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AI-driven innovations in hydrogel formulation: Unlocking next-generation biomaterials

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Abstract
Advancements in artificial intelligence (AI) are transforming the landscape of pharmaceutical research and development. Among various applications, the use of AI in hydrogel formulation offers significant potential to optimize properties, enhance therapeutic efficacy, and accelerate development timelines. This review examines the integration of AI into hydrogel design, focusing on machine learning (ML) techniques, data-driven modeling, and optimization algorithms. We highlight key studies, challenges, and future prospects in AI-based hydrogel formulation.

Keywords: Artificial intelligence (AI), machine learning (ML), predictive modeling formulation optimization, material discovery, data-driven approaches, drug delivery systems

Introduction

Hydrogels are three-dimensional, hydrophilic polymer networks capable of absorbing and retaining significant amounts of water or biological fluids [1]. These materials are highly valued in biomedical applications due to their biocompatibility, tunable mechanical properties, and ability to mimic the extracellular matrix. Hydrogels find widespread use in drug delivery systems, wound healing, tissue engineering, and biosensors, among other applications. However, the traditional approach to hydrogel formulation is often labor-intensive and relies heavily on trial-and-error methodologies [2-7]. This process involves repeated synthesis and characterization cycles, which can be both time-consuming and costly. The advent of artificial intelligence (AI) has introduced a paradigm shift in material science, offering powerful tools for predictive modeling, optimization, and data analysis [8-9]. AI techniques, particularly machine learning (ML), can analyze complex datasets, uncover hidden patterns, and predict outcomes with remarkable accuracy. In the context of hydrogel formulation, AI provides the capability to accelerate the development process, optimize material properties, and explore vast chemical spaces that would be otherwise inaccessible through conventional approaches [10-12].

Due to the presence of hydrophilic components within the polymer backbone, hydrogels have the ability to retain a significant amount of water and exhibit physicochemical properties resembling those of liquid water. This unique property allows hydrogels to display a solid-like rheological behavior on a macroscopic scale.[13] This fascinating characteristic of hydrogels opens up the possibility of mimicking various features of the ECM found in tissues. Furthermore, the gelation of hydrogels can be achieved through different methods such as physical cross-linking, dynamic cross-linking, and chemical cross-linking. These techniques offer opportunities for engineering the gelation process to meet specific needs. Additionally, advanced chemical approaches have been developed to precisely manipulate the shape, structure, and architecture of hydrogels. Through these methods, hydrogels can be tailored with desirable functionalities including adjustable properties, excellent biocompatibility, controllable degradability, and mechanical compatibility with biological tissues. This unique characteristic makes them similar to biological tissues, enabling interactions with living cells and surrounding environments [14-15].

This integration of AI into hydrogel research is driven by the increasing availability of experimental data and advancements in computational power. Researchers can leverage AI to model relationships between polymer composition, crosslinking mechanisms, and functional properties such as swelling behavior, mechanical strength, and biodegradability. Furthermore, AI can facilitate the discovery of novel polymers and crosslinking agents, paving the way for next-generation hydrogels with tailored functionalities [16-17].

The significance of AI in hydrogel formulation extends beyond efficiency. By reducing experimental redundancy and focusing resources on promising candidates, AI contributes to more sustainable research practices. Additionally, the ability to simulate and predict material behavior under various conditions can enable the design of personalized hydrogels, aligning with the growing trend of precision medicine [18].

This review explores the role of AI in hydrogel formulation, emphasizing its potential to transform the field. We discuss the methodologies employed, highlight key studies, address existing challenges, and outline future directions. By bridging the gap between computational and experimental workflows, AI-based approaches are poised to redefine the landscape of hydrogel research and development [19-20].

Table 1: Details of preparation, performance and application of typical hydrogels [21-28]

Hydrogels	Preparation	Performance	Application
Polyacrylamide (PAAm)	Free radical polymerization of acryl amide monomers in the presence of a cross linker, such as MBA.	High water absorption capacity and tunable mechanical strength, depending on the cross-linking density.	Tissue engineering, drug delivery, wound dressings, and etc. due to their biocompatibility and ability to swell in biological fluids.

