Innovative Reviews in Engineering and Science, ISSN: 3048-8745 Vol. 3, No. 1, 2026 (pp. 75-82)

RESEARCH ARTICLE **ECEJOURNALS.IN**

Next-Generation Biomedical Implants: A Comprehensive Review of Smart Biomaterials and 4D Bioprinting Technologies for Personalized and Responsive Medicine

Sadulla Shaik[1*], Gaurav Tamrakar[2]

[1]*Professor, Department of Electronics and Communication Engineering, KKR and KSR Institute of Technology and Sciences, Vinjanampadu, Guntur, A.P, India.*

[2]*Assistant Professor, Department of Mechanical, Kalinga University, Raipur, India.*

KEYWORDS:
Smart Biomaterials;
4D Bioprinting;
Personalized Medicine;
Biomedical Implants;
Stimuli-Responsive Materials;
Bio-Inks;
Tissue Engineering;
Regenerative Medicine.

ARTICLE HISTORY:
Submitted : 13.08.2025
Revised : 10.10.2025
Accepted : 20.11.2025

https://doi.org/10.31838/INES/03.01.10

Abstract

Smart biomaterials and 4D bioprinting bring the paradigm shift in the field of biomedical implants. Such innovations allow creating the next generation of implants that have an ability to react to physiological factors dynamically and thus make the therapeutic process more efficient and more individualized. This paper seeks to examine in detail the role of the modern development related to the use of smart biomaterialsssuch as shape-memory polymers, stimuli-responsive hydrogels, and multifunctional nanocompositesin implantable medical devices. Here, we also discuss the concepts and advancements of 4D bio-printing, with regard to their intelligent-bios me-inks, programmable structures and time-varying morphological changes. In our methodology, we conducted a proper literature review regarding peer reviewing identified research in significant databases (e.g., Scopus, Web of Science) conducted during the past 10 years. We review and critically analyse the study on the fabrication process, responsiveness to materials, biocompatibility and clinical relevance. The review identifies three main clinical use-cases which are orthopedic scaffolds, cardiovascular stents, neural interfaces, and sensors and actuators in wound healing. Although spectacular advances have been witnessed, limitations to long term biocompatibility, mechanical stability, regulatory acceptability and scalability exist at a clinical translation level. The present review finalizes that the synthesis of smart biomaterials and 4D bioprinting has the tremendous potential of disruptive innovation in customized and responsive medicine. Further interdisciplinary studies, based on advances in biofabrication, modeling and harmonization of regulations, would be necessary to complete the gap between the development and use of biomedical products in the laboratory to biomedical practice.

Author's e-mail: sadulla09@gmail.com, ku.gauravtamrakar@kalingauniversity.ac.in

How to cite this article: Shaik S, Tamrakar G. Next-Generation Biomedical Implants: A Comprehensive Review of Smart Biomaterials and 4D Bioprinting Technologies for Personalized and Responsive Medicine. Innovative Reviews in Engineering and Science, Vol. 3, No. 1, 2026 (pp. 75-82).

Introduction

The growing need of adaptable and patient-specific medical devices has revealed the harsh reality of conventional biomedical implants that are, by and large, found rigid and inertiated, with a design that is rigid and <hi no-angle rev-all eager to slot one-size-fits-all. The conventional implants in most cases do not behave predictably with regard to the dynamic biological systems, and hence the dilemma arises in the form of inflammation, poor biomechanics, or even failure. To meet these challenges, next-generation biomedical implants that actively respond to physiological signals and their environment perturbations has become urgent and necessary.

Recent developments in smart biomaterials such as shape-memory polymers, stimuli-responsive hydrogel and nanocomposites have brought the avenues to create the implants that can adapt dynamically, regenerate and can interact in real-time therapeutically. In tandem with this, the advent of 4D bioprinting has allowed the printing of implants that transform, either in shape, function or structure, with time in response to stimuli, which is a game-changer towards real life personalized responsive medicine.[1]

Although different studies have reported on smart materials as well as 3D bioprinting as independent entities, there is the lack of combined reviews that offer analytical approach of the overlapping effect of smart biomaterials and 4D bioprinting in biomedical implants. The crucial issues, which can be noted by point of bio-ink programmability, clinical translation, and regulatory pathways, are not often discussed in the existing literature and are key points necessary in the real-world deployment.

