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Review Article

3D Bioprinting in Organ Regeneration and Tissue Engineering: Current Status, Challenges and Future Prospects

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ABSTRACT

Organ failure remains a critical challenge in modern medicine, affecting millions of lives worldwide. Conditions such as kidney failure, heart disease, and congenital abnormalities continue to place a heavy burden on healthcare systems, with a growing number of patients on organ transplant waiting lists. Despite efforts to expand donor pools and improve organ preservation, the shortage of available organs persists. Recent advances in bioengineering, particularly three dimensional (3D) bioprinting, offer a promising alternative to traditional transplantation. 3D bioprinting, also known as additive manufacturing, involves the layer-by-layer deposition of bioinks—materials containing living cells to construct tissue-like structures. This technology utilizes a variety of materials, including polymers, ceramics, and metals, and offers advantages such as precision, automation, and customization. While the ultimate goal is to bioprint fully functional organs, current applications focus on simpler tissues like skin, bone, and cartilage. The success of 3D bioprinting depends heavily on the properties of the bioinks used, which must be biocompatible, printable, and capable of supporting cell survival and growth. Furthermore, selecting the appropriate cell types is crucial for achieving proper tissue development and function. As a tool within regenerative medicine, 3D bioprinting enhances the design and fabrication of patient-specific tissue constructs and scaffolds that closely mimic natural tissue architecture. This review provides a comprehensive overview of the current progress in 3D bioprinting, its potential clinical applications, and the key challenges that must be addressed to enable its wider integration into clinical practice. It also outlines future research directions to advance this transformative technology in healthcare.

INTRODUCTION

Organs in the human body are intricate structures composed of various tissue types that are functionally organized. The cells within these

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organs are highly specialized and work collectively to carry out distinct physiological functions.[1] Millions of lives are impacted by tissue and organ failure, which continues to be a major problem in contemporary healthcare. Conditions such as kidney failure, coronary artery disease, biliary atresia, bone tumors, and congenital deformities like microtia continue to pose significant clinical burdens. The prevalence of acute kidney injury, heart failure, and chronic pancreatic disorders is steadily increasing.[2] An estimated half a million people worldwide are on the waiting list for an organ transplant, and because organs are inaccessible, the failure of a key organ raises mortality rates. 25 distinct organs or tissues can be donated by a living or deceased donor, potentially saving as many lives as possible [3-5]. It is possible to donate organs including the kidney, liver, pancreas, lungs, heart, eyes, skin, bone, bone marrow, nerves, brain, heart valves, eardrum, ear bones, and blood [6-9] Significant efforts have been undertaken to address the persistent shortage of organ donors, including the utilization of marginal donors and advancements in organ preservation strategies. Recent advancements in bioengineering technology have led to the introduction of three-dimensional (3D) printing technology into the area of organ transplantation, which has created a new avenue for research to address the donor shortage.[10] 3D Bioprinting sometimes also known as additive manufacturing involves the layer by-layer deposition of bioinks (materials containing living cells) to fabricate complex, tissue-like structures by using several materials like ceramics, metals and polymers in the fabrication process of complex structures [11] Compared to traditional tissue engineering techniques, 3D bioprinting offers many advantages, such as automation, high precision, and easy customization for specific applications.[12] Recent developments in 3D bioprinting have been aimed at the long-term goal of printing entire organs. However, current research is also focused on more immediate applications by printing smaller, simpler tissues such as skin grafts, cartilage, and bone.[13]Tissue engineering is an application of regenerative medicine that aims to use in vitro and in situ methods to regenerate specific tissues and restore normal biological functionality.[14] With the advancement of 3D bioprinting, tissue engineers can now design and create precise, patient-specific tissue constructs and scaffolds. This technology allows for accurate control over the shape and size of scaffolds, enabling the creation of structures that closely mimic the complex architecture of natural tissues.[15] 3D bioprinting uses different methods, each with its own advantages. The choice of method depends on what is being printed and the type of bioink used. *Bioink* is a material that contains living cells and is used to create tissues or organs . Good bioinks should be easy to print, safe for cells, and strong enough to hold their shape. They should also support cell survival by acting like the natural environment of the body, providing nutrients and oxygen. The type of cells used is also very important, as different cells grow and behave in different ways . Choosing the right cells helps them survive the printing process and grow into the right tissue more quickly.[16] This review aims to give a thorough overview of recent developments in 3D bioprinting, explore its potential use in clinical settings, and highlight the challenges that limit its broader adoption in medicine. By examining these key issues and suggesting future research paths, the review hopes to support ongoing efforts to overcome existing barriers and promote the successful use of 3D bioprinting in healthcare.