Polyvinyl Alcohol (PVA)	Cross linking PVA chains with a cross linking agent, such as glutaraldehyde or borate ions.	Excellent biocompatibility, high water content and good mechanical properties.	Contact lenses, wound dressing materials, and as scaffolds for tissue engineering due to their biocompatibility and optical clarity.
Polyethylene Glycol (PEG)	Physical or chemical cross linking of PEG chains with cross linking agents or through photo polymerization.	Excellent tunability of mechanical properties and degradation rates.	3D cell culture platforms, injectable materials for tissue engineering, and drug delivery systems.
Sodium Alginate	Ionotropic gelation of sodium alginate with divalent cations, such as calcium ions.	High water absorption capacity and can form a gel under mild conditions	Pharmaceutical industry for drug delivery, food industry for encapsulation of bioactive compounds.

Role of AI in Hydrogel Formulation [29-31]

1. **Predictive Modeling:** AI tools, particularly ML algorithms, can predict hydrogel properties such as swelling ratio, mechanical strength, and degradation rates. For example, neural networks and support vector machines have been used to analyze relationships between polymer composition and functional performance.

2. **Optimization of Formulations:** AI-driven optimization techniques, including genetic algorithms and Bayesian optimization, enable precise tuning of formulation parameters. These methods reduce the reliance on trial-and-error approaches, leading to faster development cycles.

3. **Material Discovery:** AI aids in identifying novel polymers and crosslinking agents for hydrogel synthesis. Generative models, such as variationalautoencoders (VAEs) and generative adversarial networks (GANs), help explore vast chemical spaces efficiently.

Artificial Intelligence (AI) can contribute significantly to hydrogel formulation by leveraging its advanced computational capabilities and data-driven approaches. Below are the key ways AI can enhance hydrogel research and development [32-35]:

a. Predictive Modeling
AI can create predictive models for hydrogel properties such as swelling ratio, mechanical strength, and degradation rate. By training machine learning (ML) algorithms on experimental datasets, researchers can predict outcomes for new formulations without exhaustive physical testing.
- **Example Tools:** Neural Networks, Support Vector Machines, Random Forests.
- **Application:** Predicting drug release profiles in hydrogel-based drug delivery systems.

b. Optimization of formulation parameters
AI enables the optimization of key hydrogel formulation parameters, such as polymer concentration, crosslinking density, and chemical composition.
- **Methods Used:** Genetic algorithms, Bayesian optimization, reinforcement learning.
- **Outcome:** Faster fine-tuning of properties like elasticity, viscosity, and biodegradability.

c. Data Integration and Analysis
AI can process large datasets from various sources, such as experimental results, literature, and clinical studies, to identify trends and correlations.
- **Tools:** Natural Language Processing (NLP) for literature mining, clustering algorithms for dataset categorization.
- **Impact:** Efficient extraction of insights from complex, unstructured data.

d. Material discovery
AI models can explore vast chemical spaces to identify novel polymers and crosslinkers suitable for hydrogel synthesis.
- **Techniques:** Deep learning, generative models like GANs and VAEs.
- **Example:** Designing hydrogels with unique swelling behavior or stimuli responsiveness.

e. Simulation and virtual experimentation
AI-powered simulations can emulate laboratory experiments to predict how a hydrogel formulation will behave under different conditions.
- **Software:** Molecular dynamics simulations combined with AI-driven predictions.
- **Advantage:** Reduced costs and time for experimental validation.

f. Personalized Medicine
AI can design hydrogel formulations tailored to individual patient needs, considering factors like age, health condition, and metabolic profile.
- **Approach:** Integrating patient data with hydrogel property databases using AI models.
- **Benefit:** Enhanced therapeutic outcomes with patient-specific treatments.

g. Automation in 3D printing
AI optimizes parameters for 3D printing hydrogels, ensuring desired mechanical and structural properties.
- **Example:** AI-based algorithms to refine extrusion speed, nozzle temperature, and layer thickness for hydrogel scaffolds.
- **Applications:** Tissue engineering and regenerative medicine.

h. Quality control and assurance
AI algorithms can monitor hydrogel production processes in real-time, ensuring consistency and quality.
- **Use cases:** AI-powered image analysis for detecting defects or variations in hydrogel structure.
- **Tools:** Computer vision systems integrated into manufacturing lines.