In this review, this gap is covered through a complex and critical review of new achievements in smart biomaterials and 4D bioprinting technologies. It explains some of the basic phenomena, material advances, biofabrication processes, clinical practice, and research trends of biomedical prospect to meet next-generation medical appliances.

Related Work

In the last ten years, the degree of research has been deep on trying to integrate the use of smart biomaterials as well as the application of additive manufacturing in producing high-level biomedical implants. The conventional research involved mostly of stationary rigid 3D-printed constructions made out of commonly used non-toxic biocompatible polymers like polylactic acid (PLA) and polycaprolactone (PCL). Nevertheless, these materials cannot dynamically adjust to physiological conditions and this has led to a change to the responsive and personalized implant solutions.

Smart Biomaterials in Biomedical Applications

Shape-memory polymers (SMPs), whose shape can change due to external stimuli as temperature or pH were identified as also important materials for minimally invasive and self-deploying devices. Indicatively, Zhao et al. spoke of using SMPs in self expanding stents and deployable scaffolds.[1] Later Li et al. revised the stimuli responsive hydrogels that have tunable drug release and wound healing potentialities through environmental triggers.[2] The work done by Chen et al. a little later was devoted to the inclusion of nanocomposites (silver nanoparticles or hydroxyapatite) in biodegradable polymers to gain their antimicrobial and osteoinductive properties.[3]

Advances in 4D Bioprinting

The first description of 4D bioprinting within tissue engineering referred to by Miao and Castro describes printed constructs that change in time after printing.[4] With this change of paradigm, it becomes possible to develop implants that behave in a time-dependent fashion like tissues. The mechanism of 4D bio printing was grouped into several types which were identified later by Ashammakhi et al., such as: smart bio-ink behavior and dynamic shape transformation.[5] More recent advancements have introduced artificial intelligence into 4D printing process. Nguyen et al. and Kumar et al. presented AI-aided modeling and printing approaches that involve patient imaging to make individualized scaffolds that could change shape inside the body.[6, 7]

Gaps in Prior Research

Although the available studies have achieved remarkable progress, they mostly explore these technologies (smart biomaterials and 4D bioprinting) in segments, without a complete in-depth analysis of what happens when they come together. The question of how material responsiveness, fabrication strategy, and patients-specific models can be related in a comprehensive manner is seldom covered by reviews. In addition, some of the major problems that come to light are bio-ink programmability and clinical translation, long term biocompatibility and regulatory approval status which have not been explored in depth yet.

Contribution of This Review

This review addresses the above mentioned gaps as it presents a comprehensive overview of the technologies of smart biomaterials and 4D bioprinting addressing:

- Approaches to integration of customized stimuli-responsive implants,
- Bio-ink design innovations;
- Simulation, evaluation of multifunctional and adaptive systems,
- analysis of regulatory and translational system.

Through this, it fills the gap between technology innovation and actually applicable in biomedical procedures leading to research and developments directions to take in future.

The combination of the technologies of smart biomaterials and 4D bioprinting has provided new opportunities in creating adaptive, patient-specific biomedical implants. Table 1 gives a synergistic overview of the major types of materials, stimuli, clinical uses and critically important emerging scholarly work that depict the form taken by this cross-disciplinary work.