Bioprinting Techniques:

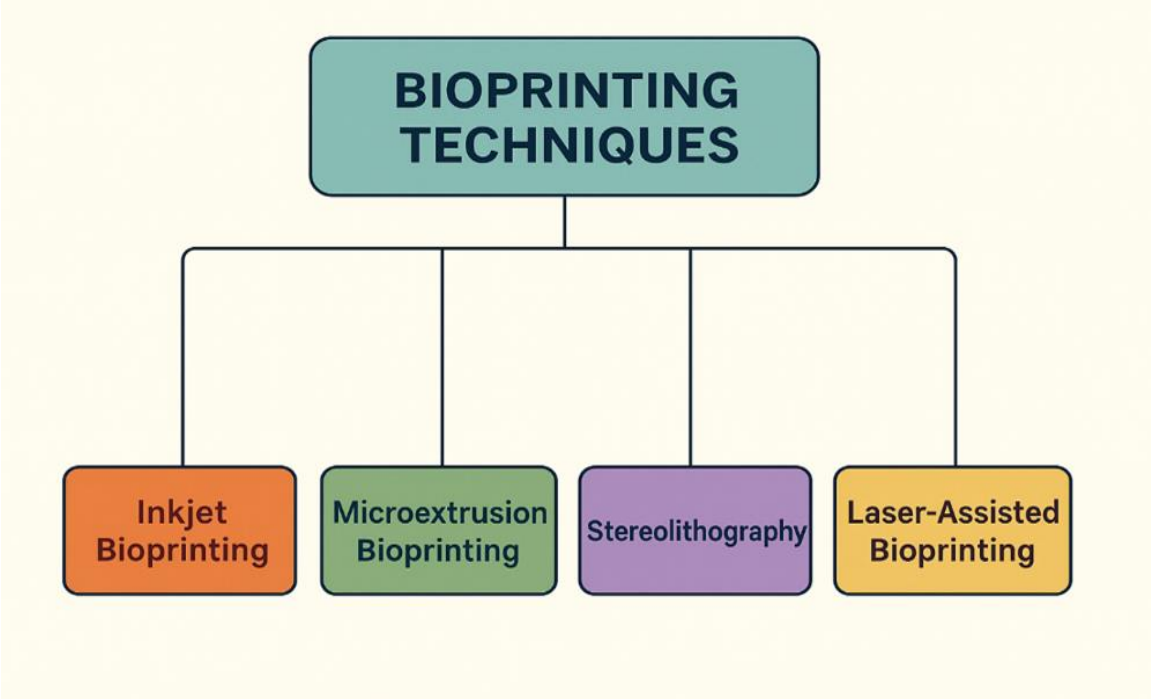

Fig 1: Bioprinting Techniques

- **Inkjet-Based Bioprinting-**

Inkjet bioprinting has become a prominent and innovative technique in the field of tissue engineering and regenerative medicine [17]. By adapting the principles of traditional inkjet printing, it allows for the precise, layer-by-layer deposition of bioinks containing living cells, biomolecules, and biomaterials. This controlled process supports the fabrication of complex three-dimensional (3D) tissue structures with high spatial accuracy and biological functionality [18–19]. Inkjet-based bioprinting functions similarly to conventional inkjet printing, but instead of ink, it utilizes bioinks that contain living cells. In this technique, tiny droplets of bioink are precisely deposited onto a substrate to build up a desired 3D structure. As a non-contact method, it relies on pressure pulses to form and eject discrete droplets, placing them accurately onto the target surface under computer control to enable interactions between the droplets and the substrate.These pressure pulses are generated by various actuator mechanisms—such as thermal, piezoelectric, or electrostatic—that overcome the surface tension of the bioink, enabling droplet ejection. In thermal inkjet systems, a brief heating pulse creates a vapor bubble that forces droplets out of the nozzle. Conversely, piezoelectric inkjet bioprinters use voltage-induced deformations in the printhead to push out droplets by momentarily compressing the bioink chamber. By adjusting the voltage, users can control droplet size and shape. Key factors influencing droplet size and dispensing rate include the physical properties of the bioink (e.g., viscosity and surface tension), the diameter of the nozzle, and the actuation frequency. Inkjet bioprinting is known for its high speed and resolution, making it well-suited for producing detailed structures with high cell densities. However, it faces challenges when working with highly viscous bioinks and maintaining cell viability throughout the printing process.[20]

- **Extrusion-Based Bioprinting-**

Extrusion-based bioprinting also known as direct ink writing, is currently the most commonly used

3D bioprinting method due to its flexibility and cost-effectiveness.[21] They can be classified in one of two categories: either pneumatically driven using compressed air to drive a syringe and nozzle, or mechanically driven by a motor or linear piston. [22,23]. Unlike inkjet printing, which dispenses individual droplets, this technique extrudes continuous filaments using steady pressure. It is capable of handling bioinks with a wide range of viscosities and varying cell densities, making it a preferred method for fabricating tissue structures with adequate mechanical strength. Additionally, extrusion-based bioprinting is well-suited for applications involving coaxial and multi-material printing, further expanding its versatility in tissue engineering.