4. **Key studies** Several studies have demonstrated the application of AI in hydrogel research:
- **Drug delivery systems:** ML models have been used to predict drug release kinetics from hydrogels based on polymer composition and crosslinking density.

- **Wound healing applications:** AI-driven image analysis has facilitated the assessment of hydrogel-based wound dressings in real-time.
- **3D printing of hydrogels:** AI algorithms optimize printability and mechanical properties in additive manufacturing of hydrogel scaffolds.

Challenges and limitations [36-39]

1. **Data quality and quantity:** AI models require extensive, high-quality datasets. The lack of standardized data in hydrogel research hinders the development of robust models.
2. **Model interpretability:** Understanding the decision-making process of complex AI models, such as deep learning networks, remains challenging, limiting their acceptance among researchers.
3. **Integration into experimental workflows:** Bridging the gap between computational predictions and experimental validation requires interdisciplinary collaboration and seamless integration of AI tools into laboratory workflows.

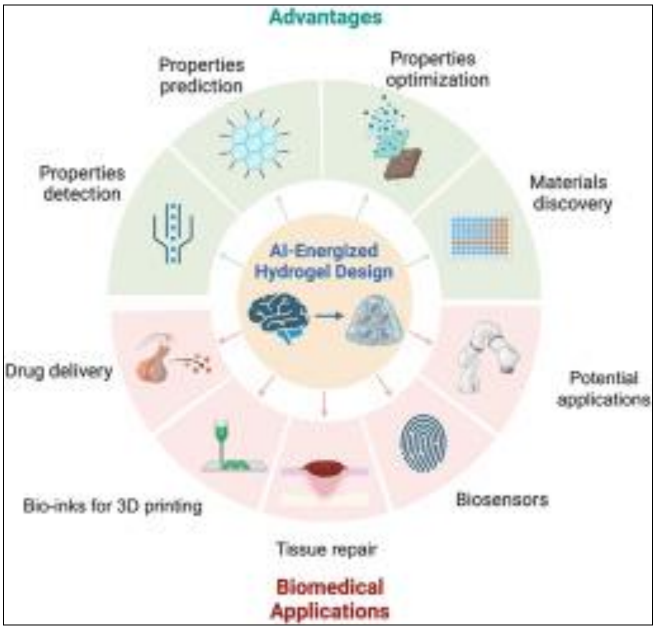

Fig 1: Biomedical application

Future Prospects[40-42]

1. **Personalized medicine:** AI could enable the development of personalized hydrogel formulations tailored to individual patient needs, enhancing therapeutic outcomes.
2. **Advances in computational techniques:** Emerging technologies such as quantum computing and explainable AI may further improve the accuracy and efficiency of hydrogel design.
3. **Open-source platforms:** Collaborative, open-source platforms for hydrogel data and AI tools could accelerate innovation and foster global research efforts.

Types of hydrogel formulation

1. Nanocomposite hydrogel formulation and design

In the ever-evolving landscape of biomaterials, the emergence of nanocomposite hydrogels is a testament to human ingenuity and the power of interdisciplinary innovation. These remarkable materials, born from the marriage of nanotechnology and hydrogel chemistry, are poised to revolutionize the field of biomedicine. Nanocomposite hydrogels, with their unique blend of properties and functionalities, promise to address critical challenges in diverse biomedical applications, ranging from tissue engineering and drug delivery to wound healing and biosensing [43-45].

2. Carbon-based nanocomposite hydrogels

Carbon-based nanoparticles, such as carbon nanotubes (CNTs) and graphene derivatives, have gained significant attention for their exceptional mechanical, electrical, and thermal properties. Incorporating these nanoparticles into hydrogels enhances strength, electrical conductivity, and thermal stability. Carbon-based nanocomposite hydrogels find applications in tissue engineering scaffolds, flexible electronics, and sensors. Nanocomposite hydrogels (NCHs) from carbon-based nanomaterials such as carbon nanotubes (CNTs) and graphene. CNTs exist in different atomic configurations (namely armchair and zig-zag) and architectures (single- and multi-walled) and can be chemically modified to enhance their hydrophilicity and, therefore, their interaction with the surrounding hydrogel. Based on the search results, there are some common methods for synthesizing carbon-based nanocomposite hydrogels [46-48].