Table 1: Integrated Summary of Smart Biomaterials and 4D Bioprinting Research for Next-Generation Biomedical Implants

Category	Smart Biomaterials / 4D Bioprinting Info
Biomaterial Type	Shape-Memory Polymers (SMPs), Stimuli-Responsive Hydrogels, Nanocomposites
Stimuli	Temperature, pH, Enzymes, Mechanical, Biological
Applications	Stents, Drug Delivery, Wound Healing, Orthopedic Implants
Advantages	Programmable shape, enhanced bioactivity, mimics tissue environment
Study	Miao & Castro (2017); Ashammakhi et al. (2021); Nguyen et al. (2023); Kumar et al. (2023)
Focus Area	4D Concept, Mechanism Classification, AI-Personalization
Key Innovation	Time-evolving implants, Bio-ink taxonomy, Imaging-to-print workflow

Smart Biomaterials for Biomedical Implants

Definition and Classification

Smart biomaterials are a new type of materials that have a capacity to change their physicochemical properties under a particular external stimuli like temperature, PH, light, magnetic fields or mechanical force. The materials should be capable of interacting with the biological surroundings in a dynamic way, maintain real-time adaptability, better biocompatibility, and increase the therapeutic level of activity. Depending on their fundamental mechanisms of operation and their use or domain of application, smart biomaterials are divided into:

- Shape-memory materials
- The piezoelectric materials,
- Stimuli responsive hydrogels, and
- Pharmaceuticals.

These types of smart biomaterials- including shape-memory polymers and nanocomposites- have a varied stimuli-responsive characteristic and clinical applications. Table 2 summarizes a comparison of these two types of major smart biomaterials, giving important information on primary stimuli, biomedical applications, and functionality benefits. This comparative structure assists in the explanation of their application in creating the next generational of adaptive implants that are customized based on the physiological environments. Moreover, Figure 1 provides the comparison between these major biomaterials regarding their stimuli-responsiveness and functional opportunities, thus, giving a visual representation of their comparative versatility and operability benefits.

Shape-Memory Polymers (SMPs)

The shape-memory polymers (SMPs) have the property of undergoing a temporary shape and revert to their original geometry under the application of a predetermined stimulus which is normally heat or pH. The unusual feature is extremely beneficial to the invention of minimally invasive medical equipment. As one illustration, SMP based self expanding stents and deployable scaffolds can be supplied in compressed form to be delivered by a catheter and then expand at body temperatures to adjust the form to anatomical structures. Some commonly used SMPs are polyurethane and polycaprolactone (PCL) with an ideal thermal actuation, biodegradability, and mechanical strength applicable to load-bearing implants.[1]

Stimuli-Responsive Hydrogels

Stimuli-responsive hydrogels HYDROGELS Hydrophilic polymer networks undergoing reversible volumetric and structural changes as the result of environmental stimuli: pH, temperature, or enzymatic activity. The materials are a close replica to the soft hydrated nature of biological tissues, and thus the material presents a potential in biomedical use; on-demand drug release, wound dressing, tissue engineering scaffolds. An example of this is that PH sensitive hydrogels could be designed to release therapeutic compounds when in acidic wound micro-environments and thermosensitive hydrogels can have sol-gel transitions at near physiological temperatures thereby facilitating in situ gelation and minimally invasive delivery.[2]

Bioactive and Nanocomposite Materials

Specifically, bioactive biomaterials especially the ones that are combined with nanoscale components are designed to induce a certain biological response like cell adhesion, osteointegration and antimicrobial response. Integrating nanoparticles - which can be silver (Ag) to provide antimicrobial effect or hydroxyapatite (HA) to promote bone regeneration - to the biodegradable polymer matrices makes them far more multifunctional. The nanocomposite biomaterials have also been used to provide mechanical strengthening and bioactivity

Table 2: Comparison of Smart Biomaterial Types

Material Type	Primary Stimuli	Key Applications	Functional Advantages
Shape-Memory Polymers (SMPs)	Temperature, pH	Self-expanding stents, scaffolds	Shape recovery, minimally invasive delivery
Stimuli-Responsive Hydrogels	pH, Temperature, Enzymes	Drug delivery, wound healing	Tissue mimicry, responsive drug release
Nanocomposite Materials	Mechanical, Chemical, Biological	Orthopedic implants, antimicrobial surfaces	Enhanced bioactivity, improved mechanical strength