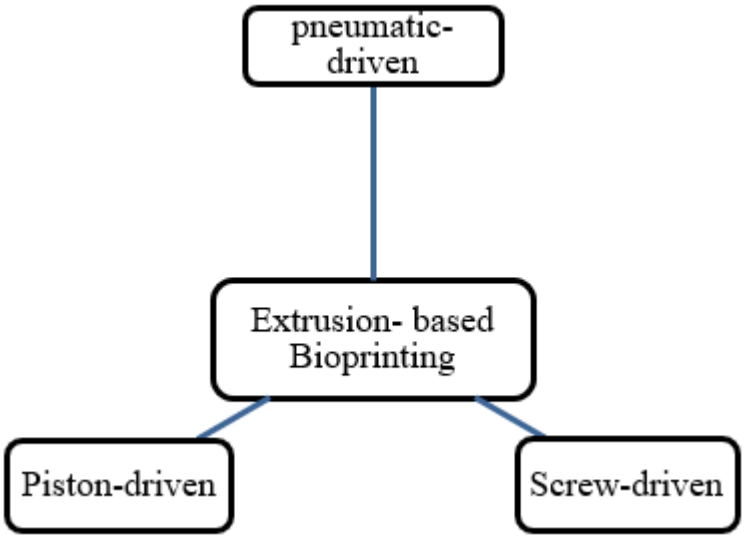

Fig.2 Types of Extrusion-Based Bioprinting

Principle -

Extrusion-based bioprinting works by pushing bioink through a nozzle—usually from a syringe—using mechanical or pneumatic force to create continuous filaments that are layered into 3D structures. The substrate can be solid, liquid, or gel-like, and the nozzle follows a path generated by software from digital models. Based on the extrusion mechanism, systems are typically classified as pneumatic, piston, or screw-driven.[21] Rapid construction of huge and complicated structures is made possible by this technology's broad range of material applicability and straightforward hardware structure [24,25]. Controlling the nozzle size, extrusion speed, pressure, and the 3D platform's movement to modify printing resolution can result in customized 3D structure printing [26,27]. The shear stress that cells experience during extrusion via the nozzle is the primary cause of cell damage and/or death, even though extrusion bioprinting can support large cell densities for printing [28]

- **Laser Assisted Bioprinting-**

Laser-assisted bioprinting (LAB) employs a laser as an energy source to accurately deposit biomaterials onto a substrate. This method typically consists of three main elements: a receptive substrate, a ribbon coated with liquid biological materials placed on a metallic layer, and a pulsed laser source that enables controlled deposition [29]. The printing device is non-contact [30]. It consists of two glass slides that are horizontally co-planar. The upper slide is called

the "Donor slide," whereas the bottom slide is called the "Collector slide." Two distinct laser-absorbing materials—a cell layer or biological substance and a light-absorbing gold layer—are applied to upper donor slide. Through top portion of donor slide, the laser is directed into the locally evaporated absorbent gold layer. To avoid dehydration, the collector slide offers the bio-ink (often a cell-embedded solution) an appropriate environment [31,32]. Laser-assisted bioprinting originated from techniques used to deposit metals onto receiver substrates. Later, Odde and Renn adapted this approach to successfully print living embryonic chick spinal cord cells. LAB involves three key components: a donor slide (also known as a ribbon), a laser pulse, and a receiver slide. The ribbon consists of a transparent glass layer, a thin metal film, and a layer of bioink. When a laser pulse is directed at the metal layer, it causes localized vaporization, generating a high-pressure bubble that propels the bioink from the ribbon onto the receiver slide. This process, illustrated in Figure 4, allows for precise deposition of bioink without physical contact, making it a scaffold-free technique. LAB is noted for achieving very high cell viability rates often exceeding 95% and offers fine spatial resolution in the range of 10–50 μm. Some research has even shown that LAB can accurately deposit individual cells in separate droplets, demonstrating its exceptional precision and control [33]. LAB offers distinct advantages over other bioprinting technologies, such as a nozzle-free, non-contact process, the ability to print cells with high activity and high resolution, and the ability to precisely manipulate ink droplets and delivery characteristics. Shear stress, laser pulse energy, and ink bubble dynamics are all significant factors in the bioprinting process [34–36]. Even though there are many different biomaterials that can be used, many technical obstacles still need to be overcome. UV light used in SL, for instance, aims to polymerize layers in a particular 2D pattern. Therefore, the mechanism of layer-by-layer deposition caused by the laser motivating cross-linking exclusively in the focused zone is resulting in an anisotropic 3D structure [37] The restricted number of photosensitive polymers and the cytotoxic effect of photoinitiators are two drawbacks of this approach, despite the fact that it garners respectable interest from researchers and industry [38].

- **Stereolithography Bioprinting-**

In the 19th century, a high-resolution printing technique was introduced based on the polymerization of highly photosensitive polymers. This method, known as stereolithography (SL), relies on a UV laser beam directed by a mirror array to selectively cure (solidify) a liquid photocurable resin. The process is repeated layer by layer along the Z-axis to create a full 3D structure. However, a major limitation of traditional SL is the use of UV light, which can be harmful to living cells and is also associated with health risks such as skin cancer. To address this issue, visible light-based stereolithography has emerged as a promising alternative. Wang et al. reported on this development, and ongoing research focuses on optimizing and stabilizing the printed structures for bioprinting application. As shown schematically in Figure 7, stereolithography bioprinting enables the fabrication of 3D scaffolds with improved resolution and structural integrity compared to conventional methods, which often produce weak, porous networks. In SL bioprinting, structures are built layer-by-layer using bioinks that are sensitive to specific light wavelengths, allowing precise control over the geometry and mechanical properties of the printed constructs.[39] A projection stereolithography (PSL) platform was suggested in a new study to create 3D tissue

scaffolds using computer-aided design [40]. Different GelMA concentrations and topologies were used to regulate the scaffolds' mechanical characteristics. HUVECs were used to seed complex porous structures, which were then examined in vitro. It has been demonstrated that carefully constructed scaffolds with interconnected pores promote cell development, leading to large cell densities. In another work, Melchels et al. used stereolithography to create porous structures using a resin that contained a 2-armed poly(D,L-lactide), ethyl lactate, dye, photoinitiator, and inhibitor [41]. Supporting structures that fasten to the elevator platform are necessary for stereolithography in order to stop deflection from gravity, withstand lateral pressure from the resin-filled blade, or hold onto freshly formed parts during the "vat rocking" of bottom-up printing. Although they can be built manually, supports are usually generated automatically when CAD models are being prepared. Either way, after printing, the supports need to be physically removed.[42] Other stereolithography techniques use a DLP projector or LCD masking to construct each layer. [43] [44]