3. Polymeric-based nanocomposite hydrogels

Polymeric nanoparticles, including nanofibers, micelles, and dendrimers, offer a diverse toolkit for tailoring hydrogel properties. These nanoparticles can provide structural support, enhance drug encapsulation, and regulate release kinetics. Polymeric-based nanocomposite hydrogels are utilized in drug delivery, wound healing, and tissue regeneration. Polymer-based hydrogels are hydrophilic polymer networks with crosslinks widely applied for drug delivery applications because they hold large amounts of water and biological fluids and control drug release based on their unique physicochemical properties and biocompatibility. Current trends in developing hydrogel drug delivery systems involve the release of drugs in response to specific triggers such as pH, temperature, or enzymes for targeted drugs. The most common methods for synthesizing polymeric-based nanocomposite hydrogels include *in situ polymerization*. This method involves the polymerization of monomers and the incorporation of nanoparticles within the hydrogel matrix. The nanoparticles can be added during the polymerization process, allowing for the formation of a nanocomposite hydrogel. *Crosslinking*: nanocomposite hydrogels can be synthesized by crosslinking pre-formed polymers with nanoparticles [49-50].

4. Inorganic-based nanocomposite hydrogels

Inorganic nanoparticles, such as silica, hydroxyapatite, and metal oxides, confer unique physicochemical properties to hydrogels. These nanoparticles can modulate mechanical strength, improve bioactivity, and facilitate controlled ion release. Inorganic-based nanocomposite hydrogels are applied in bone tissue engineering, dental materials, and controlled drug delivery. This approach can be exploited in synthesizing materials that exhibit defined nanoporosity.

Inorganic-based nanocomposite hydrogels are promising materials with superior physicochemical and biological properties. They have found broad applicability in various fields of science and technology, including biomedical sciences and engineering. Nanomaterial-filled, hydrated polymeric networks exhibit higher elasticity and strength than traditionally made hydrogels. A range of natural and synthetic polymers are used to design nanocomposite networks. By controlling the interactions between nanoparticles and polymer chains, a range of physical, chemical, and biological properties can be engineered [51-52].

5. Metallic-based nanocomposite hydrogels

Metallic nanoparticles, such as gold nanoparticles and silver nanoparticles, bring forth distinct optical, antimicrobial, and catalytic properties to hydrogel matrices.C metallic nanoparticles can enhance antimicrobial activity, photothermal therapy, and localized drug release. Metallic-based nanocomposite hydrogels find utility in wound dressings, cancer therapy, and antibacterial applications. Synthesizing metallic-based nanocomposite hydrogels involves incorporating metallic nanoparticles into the hydrogel matrix. *In situ* synthesis: one approach synthesizes metallic nanoparticles within the hydrogel matrix. This involves incorporating the precursors for metallic nanoparticles during the hydrogel synthesis process, allowing for the simultaneous formation of the hydrogel and nanoparticles. Incorporation of pre-synthesized nanoparticles: metallic nanoparticles, such as gold (Au) and silver (Ag), can be incorporated into hydrogels. These nanoparticles are typically synthesized separately and mixed with the hydrogel matrix during fabrication. Structural modification: factors such as structural modification, material stability, processability, and solubility must be considered during the fabrication or modification of metallic nanocomposite hydrogels [53-54].

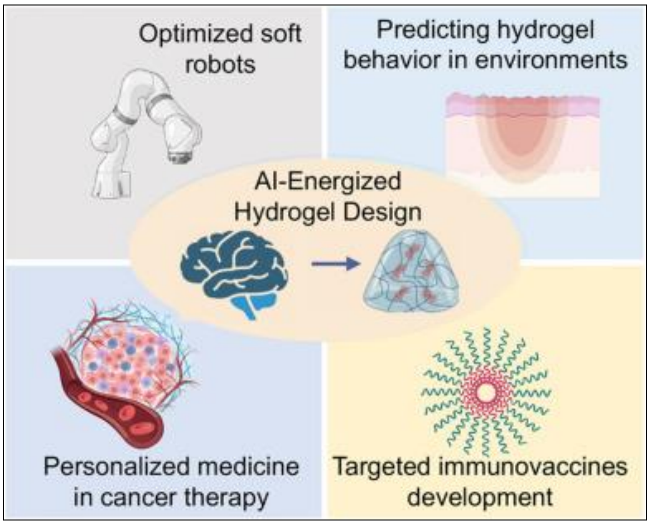

Fig 2: The current development trends and potential applications of AIenergized design and optimization of hydrogels in biomedicine