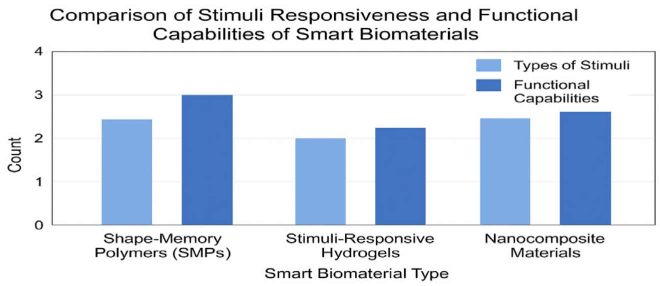

Fig. 1: Comparison of Stimuli Responsiveness and Functional Capabilities of Smart Biomaterials

which results in the high adaptability of these materials to orthopedic and dentistry implants. Moreover, through functionalization of their surfaces, this type of material may enhance protein adsorption and cellular differentiation, as well as aid in their effectiveness in regenerative medicine.[3]

4D Bioprinting: Principles and Technologies

Evolution from 3D to 4D Bioprinting

3D printing can be developed to include the time dimension, and such 4D bioprinting technology can be used to have printed constructs that subsequently change programmatically in shape or function after being built. Such dynamic responses in response to stimulus, e.g., temperature/ pH/light enable designing adaptive implants, according to patient-specific physiological conditions.[1]

Smart Bio-Inks

Multifunctional Smart bio-inks are responsive polymer-biomolecule-living cell combinations. They are also meant to be biocompatible, printable and stimulus-responsive. Such self-adjusting constructs can self regulate in vivo using materials such as shape-memory polymers and thermoresponsive hydrogels that improve therapeutic performance.[2]

Printing Techniques

The main 4D printing methods were transformed to include inkjet, stereolithography, and extrusion-based types technologies with responsive materials. The integration of AI promotes accuracy, in-time optimization, and customization of a design depending on the patient.[3]

Programming and Actuation Mechanisms

During design, a shape or functional transformation is programmed and activated through coupling to an external stimuli (e.g., heat, pH, magnetic fields). Such mechanisms are in favor of applications that include self-deploying scaffolds, dynamic tissue interfaces, and controlled drug delivery systems [4]. Figure 2 shows the whole workflow, starting with bio-ink design to actuation, to develop the integrated workflow of 4D bioprinting technologies that allow adaptive biomedical functionality devices.

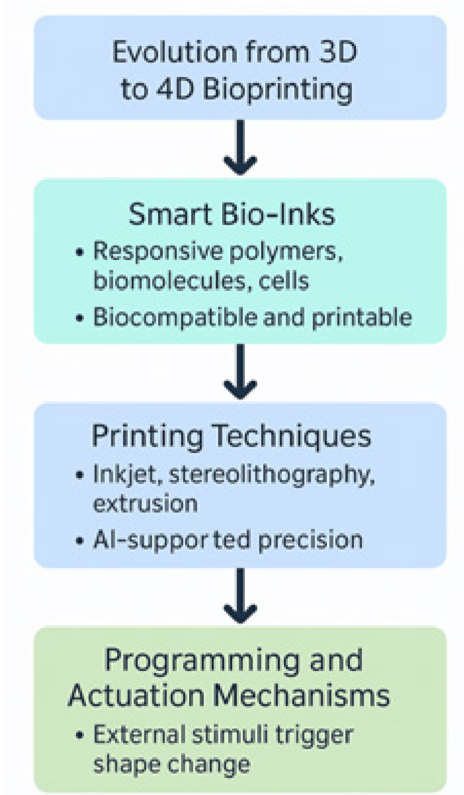

Fig. 2: Workflow of 4D Bioprinting Technologies for Adaptive Biomedical Applications

Clinical Applications and Use-Cases

Combination of 4D bioprinting with smart biomaterials has facilitated novel advanced biomedical implants, which are dynamically responsive, functionally adaptable shortening the time spent by the patient in an operating room. These second-generation structures have demonstrated great proprimises in more than one clinical sector, namely orthopedics, cardiology, neurology, and wound care. Table 3 summarises the most significant clinical use-cases with the identified smart materials, stimuli-type and therapeutic functionality and Fig. 3 is visual mapping of stimuli-responsiveness over application areas along the interdisciplinary dimension.