Challenges and limitations-

Tissue bioprinting offers multiple advantages, yet before it is widely used, there are numerous hurdles to be addressed. Tissue complexity engineering, post-print tissue maturation and maintenance, standardized and scalable manufacturing, and, for translation, a clear regulatory framework for bioprinted structures are a few of these difficulties. Most bioprinted tissues still lack some functioning components, including lymphatics, the nervous system, vasculature, and several supporting cell types, despite being geometrically complicated on a macroscale [45-56]. As a result, a lot of study has been carried out regarding ways to use microstructures, like creating interconnected networks of channels to resemble blood arteries and encourage vascularization [57,58]. The selection of bioink is a critical factor in bioprinting, as it helps address several key challenges. Bioinks are designed to replicate the complex structure and composition of various tissues and organs. They protect cells during printing and create an environment that supports tissue development and maturation. Choosing the right bioink is essential, as its chemical and physical properties influence cell behaveior , including growth, proliferation, and function. Bioinks are typically made from natural or synthetic polymers—or a combination of both—to provide mechanical strength, structural support, and a biochemically relevant environment for cells.[59] likewise, the preservation of personal genetic information raises ethical and legal concerns, particularly with regard to its collection and storage. Patient information is likely to be exchanged because three-dimensional printing involves multiple experts, and leakage is unavoidable if due caution is not taken. Moreover, patients may encounter difficulties while attempting to leave three-dimensional bioprinting trials. It is very difficult to reverse the transplant or replace a designed organ if it has already been placed [60]. Another challenge is, it is necessary to manufacture an adequately stable as well as mechanically inflexible 3D construct during transplantation. During hard tissue repairing, porosity and structure designed by 3D bioprinting should maintain a high elastic modulus so that they can support the natural cell growth during implantation [61]

Application of 3D Bioprinting in Tissue Engineering:

3D bioprinting plays a crucial role in several major areas of tissue engineering, including the regeneration of skin, neural, bone, and cartilage

tissues [62]. Its ability to fabricate three-dimensional biological constructs by sequentially depositing cell-laden biomaterials makes it highly relevant to regenerative medicine and the creation of organ models for drug screening and disease research [63]. The main applications of 3D bioprinting in tissue engineering are summarized below.

- **Bone and Cartilage –**

Through 3D bioprinting, it is possible to integrate bone-forming cells and growth factors that enhance osteogenesis and facilitate strong bone integration. The technique also allows the production of scaffolds with precisely controlled mechanical and porosity characteristics [64]. Moreover, patient-specific scaffolds created using 3D bioprinting provide an effective solution for repairing large bone defects that are otherwise incapable of natural healing [65].By producing thick bone tissue structures (up to 1 cm) with embedded vascular networks, certain advanced bioprinting techniques may improve integration and durability [66]. Bioactive ceramics and other materials can be used by bioprinters to produce scaffolds that enhance osteoconductive and mechanical qualities [67]. Scaffolds with gradient properties that replicate the cellular transition between various kinds of tissues can be produced through 3D bioprinting. Advanced bioprinters in cartilage tissue engineering enable the production of hydrogel-based cartilage constructions and biphasic constructs with integrated bone and cartilage regions, thus dealing with joint repair issues [68].

- **Vascularized Tissues –**

3D bioprinting is significantly advancing the development of vascularized tissues [69]. The ability to fabricate vascular networks enables the creation of tissue constructs that mimic the body's natural blood vessel systems, ensuring adequate nutrient and oxygen delivery for cell survival [70]. Such vascularized structures are essential for sustaining large and complex tissues like skin, liver, and muscle. This approach addresses a major limitation in tissue engineering—expanding tissue size while maintaining cell viability and proper functionality [71]. One of the most notable applications of this technique is organ regeneration, as a well-developed vascular system is critical for supporting the metabolic functions of complex organs such as the heart, liver, and kidneys [72].

- **Skin Grafts –**

Traditional skin grafts often fail to integrate effectively with host tissues due to insufficient vascularization, which can lead to delayed healing or graft rejection [73]. Using 3D bioprinting, vascularized skin grafts can be fabricated with intricate networks of blood vessels that enhance oxygen and nutrient transport throughout the graft [74]. The inclusion of these vascular structures significantly improves graft integration, promotes faster healing, and enhances overall tissue functionality [75].Due to their ability to accelerate tissue integration and healing, these grafts are especially helpful in the treatment of severe burns, diabetic ulcers, and chronic wounds [76]. The technique known as "wearable edgeless skin constructs" (WESCs) employs 3D laser scanning to produce grafts that fit perfectly, akin to a glove, thereby enhancing both medical and cosmetic results [108]. Vascularized 3D bioprinted skin grafts have demonstrated better integration with adjacent tissue. In animal experiments, these grafts merged with the surrounding tissue within four weeks while preserving complete mobility [77].