Conclusion

The integration of AI into hydrogel formulation research has the potential to revolutionize the field, offering unprecedented capabilities in material design, optimization, and application. Despite current challenges, ongoing advancements in AI technology and interdisciplinary collaboration promise a bright future for this synergy.

References

1. Nazarzadeh ZE, Danial K, Atefeh Z, Hulya Y, Tarun A, Sara H, *et al*. Biomedical applications of engineered heparin-based materials. Bioact Mater,2023:31:87. doi: 10.1016/j.bioactmat.2023.08.002.
2. Xiao Y, Pang YX, Yan Y, Qian P, Zhao H, Manickam S, *et al*. Synthesis and functionalization of graphene materials for biomedical applications: recent advances, challenges, and perspectives. Adv Sci,2023:22:100741. doi:10.1002/advs.202205292.
3. Hao S, Wang M, Yin Z, Jing Y, Bai L, Su J. Microenvironment-targeted strategy steers advanced bone regeneration. Mater Today Bio,2023:22:100741. doi: 10.1016/j.mtbio.2023.100741.
4. Li M, Yu B, Wang S, Zhou F, Cui J, Su J. Microenvironment-responsive nanocarriers for targeted bone disease therapy. Nano Today,2023:50:101838. doi: 10.1016/j.nantod.2023.101838.
5. Bai H, Zhao Y, Wang C, Wang Z, Liu H, Feng Y, *et al*. Enhanced osseointegration of three-dimensional supramolecular bioactive interface through osteoporotic microenvironment regulation. Theranostics,2020:10:4779-4794. doi:10.7150/thno.43736.
6. Gong Q, Zhao Y, Qian T, Wang H, Li Z. Functionalized hydrogels in ophthalmic applications: ocular inflammation, corneal injuries, vitreous substitutes and intravitreal injection. Mater Des,2022:224:111277. doi: 10.1016/j.matdes.2022.111277.
7. Ahmed EM. Hydrogel: preparation, characterization, and applications: a review. J Adv Res,2015:6:105-121. doi: 10.1016/j.jare.2013.07.006.
8. Daly AC, Riley L, Segura T, Burdick JA. Hydrogel microparticles for biomedical applications. Nat Rev Mater,2020:5:20-43. doi:10.1038/s41578-019-0148-6.
9. Deligkaris K, Tadele TS, Olthuis W, van den Berg A. Hydrogel-based devices for biomedical applications. Sens Actuators B Chem,2010:147:765-774. doi: 10.1016/j.snb.2010.03.083.
10. Xiang L, Jinglin W, Xiangyi W, Yuan L, Yongan W, Yuanjin Z. Marine-derived hydrogels for biomedical applications. Adv Funct Mater,2022:33:2211323.
11. Omkar M, Avishek M, Debasish M, SurjyaKanta P, ParthaPratim C, Arpan P. A critical review on applications of artificial intelligence in manufacturing. Artif Intell Rev,2023:56:661. doi:10.1007/s10462-023-10535-y.
12. Xia Z, Wang Q. The emergence of AI tools in scientific writing and research. Biomater Transl,2023:4:1-2. doi:10.12336/biomatertransl.2023.01.001.
13. Greener JG, Kandathil SM, Moffat L, Jones DT. A guide to machine learning for biologists. Nat Rev Mol Cell Biol,2022:23:40-55. doi:10.1038/s41580-021-00407-0.
14. Hao H, Xue Y, Wu Y, Wang C, Chen Y, Wang X, *et al*. A paradigm for high-throughput screening of cell-selective surfaces coupling orthogonal gradients and machine learning-based cell recognition. Bioact Mater,2023:28:1-11. doi: 10.1016/j.bioactmat.2023.04.022.