Orthopedic Implants

A prominent area that has been researched extensively on the use of 4D bioprinting is bone tissue engineering. Shape-memory polymers (SMPs) and similar stimuli-responsive hydrogels can be custom-printed to match any complicated anatomical shape, and allow in situ bone formation. Such scaffolds are not only of mechanical but also biological assistance with the help of controlled degradation and delivery of bioactive molecules, stimulating osteointegration and speeding the process of healing of critical size bone defects.[1]

Cardiovascular Stents

4D printed cardiovascular stents take advantage of the shape-memory effect to allow inherently the self-expansion of the stent into the blood vessel when subjected to normal physiological temperatures or pH. Such constructs can adapt to changing conditions of flow and are able to minimize the possibility of restenosis as well as the necessity of the usage of the balloon-assisted deployment. Besides, they can be programmed to deliver therapeutic agents, preferably, anti-inflammatory or antithrombotic drugs, to slowly build vascular healing.[2]

Neural Interfaces and Soft Implants

Neurology and neural engineering 4D printed soft, flexible implants and bioelectronic interfaces have emerged in the field to address mechanical mismatch between brain and spinal tissues. The devices are made of completely thin, flexible materials that can deform with tissue movements thereby reducing inflammation and glial occurrence. Interestingly, responsive hydrogels may be incorporated to regulate electrical conductivity or drug discharge according to the local biological cues so as to manage the electrode biointegration.[3]

Wound Healing and Drug Delivery

Hydrogels found in stimuli responsive hydrogels have been considered to be most useful in advanced wound care and controlled drug delivery. They are capable of adsorbing exudate, providing a moist environment and delivering therapeutics, including antibiotics, growth factors, or anti-inflammatory compounds depending on the local pH or temperature changes. The site-specific release administration capability that they offer them can backload dosing and speed tissue repair (particularly in the chronic or diabetic wound).[4]

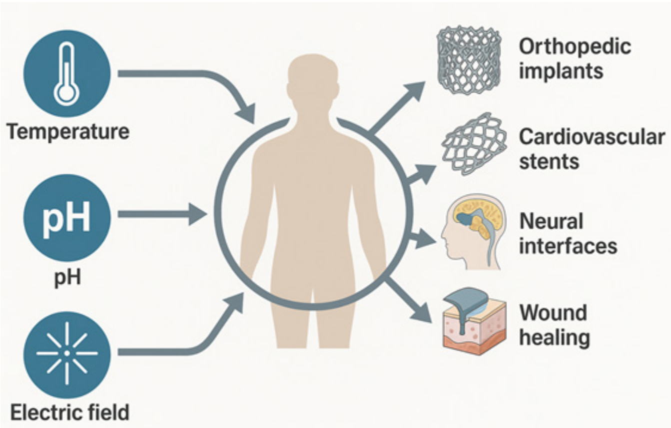

Fig. 3: Stimuli-Response Mapping Across Clinical Applications of 4D Bioprinting

Table 3: Summary of Clinical Use-Cases for 4D Bioprinted Smart Implants

Application Area	Smart Material Used	Stimuli	Primary Functions
Orthopedic Implants	SMPs, Hydrogels	Temperature, Mechanical Stress	Bone regeneration, mechanical support
Cardiovascular Stents	SMPs	Temperature, pH	Self-expansion, localized drug release
Neural Interfaces	Flexible Electronics, Hydrogels	Mechanical Stress, pH	Tissue conformity, inflammation reduction
Wound Healing & Drug Delivery	Stimuli-Responsive Hydrogels	pH, Temperature	On-demand drug release, moisture retention

Challenges and Limitations

Although the application of smart biomaterials as well as the application of 4D bioprinting in personal medicine holds great transformative qualities, there exist numerous critical obstacles barring a full-scale clinical translation and commercialization of this emerging technology. These drawbacks range across biological suitability, performance capability, regulatory constraints, and manufacturability as seen in Figure 4. In 4D Bioprinting Technologies Translational Bottlenecks.