- **Neural Tissue-**

Bioprinting enables the precise arrangement of neural cells and biomaterials, resulting in tissue architectures that include neurons and glial cells, closely mimicking the intricate organization of the nervous system [78]. This technology facilitates the creation of functional neural networks, which are essential for enhancing nerve regeneration and repair, particularly in addressing conditions such as traumatic brain injuries, Parkinson's disease, and Alzheimer's [79]. In vitro neural tissue modeling: 3D bioprinting allows for the construction of complex neural tissue structures that more accurately reflect the composition and functions of the brain and nervous system [80]. 3D bioprinted brain tissues can be used to build personalized treatment strategies for neurological diseases by using patient-derived cells [81]. In regenerative medicine, bioprinted neural structures can be utilised as implants to treat diseased or damaged brain tissue [78].

Application of 3D bioprinting in Organ Regeneration:

A. Bioprinting of Skin and Cartilage –

3D bioprinting has emerged as a transformative approach for skin regeneration, offering solutions for burn injuries, chronic wounds, and skin diseases. Unlike traditional grafts, which face limitations such as donor shortage and immune rejection, bioprinting enables patient-specific skin constructs with precise cellular architecture. Layers of bioinks containing keratinocytes, fibroblasts, endothelial cells, and biomaterials like collagen or hyaluronic acid mimic the extracellular matrix. Advanced techniques facilitate vascular network formation to enhance cell survival and functionality. In-situ bioprinting further allows direct application to wound sites for real-time healing. Remaining challenges include achieving pigmentation, nerve integration, and long-term durability, necessitating further research on vascularization, cell differentiation, and immune modulation [82].

B. Bioprinting of Liver Tissue-

The bioprinting of liver tissue is one of the most promising applications of 3D bioprinting in organ regeneration, offering potential solutions for liver failure, drug testing, and transplantation. The liver is a highly complex organ responsible for detoxification, metabolism, and protein synthesis, making its regeneration particularly challenging. Liver diseases, including cirrhosis, hepatitis, and liver cancer, are major global health concerns, often requiring organ transplants. However, the shortage of donor livers has driven the need for alternative solutions, such as bioengineered liver tissues[83].

C. Bioprinting of Kidney Structures-

Bioprinting kidney structures presents a promising strategy to tackle the shortage of donor organs and support patients with chronic kidney disease or renal failure. Given the kidney's complex roles in filtration, waste elimination, electrolyte homeostasis, and hormone production, replicating its architecture is challenging. Bioinks composed of renal cells—such as podocytes, proximal tubular cells, and endothelial cells—along with extracellular matrix components like collagen and fibrin, are employed to mimic the native microenvironment. Techniques including extrusion-based, inkjet, and microfluidic-assisted bioprinting facilitate the creation of nephron-like structures, the functional units of the kidney [84].

D. Bioprinting of Heart Tissues and Valves-

The bioprinting of heart tissues and valves is a groundbreaking advancement in regenerative medicine, offering potential solutions for cardiovascular diseases, heart failure, and

congenital heart defects. The heart is a highly specialized organ composed of cardiomyocytes, endothelial cells, smooth muscle cells, and extracellular matrix (ECM) proteins, all of which must function in a synchronized manner. Using bioinks containing patient derived stem cells, cardiac fibroblasts, and ECM components like collagen and fibrin, researchers are developing bioprinted heart tissues that mimic the native myocardium. One of the biggest challenges in cardiac tissue engineering is achieving vascularization and electrical conductivity, as the heart requires a dense network of blood vessels and synchronized electrical signaling to function properly.[85]

E. Neural Tissue Engineering and Brain Organoids-

Neural tissue engineering and brain organoids are at the forefront of regenerative medicine, disease modeling, and drug development, providing potential therapies for neurodegenerative disorders, brain injuries, and spinal cord damage. Conventional treatments for conditions such as Alzheimer's, Parkinson's, and traumatic brain injuries are limited due to the brain's low regenerative capacity. Using 3D bioprinting and stem cell technologies, researchers are creating neural tissue constructs and brain organoids that replicate the brain's cellular composition and microarchitecture. Bioinks containing neural stem cells, astrocytes, oligodendrocytes, and extracellular matrix proteins are employed to fabricate functional neural networks that support neuronal differentiation and synaptic connectivity.[85]

Advancements and Future Developments in Bioprinting and 3D Printing Technologies

Bioprinting Technologies

1. In recent years, bioprinting technologies have undergone substantial advancement, marking a pivotal phase in the evolution of biomedical engineering.

2. Future innovations are expected to emphasize the development of compact, user-friendly, and portable bioprinters that can be efficiently utilized within clinical settings.

3. For instance, a recently developed handheld bioprinter has demonstrated the capacity to fabricate skin tissues using multimaterial bioinks, while remaining simple and practical to operate [86].

4. Furthermore, the field is witnessing a transition toward **in situ** bioprinting applications, which allow for direct printing of biological materials at the site of tissue injury or structural defect.

5. A significant achievement in this regard includes laser-assisted **in situ** bioprinting of mesenchymal stromal cells embedded within collagen and hydroxyapatite matrices, facilitating bone tissue regeneration.

6. Among the most ambitious aspirations of bioprinting research is the fabrication of fully functional, structurally complex human organs [87,88].

