release, Responsiveness, and Biocompatibility.

6-MWCNT hydrogel's potential efficiency in wound healing and other biomedical applications

MWCNT-reinforced hydrogels are gaining increasing attention in the biomedical field due to their favorable combination of physical and functional properties illustration in fig 6. In the context of wound healing, these hybrid systems exhibit enhanced mechanical strength and flexibility, which support the structural integrity of the wound environment during the healing process. The inclusion of MWCNTs.(47) also introduces electrical conductivity, a feature that can play a supportive role in stimulating cellular activity and accelerating tissue repair, particularly in electrically active tissues such as skin and nerves. Furthermore, the porous nature of the hydrogel matrix, combined with the high surface area of MWCNTs, provides an efficient platform for the sustained delivery of bioactive compounds, including antimicrobial agents, anti-inflammatory drugs, or growth-promoting molecules(48)Beyond wound care, MWCNT-based hydrogels have shown potential in tissue engineering, especially as scaffolds for nerve and bone regeneration, due to their tunable surface chemistry and ability to interact with biological environments. The responsive behavior of the hydrogel system—triggered by changes in pH, temperature, or biochemical signals—further broadens its usability in controlled drug release, implantable devices, and regenerative therapies (49). Importantly, with appropriate surface modification of MWCNTs, the biocompatibility of the

composite can be significantly improved, reducing concerns related to cytotoxicity and enhancing its suitability for in vivo applications.In the early stage of infection, the Gram-positive bacteria such as Staphylococcus aureus and Streptococcus pyogenes are more populated, whereas the Gram-negative bacteria, such as Escherichia coli (E. coli) and Pseudomonas aeruginosa (P. aeruginosa), are populated later nearby wounded areas (50). Usually, infection is avoided by activating the immune system for abolishing the invading pathogens. In this process, macrophages initiate the migration to the wound site and subsequently perform phagocytosis of the pathogens (destroyed in a phagolysosome or by nitric acid production). In a later stage of infection, the immune response is performed by activating T-helper lymphocytes, which secrete interferon-γ and CD40 ligand to coordinate the immune adaptive and humoral response to kill and remove the invading bacteria , Infection typically occurs during the immune system's dormant phase,(51) interfering with the normal wound-healing process by breaking down granulation tissue, essential growth factors, and key extracellular matrix elements such as collagen, elastin, and fibrin. To prevent microbial invasion or inhibit bacterial proliferation, it is essential to design wound dressing materials with effective antimicrobial properties.(52).

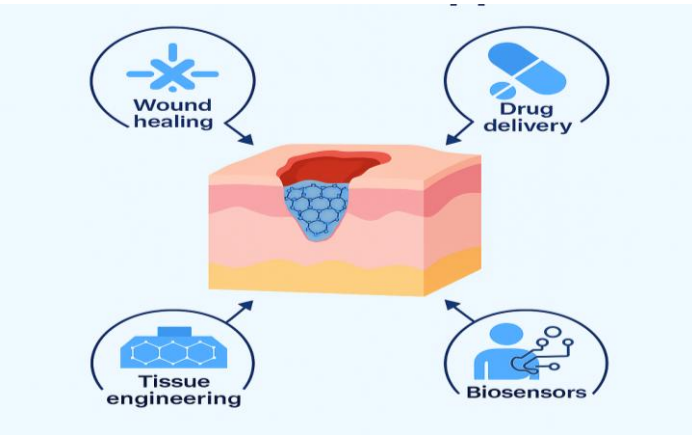

Figure 6..Multifunctional Role of MWCNT Hydrogels in Wound Repair, Drug Delivery, and Tissue Engineering

II-Recent Advances in the Removal of Dyes and Drugs from Wastewater Using MWCNT-Based Hydrogel Composites

This table summarizes 20 recent studies demonstrating the use of multi-walled carbon nanotube (MWCNT)-reinforced hydrogel composites for removing dyes and pharmaceutical compounds from wastewater.

Table 3: Comparison of Adsorption Performance of MWCNT-Based Hydrogels for Various Pollutants.