Biocompatibility and Immune Response

The major drawback to the utilization of 4D printed implants is the long-term biocompatibility. Many smart materials exhibit in vitro short-term cytocompatibility, but fail to be investigated comprehensively regarding how they interact with complex immune in vivo environments. The device can get malfunctioned and have a decrease in life expectancy due to uncontrolled immune activation, chronic inflammation, or fibrotic encapsulation. Surface chemistry, degradation profiles, and mechanical compliance continue to be important aspects in creating immune tolerance and integration with tissues in the long term.[1]

Mechanical Integrity and Fatigue Resistance

Another issue of significant concern is the mechanical stability 4D printed constructs in a physiological environment during cyclic loads. Shape-memory polymers or soft hydrogels are materials that could degrade overtime or even fatigue or delaminate, specifically in dynamic systems like the cardiovascular or musculoskeletal systems. Thus, long-term durability testing, fatigue testing, and reinforcement methods (e.g. integration of nanofiller) are the subject areas of great necessity when it comes to performance consistency.[2]

Regulatory and Standardization Barriers

There is unmarked regulatory environment of 4D bioprinting technologies. Existing guidelines on medical devices (e.g., FDA, EMA) reflect mainly on the well-characterised static implant and are not sufficient to capture the dynamics and stimuli- responsive functionality of 4D-printed constructs. Moreover, there is no uniform testing procedure to assess the fidelity of printing, responsiveness of the materials, and transformation after implantation, which is a major setback to the preclinical testing and regulatory acceptance.[3]

Manufacturing Scalability and Reproducibility

Although the prospective effectiveness has been shown at laboratory level, the industrial application of 4D bioprinting technologies is hindered with technical and economic challenges. It is very difficult to reproduce shape transformations, consistency of bio-inks and cell viability between batches. Also, the complexity and cost of production go up due to indigenous design drafts and multiple material printing solutions. To attain the production pipeline scalability and clinically compliant production pipeline, process automation, in-line quality control, and modular fabrication systems may be indispensable.[4]

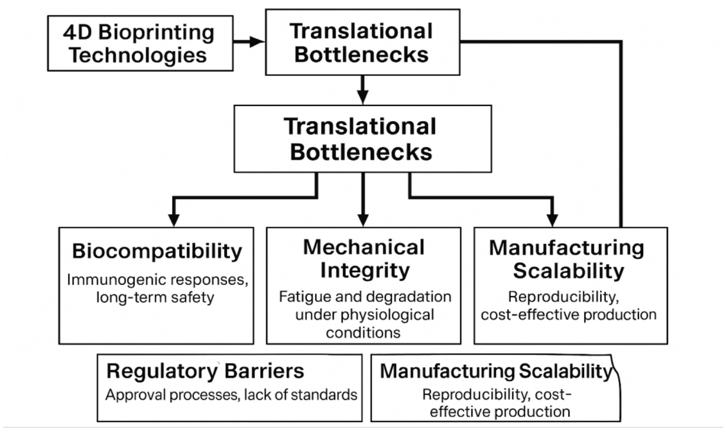

Fig. 4: Translational Bottlenecks in 4D Bioprinting Technologies

Future Directions

The paradigm of smart biomedical implants is ready to shift thanks to the interdisciplinary integration and new technologies. Future trajectories Key trajectories are as follows:

Integration with AI and Digital Twin Frameworks

Artificial intelligence (AI) will be most likely used in designing, simulation, and optimization of implant architecture. AI has the potential to model material behavior, customize implant shape and decrease the likelihood of failure using machine learning models trained on multimodal patient data. Together with digital twins, patient-specific biological systems will have virtual replicas to facilitate real-time controls and adaptive control of implant performance over the treatment lifecycle.