7. Experts predict that the successful production of a bioprinted, functional human heart may be achievable within the next two decades.

8. However, major scientific and technical challenges persist—particularly the replication of intricate vascular networks essential for sustaining organ viability [89].

9. Despite these limitations, the progress achieved thus far remains remarkably encouraging.

10. As research continues to advance, it is anticipated that the bioprinting of complex, heterogeneous tissues such as liver and kidney structures will become feasible in the near future [90].

Future of 3D Printing (3DP) Systems

1. The future of 3D printing (3DP) systems is poised for transformative growth across several promising domains.

2. Future system advancements will focus on integrating diverse 3DP configurations and optimizing them for polymer matrix composites (PMCs) to enhance performance, precision, and compatibility.

3. Another critical direction involves the development of customized feedstock materials specifically tailored to meet the requirements of distinct 3DP technologies and end-use applications, which will necessitate interdisciplinary collaboration.

4. In terms of production processes, future initiatives are expected to employ advanced optimization algorithms and statistical techniques to determine optimal process parameters, thereby improving efficiency and product quality.

5. Moreover, the testing and evaluation of 3D-printed components will increasingly aim to simulate real-world operational conditions to provide more accurate assessments of structural integrity and durability.

6. Finally, the establishment of harmonized certification and standardization frameworks across international borders will be essential to streamline commercialization and facilitate the global deployment of 3DP-based innovations [91].

3D Printing in Construction

1. Within the construction sector, 3D printing holds significant potential to promote sustainability, minimize material waste, and enable the realization of highly intricate and innovative architectural designs.

2. However, achieving these benefits will require substantial investment in research and development, alongside the formulation of new safety protocols and quality assurance standards.

3. Furthermore, the effective integration of 3D printing technologies in construction will depend on close collaboration among architects, engineers, and construction professionals to ensure seamless, ethical, and responsible implementation [92].

Future Outlook of 3D Printing in Construction

1. Looking ahead, 3D printing is expected to revolutionize the construction industry by replacing conventional methodologies with processes that are faster, more economical, and environmentally sustainable.

2. The technology offers notable advantages such as enhanced design flexibility, reduced material consumption, and improved safety in construction environments.

3. Ongoing research efforts are focusing on utilizing concrete as a primary printing material, enabling large-scale, on-site construction without the need for traditional formwork.

4. Additionally, the incorporation of industrial waste materials in 3D printing is being explored to advance sustainability and promote circular economy practices.

5. In the long term, this technology is anticipated to support the construction of extraterrestrial habitats for astronauts, signifying a groundbreaking milestone in both terrestrial and space-based construction [93].

CONCLUSION:

3D bioprinting has established itself as a groundbreaking technology in regenerative medicine and tissue engineering, offering novel solutions for organ regeneration, tissue repair, and personalized therapeutic interventions. By enabling the precise, layer-by-layer deposition of bioinks containing living cells and biomaterials, it allows for the fabrication of complex tissue constructs that closely mimic native architecture and function. Significant progress has been made in the bioprinting of skin, cartilage, bone, vascularized tissues, neural constructs, and vital organs such as the liver, kidney, and heart, demonstrating the immense potential of this technology to address limitations associated with conventional grafts, including donor shortages, immune rejection, and inadequate tissue integration. Despite these advances, several critical challenges remain, including the development of fully functional vascular networks, achieving long-term tissue maturation, ensuring mechanical stability of printed constructs, and standardizing processes for scalable clinical applications. Future research is expected to focus on the optimization of bioink formulations, enhancement of printing precision and resolution, development of portable and in situ bioprinting systems, and integration of multi-tissue constructs with appropriate vascularization. With continued interdisciplinary collaboration, technological refinement, and adherence to ethical and regulatory standards, 3D bioprinting is poised to revolutionize regenerative medicine, offering the promise of functional tissue and organ regeneration and transforming patient-specific healthcare outcomes.

REFERENCES

1. Widmaier EP, Raff H, Strang KT. Vander's Human Physiology. McGraw-Hill Education; Boston, NY, USA: 2010
2. Global, regional, and national burden of congenital anomalies of the kidney and urinary tract from 1990 to 2021, with projections to 2036: a systematic analysis of the global burden of disease study 2021
3. Organ Procurement and Transplantation Network. U.S. Department of Health & Human Services https://optn.transplant.hrsa.gov/ (Date accessed 22/04/2021).
4. Organ Donation and Transplantation Statistics. National Kidney Foundation. https://www.kidney.org/news/newsroom/factsheets/Organ-Donation-and-Transplantation-Stats (Date accessed 22/04/2021)
5. Indian Transplant Registry. Indian society of organ transplantation.http://www.transplantindia.com (Date accessed 22/04/2021)
6. Calne RY. Organ transplantation has come of age. Sci Prog. 2010;93:141–150. doi: 10.3184/003685010X12708274571283. [DOI] [PMC free article] [PubMed] [Google Scholar]
7. Abouna GM. Organ shortage crisis: problems and possible solutions. Transplant Proc. 2008;40:34–38. doi: 10.1016/j.transproceed.2007.11.067. [DOI] [PubMed] [Google Scholar]