15. Hamet P, Tremblay J. Artificial intelligence in medicine. Metabolism,2017:69S:S36-S40. doi: 10.1016/j.metabol.2017.01.011.
16. Reker D, Rybakova Y, Kirtane AR, Cao R, Yang JW, Navamajiti N, *et al*. Computationally guided high-throughput design of self-assembling drug nanoparticles. Nat Nanotech,2021:16:725. doi:10.1038/s41565-021-00870-y.
17. Suwardi A, Wang F, Xue K, Han MY, Teo P, Wang P, *et al*. Machine learning-driven biomaterials evolution. Adv Mater,2022:34:2102703. doi:10.1002/adma.202102703.
18. Yasin S, Pengfei D, Peshala TG, Nashaita P, Vipuil K, Hozhabr M, *et al*. Finite element-based machine learning model for predicting the mechanical properties of composite hydrogels. Appl Sci,2022:12:10835. doi:10.3390/app122110835.
19. Boztepe C, Kunkul A, Yuceer M. Application of artificial intelligence in modeling of the doxorubicin release behavior of pH and temperature responsive poly(NIPAAm-co-AAc)-PEG IPN hydrogel. J Drug Deliv Sci Technol,2020:57:101613. doi: 10.1016/j.jddst.2020.101603.
20. Shuyu W, Zhaojia S. Hydrogel and machine learning for soft robots' sensing and signal processing: a review. J Bionic Eng,2022:20:845.
21. Awasthi S, Gaur JK, Bobji MS, Srivastava C. Nanoparticle-reinforced polyacrylamide hydrogel composites for clinical applications: a review. J Mater Sci,2022:57:8041-8063. doi:10.1007/s10853-022-07146-3.
22. Saraiva MM, Campelo MdS, CamaraNeto JF, Nogueira Lima AB, Silva GdA, de Freitas Figueredo Dias AT, *et al*. Alginate/polyvinyl alcohol films for wound healing: advantages and challenges. J Biomed Mater Res B Appl Biomater,2023:111:220-233. doi:10.1002/jbm.b.35146.
23. Zulkiflee I, Fauzi MB. Gelatin-Polyvinyl alcohol film for tissue engineering: a concise review. Biomedicines,2021:9:979. doi:10.3390/biomedicines9080979.
24. Chen BM, Cheng TL, Roffler SR. Polyethylene glycol immunogenicity: theoretical, clinical, and practical aspects of anti-polyethylene glycol antibodies. ACS Nano,2021:15:14022-14048. doi:10.1021/acsnano.1c05922.
25. D'Souza AA, Shegokar R. Polyethylene glycol (PEG): a versatile polymer for pharmaceutical applications. Expert Opin Drug Deliv,2016:13:1257-1275. doi:10.1080/17425247.2016.1182485.
26. Frent O, Vicas L, Duteanu N, Morgovan C, Jurca T, Pallag A, *et al*. Sodium alginate-natural microencapsulation material of polymeric microparticles. Int J Mol Sci,2022:23:12108. doi:10.3390/ijms232012108.
27. Shaikh MAJ, Alharbi KS, Almalki WH, Imam SS, Albratty M, Meraya AM, *et al*. Sodium alginate-based drug delivery in management of breast cancer. Carbohydr Polym,2022:292:119689. doi: 10.1016/j.carbpol.2022.119689.
28. Yan P, Lan W, Xie J. Modification on sodium alginate for food preservation: a review. Trends Food Sci Tech,2024:143:104217.
29. Sun Y, Yu K, Gao Q, He Y. Projection-based 3D bioprinting for hydrogel scaffold manufacturing. Bio-Design and Manufacturing,2022:5:633-639. doi:10.1007/s42242-022-00189-0.
30. Verhulsel M, Vignes M, Descroix S, Malaquin L, Vignjevic DM, Viovy JL. A review of microfabrication and hydrogel engineering for micro-organs on chips. Biomaterials,2014:35:1816-1832. doi: 10.1016/j.biomaterials.2013.11.021.
31. Dreiss CA. Hydrogel design strategies for drug delivery. Curr Opin Colloid Interface Sci,2020:48:1-17. doi: 10.1016/j.cocis.2020.02.001.