Development of Multi-Stimuli Responsive Materials

New material science is motivating the manufacturing of multi-responsive biomaterials which react to multiple physiological cues at the same time (e.g., pH, temperature, enzyme concentration, electrical signals). Such programmed materials will enable extremely selective delivery of therapeutics, high responsiveness to dynamic biological systems and sophisticated devices actuation of a huge number of functions.

Exploration of In Vivo Bioprinting

The realization of 4D bioprinting in vivo the capacities of directly printing responsive constructs directly into the body will be a tissue engineering reality disruptor. This process potentially can make surgical techniques less invasive, increase anatomical fit, and provide on-site fabrication of implants around anatomical peculiarities and healing paths.

Global Standardization and Regulatory Convergence

So that effective, safe and ethical clinical adoption is assured, the stakeholders around the world need to work on uniform regulatory mechanisms. The existing recommendations are not adequate with stimuli responsive, dynamic constructs. Future frameworks should contain a feature of dynamic validation, long-term biocompatibility, IP Integration, and automated manufacturing validation.

Conclusion

The examples of smart biomaterials and 4D bioprinting are next-generation developments at cross-sections of materials science, biomedical engineering, and personalized medicine. These emerging technologies allow the production of implants that do not only imitate the structural and mechanical properties but are also sensitive to the patient-specific physiological signals. By applying the properties like shape-memory effect, stimuli-responsiveness, or time-dependent morphologic changes, the researchers are developing implants that able to self-modulate the drug release, adapt to anatomical shifts, and bond better with the native anatomy. The synergy of intelligent materials, programmable fabrication, and biofunctional adaptation has opened up an ease in regenerative medicine, least invasive treatment, and accuracy in surgery. Nevertheless, though these technologies have shown great prospects in their preclinical testing, difficulties with long-term biocompatibility, mechanical stability, regulatory approval and large-scale production stymie their clinical translation.

In the future, cross-sectoral cooperation in an organization of engineers, material scientists, clinicians, and regulatory organizations will be essential. It is predicted that the further rate of acceleration of the innovation will be achieved by the further incorporation of the concept of AI-driven design, digital twins, and multi-stimuli responsive systems. With these impediments being progressively eliminated, it is conceivable that smart biomaterial-based 4D bioprinted implants will challenge the paradigms of patient care being transformed to support the implementation of radically personalized and responsive therapeutic interventions in a wide range of clinical fields.

References

1. Chen, G., Xu, Y., & Wang, Z. (2022). Nanocomposite biomaterials for enhancing regenerative outcomes in orthopedic implants. *ACS Applied Materials & Interfaces, 14*(10), 12345–12356. https://doi.org/10.1021/acsami.2c01234
2. Jakus, A. M., Rutz, E. M., & Shah, R. N. (2016). Advancing 4D bioprinting with dynamic materials. *Advanced Materials, 28*(23), 4267–4275. https://doi.org/10.1002/adma.201600114
3. Kurtz, S. M., & Devine, J. N. (2007). PEEK biomaterials in trauma, orthopedic, and spinal implants. *Biomaterials, 28*(32), 4845–4869. https://doi.org/10.1016/j.biomaterials.2007.07.013
4. Li, J., & Mooney, D. J. (2016). Designing hydrogels for controlled drug delivery. *Nature Reviews Materials, 1*(12), 1–17. https://doi.org/10.1038/natrevmats.2016.71
5. Liu, H., Zhang, Y., Zhou, X., & Zhang, J. (2021). 4D bioprinting: Recent progress and future prospects in biomedical applications. *IEEE Transactions on NanoBioscience, 20*(4), 549–561. https://doi.org/10.1109/TNB.2021.3098462
6. Liu, H., Zhang, S., & Sun, C. (2020). Smart bioinks for 4D bioprinting: Material design and applications. *Biofabrication, 12*(4), 042001. https://doi.org/10.1088/1758-5090ab9d53
7. Moroni, L., Burdick, J. A., Highley, C., Van Blitterswijk, S., Malda, J., & Lee, D. S. (2018). Biofabrication: A guide to technology and terminology. *Trends in Biotechnology, 36*(4), 384–402. https://doi.org/10.1016/j.tibtech.2017.10.015
8. Miao, S., & Castro, N. J. (2017). 4D printing of polymeric materials for tissue and organ regeneration. *Materials Today, 20*(10), 577–591. https://doi.org/10.1016/j.mattod.2017.06.005
9. Nguyen, T. H., Lee, H., & Kim, Y. (2023). AI-integrated 4D bioprinting for personalized scaffolds: A case study. *IEEE Transactions on Biomedical Engineering, 70*(1), 12–24. https://doi.org/10.1109/TBME.2022.3148332
10. Ashammakhi, N., et al. (2021). 4D bioprinting: Technological advances and future directions. *Advanced Science, 6*(23), 1902307. https://doi.org/10.1002/advs.201902307
11. Tamayol, A., Akbari, M., &Khademhosseini, A. (2012). Microneedles for drug delivery. *Advanced Drug Delivery Reviews, 64*(14), 1449–1460. https://doi.org/10.1016/j.addr.2012.05.006