8. Saidi RF, Hejazii Kenari SK. Challenges of organ shortage for transplantation: solutions and opportunities. Int J Organ Transplant Med. 2014;5:87–96. [PMC free article] [PubMed] [Google Scholar]
9. Wall SP, Plunkett C, Caplan A. A potential solution to the shortage of solid organs for transplantation. JAMA. 2015;313:2321. doi: 10.1001/jama.2015.5328. [DOI] [PubMed] [Google Scholar
10. T. Ikegami and Y. Maehara, Transplantation: 3D printing of the liver in living donor liver transplantation, Nat. Rev. Gastroenterol. Hepatol., 2013, 10(12), 697–698,
11. Jason M Kronenfeld, Lukas Rother, Max A Saccone, Maria T Dulay, Joseph M DeSimone. Roll-to-roll, high-resolution 3D printing of shape-specific particles. Nature. 2024; 627: 306-312.
12. McMillan A, McMillan N, Gupta N, Kanotra SP, Salem AK. 3D bioprinting in otolaryngology: a review. Advanced healthcare materials. 2023 Jul;12(19):2203268.
13. Xiangyu Zhao, Na Li, Ziqi Zhang, Jinjia Hong, Xiaoxuan Zhang, Yujia Hao, et al. Beyond hype: unveiling the Real challenges in clinical translation of 3D printed bone scaffolds and the fresh prospects of bioprinted organoids. J Nanobiotechnol. 2024; 22: 500.
14. Caddeo S, Boffito M, Sartori S. Tissue engineering approaches in the design of healthy and pathological in vitro tissue models. Frontiers in bioengineering and biotechnology. 2017 Jul 26;5:40.
15. Hongjian Zhang, Chengtie Wu. 3D printing of biomaterials for vascularized and innervated tissue regeneration. Int J Bioprinting. 2023a; 9: 706.
16. Sun X, Ren W, Xie L, Ren Q, Zhu Z, Jia Q, Jiang W, Jin Z, Yu Y. Recent advances in 3D bioprinting of tissues and organs for transplantation and drug screening. Virtual and Physical Prototyping. 2024 Dec 31;19(1):e2384662.
17. Park JA, Lee Y, Jung S. Inkjet-based bioprinting for tissue engineering. Organoid. 2023;3(e12):1-16.
18. Kim W, Lee Y, Kang D, Kwak T, Lee HR, Jung S. 3D inkjet-bioprinted lung-on-a-chip. ACS Biomater Sci Eng. 2023;9(5):2806-2815.
19. Ng WL, Huang X, Shkolnikov V, Suntornnond R, Yeong WY. Polyvinylpyrrolidone-based bioink: influence of bioink properties on printing performance and cell proliferation during inkjet-based bioprinting. Bio-Des Manuf. 2023:1-15.
20. Mirshafiei M, Rashedi H, Yazdian F, Rahdar A, Baino F. Advancements in tissue and organ 3D bioprinting: Current techniques, applications, and future perspectives. Materials & Design. 2024 Apr 1;240:112853.
21. Gu Z, Fu J, Lin H, He Y. Development of 3D bioprinting: From printing methods to biomedical applications. Asian journal of pharmaceutical sciences. 2020 Sep 1;15(5):529-57.
22. Hospodiuk M, Moncal KK, Dey M; I.T. Ozbolat, Biofabrication, Extrusion-Based Biofabrication in Tissue Engineering and Regenerative Medicine. Springer International Publishing; 2016:1-27.
23. Ozbolat IT, Hospodiuk M. Current advances and future perspectives in extrusion-based bioprinting. Biomaterials. 2016;76:321-343.
24. Zhang YS, Haghiashtiani G, Hübscher T, et al. 3D extrusion bioprinting. Nat. Rev. Methods Primers. 2021;1(1):75. doi:10.1038/s43586-021-00073-8
25. Zhang J, Wehrle E, Vetsch JR, et al. Alginate dependent changes of physical properties in 3D bioprinted cell-laden porous scaffolds affect cell viability and cell morphology.