32. Mo F, Jiang K, Zhao D, Wang Y, Song J, Tan W. DNA hydrogel-based gene editing and drug delivery systems. Adv Drug Deliv Rev,2021:168:79-98. doi: 10.1016/j.addr.2020.07.018.
33. Tian B, Liu J. Smart stimuli-responsive chitosan hydrogel for drug delivery: a review. Int J Biol Macromol,2023:235:123902. doi: 10.1016/j.ijbiomac.2023.123902.
34. Iqbal S, Ahmed F, Xiong H. Responsive-DNA hydrogel based intelligent materials: preparation and applications. Chem Eng J,2021:420:130384. doi: 10.1016/j.cej.2021.130384.
35. Nishat ZS, Hossain T, Islam MN, Phan H-P, Wahab MA, Moni MA, *et al*. Hydrogel nanoarchitectonics: an evolving paradigm for ultrasensitive biosensing. Small,2022:18:2107571. doi:10.1002/smll.202107571.
36. Almawash S, Osman SK, Mustafa G, El Hamd MA. Current and future prospective of injectable hydrogels—design challenges and limitations. Pharmaceuticals,2022:5:371. doi:10.3390/ph15030371.
37. Haiyan L, Keerthi Subramanian I, Lei B, Jiali Z, Jiao Jiao L. Advances in the development of granular microporous injectable hydrogels with non-spherical microgels and their applications in tissue regeneration. Adv Health Mater,2023:35:2211597. doi:10.1002/adhm.202301597.
38. Nunez R, Allen M, Gao R, Rigoli CM, Relaford-Doyle J, Semenuks A. What happened to cognitive science. Nat Hum Behav,2019:3:782-791. doi:10.1038/s41562-019-0626-2.
39. Li Z, Song P, Li G, Han Y, Ren X, Bai L, *et al*. AI energized hydrogel design, optimization and application in biomedicine. Materials Today Bio,2024:25:101014.
40. Dwivedi YK, Hughes L, Ismagilova E, Aarts G, Coombs C, Crick T, Duan Y, *et al*. Artificial Intelligence (AI): multidisciplinary perspectives on emerging challenges, opportunities, and agenda for research, practice and policy. Int J Inf Manag,2021:57:101994. doi: 10.1016/j.ijinfomgt.2019.08.002.
41. Haenlein M, Kaplan A. A brief history of artificial intelligence: on the past, present, and future of artificial intelligence. Calif Manag Rev,2019:61:5-14. doi:10.1177/0008125619864925.
42. Miller GA. The cognitive revolution: a historical perspective. Trends Cognit Sci,2003:7:141-144.
43. Kuila C, Maji A, Murmu NC, Kuila T, Srivastava SK. Carbon,2023:210:118075.
44. Davis R, Singh A, Jackson MJ, Coelho RT, Prakash D, Charalambous CP, *et al*. Int J Adv Des Manuf Technol,2022:120:1473-1530.
45. Nandhakumar M, Thangaian DT, Sundaram S, Roy A, Subramanian B. Sci Rep,2022:12:16162.

46. Bovone G, Guzzi EA, Bernhard S, Weber T, Dranseikiene D, Tibbitt MW. Adv Mater,2022:34:2106941.
47. Biondi M, Borzacchiello A, Mayol L, Ambrosio L. Gels,2015:1:162-178.
48. Peng L, Su Y, Yang X, Sui G. J Colloid Interface Sci,2023:638:313-323.
49. Barbero CA. Polymers,2023:15:2240.
50. Thakur S. In: Green-Based Nanocomposite Materials and Applications. Springer, 2023, 295-315.
51. Naderi N, Lalebeigi F, Sadat Z, Eivazzadeh-Keihan R, Maleki A, Mahdavi M. Colloids Surf B,2023:113430.
52. Patil TV, Patel DK, Dutta SD, Ganguly K, Randhawa A, Lim K-T. Appl Sci,2021:11:9550.
53. Belmonte D, Mella CM, Sánchez-Sanhueza G, Opazo-Capurro A, Aguilar-Bolados H, Boury B, *et al*. J Mater Chem B,2023:11:1987-1997.
54. Ghobashy MM, El-Damhougy BK, El-Wahab HA, Madani M, Amin MA, Naser EM, *et al*. Polym Adv Technol,2021:32:514-524.