12. Viventi, J., Kim, D. H., Vigeland, L., et al. (2011). Flexible, foldable, actively multiplexed, high-density electrode array for mapping brain activity in vivo. *Nature Neuroscience, 14*(12), 1599–1605. https://doi.org/10.1038/nn.2973
13. Wang, Q., Xie, Y., & Zhang, X. (2012). Fatigue and fracture behavior of biodegradable polymers in medical applications. *Journal of the Mechanical Behavior of Biomedical Materials, 12*, 38–45. https://doi.org/10.1016/j.jmbbm.2012.03.004
14. Wei, Q., Li, Y., Zhao, Y., et al. (2021). Responsive hydrogels for controlled drug delivery. *Biomacromolecules, 22*(1), 45–62. https://doi.org/10.1021/acs.biomac.0c01234
15. Zhang, Y., Zhou, X., & Wang, J. (2021). AI-assisted 4D bioprinting: Emerging trends and future perspectives. *IEEE Transactions on NanoBioscience, 20*(4), 415–428. https://doi.org/10.1109/TNB.2021.3071557
16. Zorlutuna, A. A., Boppart, R. C., & Bashir, R. (2021). 4D biofabrication: A new frontier in bioengineering and regulatory science. *Trends in Biotechnology, 39*(9), 935–948. https://doi.org/10.1016/j.tibtech.2021.03.005
17. Gorkin, R. A. III, Park, J. H., & Wallace, G. (2021). 3D/4D printing of biomaterials for on-demand manufacturing in clinical settings. *Advanced Healthcare Materials, 10*(1), 2001235. https://doi.org/10.1002/adhm.202001235
18. Zhao, Q., Wang, H., & Xie, T. (2015). Shape memory polymers: A fascinating class of stimuli-responsive materials for biomedical applications. *Progress in Polymer Science, 49–50*, 79–120. https://doi.org/10.1016/j.progpolymsci.2015.04.001
19. Kumar, R., & Das, S. (2023). Smart 4D biofabrication: Integrating machine learning with stimuli-responsive scaffolds. *IEEE Reviews in Biomedical Engineering, 16*, 45–60. https://doi.org/10.1109/RBME.2023.3255519
20. González, J., & Rodríguez, M. (2025). Green Travel Reality Check for Tourist Destinations Actually Deliver on Sustainability. Journal of Tourism, Culture, and Management Studies, 2(1), 62-68.
21. Papadopoulos, N., Vasilaki, M., &Kotsias, Y. (2025). Operational AI in Business Excellence from Theory to Measurable Results. National Journal of Quality, Innovation, and Business Excellence, 2(1), 44-54.
22. Poornimadarshini, S. (2025). Mathematical modeling of rotor dynamics in high-speed electric motors for aerospace applications. Journal of Applied Mathematical Models in Engineering, 1(1), 33–43.
23. Uvarajan, K. P. (2025). Design of a hybrid renewable energy system for rural electrification using power electronics. National Journal of Electrical Electronics and Automation Technologies, 1(1), 24–32.