Target Pollutant	Composite Type	Adsorption Capacity (mg/g)	Removal M echanism	Reference
Methylene Blue	MWCNTs/Chitosan Hydrogel	233.1	π–π stacking, hydrogen bonding	(53)
Congo Red	MWCNTs/Alginate Hydrogel	201.8	Electrostatic interaction, pore-filling	(54)
Tetracycline	PEG-MWCNT Hydrogel	156.7	H-bonding, hydrophobic interaction	(55)
Cadmium (Cd^{2+})	MWCNTs/PVA Hydrogel	148.2	Electrostatic interaction, coordination	(56)
Phenol	Oxidized MWCNT Hydrogel	110.3	π–π interaction, surface adsorption	(57)
Amoxicillin	MWCNT/Alginate-Bead Hydrogel	115.2	Electrostatic interaction, H-bonding	(58)
Reactive Black 5	MWCNT-Gelatin Composite	198.9	Hydrophobic and ionic interactions	(59)
Diclofenac	MWCNTs/Hydrogel	121.4	H-bonding, π–π stacking	(60)
safranin-o dye	(κC-g-poly (AAC-co-IA)/MWCNT)	366.857	Ion exchange, electrostatic interaction	(61)
Nickel (Ni^{2+})	alginate-chitosan	130.6	Surface complexatio n	(62)
Cd (II)	alginate-chitosan	175.4	Electrostatic attraction, ion exchange	(62)
Malachite Green	MWCNTs/Starch Hydrogel	189.0	π–π stacking, H-bonding	(63)
Ibuprofen	MWCNTs/PNIPAM Hydrogel	95.0	Hydrophobic interaction	(18)
Norfloxacin	MWCNTs/SA Hydrogel	160.2	H-bonding, electrostatic attraction	(64)
Methyl Orange	MWCNTs/Agarose Hydrogel	140.0	Electrostatic and π–π interactions	(65)
Chloramphenic ol	MWCNTs/TiO2	102.8	H-bonding, diffusion control	(66)
Rhodamine B	CX/MWCNTs	210.3	π–π interaction, adsorption	(67)
Toluene	oxidized MWCNTs	87.0	Hydrophobic interaction	(68)
Sulfasalazine	MWCNTs/G O Incorporated MIL-101(Cr)	132.6	Electrostatic and π–π interactions	(69)
Erythromycin	MWCNTs	116.4	H-bonding and complexatio n	(70, 71)

RESULT & DISCUSSION

Research Gaps and Challenges

. Despite the substantial progress in the development and application of hydrogel-based nanocomposites reinforced with MWCNTs, several critical challenges remain unresolved:

1- Biocompatibility and Long-Term Safety: While surface functionalization improves MWCNT compatibility, concerns regarding long-term cytotoxicity, bioaccumulation, and immune responses still require comprehensive in vivo investigations.

2- Dispersion Uniformity: Achieving stable and homogeneous dispersion of MWCNTs within hydrogel matrices remains technically challenging, particularly under

physiological or environmental conditions. Aggregation limits performance consistency and repeatability.

3- Scalability of Production: Most studies are conducted at laboratory scale using complex or expensive fabrication techniques. There is a lack of cost-effective, reproducible methods for large-scale manufacturing of these nanocomposites.

4- Integration of Multifunctionality: Many systems are optimized for a single function (e.g., adsorption or drug release), but fail to integrate mechanical strength, stimuli-responsiveness, biodegradability, and bioactivity in a unified platform.

5- Regulatory and Ethical Considerations: The clinical and environmental application of MWCNTs is hindered by limited toxicological data and undefined regulatory pathways, creating barriers for commercial translation

8. Future Perspectives

Future research should focus on:

Green and Sustainable Synthesis: The development of eco-friendly, low-energy methods—such as plant-extract mediated synthesis or enzymatic crosslinking—can reduce environmental impact and promote safer materials.

- Design of Multi-Stimuli Responsive Systems: Incorporating multiple triggers (pH, temperature, redox, light) will enable precise control over drug release and adsorption behavior in complex physiological or environmental settings.
- Hybrid Material Engineering: Combining MWCNTs with other advanced nanomaterials such as graphene oxide, quantum dots, or metal-organic frameworks may yield synergistic effects and expand functionality.
- In Vivo and Long-Term Evaluation: Preclinical and clinical studies must be prioritized to assess chronic toxicity, degradation kinetics, biodistribution, and immune compatibility, especially for biomedical applications.
- Predictive Modeling and Optimization: Integrating computational tools such as machine learning and molecular simulations can streamline formulation design and performance prediction based on application-specific parameters

CONCLUSION

Hydrogel composites enhanced with multi-walled carbon nanotubes (MWCNTs) have gained attention as advanced materials with significant potential in fields such as wastewater treatment and drug delivery. The integration of MWCNTs with hydrogels combines the mechanical strength, electrical conductivity, and high adsorption capacity of nanotubes with the hydrogels' responsiveness to environmental stimuli, creating a multifunctional and adaptable system. However, realizing the full potential of these composites requires overcoming several challenges, including concerns regarding their biocompatibility, the difficulty in achieving uniform dispersion of MWCNTs, and the limitations related to large-scale production. Overcoming these issues will necessitate collaborative efforts across disciplines, particularly involving chemists, materials scientists, and biomedical engineers, to develop the next generation of smart and safe hydrogel-MWCNT composit

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