Biomed Mater 2019;14 (6):065009. doi:10.1088/1748-605X/ab3c74

26. Cui H, Zhu W, Huang Y, et al. In vitro and in vivo evaluation of 3D bioprinted small-diameter vasculature with smooth muscle and endothelium. Biofabrication. 2020;12(1):015004. doi:10.1088/1758-5090/ab402c
27. Andrique L, Recher G, Alessandri K, et al. A model of guided cell self-organization for rapid and spontaneous formation of functional vessels. Sci Adv 2019;5(6):eaau6562. doi:10.1126/sciadv.aau6562
28. Tan CT, Liang K, Ngo ZH, et al. Application of 3D Bioprinting Technologies to the Management and Treatment of Diabetic Foot Ulcers. Biomedicines. 2020;8(10):441. doi:10.3390/biomedicines8100441
29. Jana S, Lerman A. Bioprinting a cardiac valve. Biotechnol Adv. 2015;33:1503–21.
30. Han T, Nag A, Afsarimanesh N, Mukhopadhyay SC, Kundu S, Xu Y. Laser assisted printed flexible sensors: a review. Sensors. 2019 Mar 25;19(6):1462. https://doi.org/10.3390/s19061462
31. Sorkio A, Koch L, Koivusalo L, Deiwick A, Miettinen S, Chichkov B, Skottman H. Human stem cell based corneal tissue mimicking structures using laser-assisted 3D bioprinting and Biomaterials. 2018 functional Jul bioinks. 1;171:57-71. https://doi.org/10.1016/j.biomaterials.2018.04.034
32. Koch L, Kuhn S, Sorg H, Gruene M, Schlie S, Gaebel R, Polchow B, Reimers K, Stoelting S, Ma N, Vogt PM. Laser printing of skin cells and human stem cells. Tissue Engineering Part C: Methods. 2010 Oct 1;16(5):847-54. https://doi.org/10.1089/ten.tec.2009.0397
33. Kačarević ŽP, Rider PM, Alkildani S, Retnasingh S, Smeets R, Jung O, Ivanišević Z, Barbeck M. An introduction to 3D bioprinting: possibilities, challenges and future aspects. Materials. 2018 Nov 6;11(11):2199.
34. Serra P, Duocastella M, Fernández-Pradas JM, Morenza JL. Liquids microprinting through laser-induced forward transfer. Appl Surf Sci. 2009;255:5342–5.
35. Patrascioiu A, Fernández-Pradas JM, Palla-Papavlu A, Morenza JL, Serra P. Laser-generated liquid microjets: correlation between bubble dynamics and liquid ejection. Microfluidics Nanofluidics. 2014;16:55–63.
36. Ali M, Pages E, Ducom A, Fontaine A, Guillemot F. Controlling laser-induced jet formation for bioprinting mesenchymal stem cells with high viability and high resolution. Biofabrication. 2014;6:045001.
37. B. Dhariwala, E. Hunt, T. Boland Rapid prototyping of tissue-engineering constructs, using photopolymerizable hydrogels and stereolithography Tissue Eng., 10 (9–10) (2004), pp. 1316-1322
38. V.B. Morris, S. Nimbalkar, M. Younesi, P. McClellan, O. Akkus Mechanical properties, cytocompatibility and manufacturability of chitosan: PEGDA hybrid-gel scaffolds by stereolithography Ann. Biomed. Eng., 45 (1) (2017), pp. 286-296
39. Vanaei S, Parizi MS, Salemizadehparizi F, Vanaei HR. An overview on materials and techniques in 3D bioprinting toward biomedical application. Engineered Regeneration. 2021 Jan 1;2:1-8.
40. R. Gauvin, et al. Microfabrication of complex porous tissue engineering scaffolds using 3D projection stereolithography Biomaterials, 33 (15) (2012), pp. 3824-3834
41. F.P.W. Melchels, J. Feijen, D.W. Grijpma A poly(D,L-lactide) resin for the preparation of tissue engineering scaffolds by stereolithography Biomaterials, 30 (23–24) (2009), pp. 3801-3809

42. The Ultimate Guide to Stereolithography (SLA) 3D Printing". Formlabs. Formlabs, Inc. Retrieved 26 December 201
43. rsilvers (2019-03-02). "On the difference between DLP and LCD based SLA printers | Matter Replicator". Matter Replicator. Archived from the original on 2023-11-13. Retrieved 2019-03-17.
44. Ali, Farhad (2024-01-19). "Difference Between DLP and LCD-Based SLA Printers". Lets3dPrint. Retrieved 2024-09-02.
45. Bliley J.M., Shiwarski D.J., Feinberg A.W. 3D-bioprinted human tissue and the path toward clinical translation. Sci. Transl. Med. 2022;14:eabo7047. doi: 10.1126/scitranslmed.abo7047. [DOI] [PubMed] [Google Scholar]
46. 3.Gu Z., Fu J., Lin H., He Y. Development of 3D bioprinting: From printing methods to biomedical applications. Asian J. Pharm. Sci. 2020;15:529–557. doi: 10.1016/j.ajps.2019.11.003. [DOI] [PMC free article] [PubMed] [Google Scholar]
47. 4.Heinrich M.A., Liu W., Jimenez A., Yang J., Akpek A., Liu X., Pi Q., Mu X., Hu N., Schiffelers R.M., et al. 3D Bioprinting: From Benches to Translational Applications. Small. 2019;15:e1805510. doi: 10.1002/smll.201805510. [DOI] [PMC free article] [PubMed] [Google Scholar]
48. 5.Matthews N., Pandolfo B., Moses D., Gentile C. Taking It Personally: 3D Bioprinting a Patient-Specific Cardiac Patch for the Treatment of Heart Failure. Bioengineering. 2022;9:93. doi: 10.3390/bioengineering9030093. [DOI] [PMC free article] [PubMed] [Google Scholar]
49. 6.Shopova D., Yaneva A., Bakova D., Mihaylova A., Kasnakova P., Hristozova M., Sbirkov Y., Sarafian V., Semerdzhieva M. (Bio)printing in Personalized Medicine—Opportunities and Potential Benefits. Bioengineering. 2023;10:287. doi: 10.3390/bioengineering10030287. [DOI] [PMC free article] [PubMed] [Google Scholar]
50. 7.Fonseca A.C., Melchels F.P.W., Ferreira M.J.S., Moxon S.R., Potjewyd G., Dargaville T.R., Kimber S.J., Domingos M. Emulating Human Tissues and Organs: A Bioprinting Perspective Toward Personalized Medicine. Chem. Rev. 2020;120:11128–11174. doi: 10.1021/acs.chemrev.0c00342. [DOI] [PMC free article] [PubMed] [Google Scholar]
51. 8.McGivern S., Boutouil H., Al-Kharusi G., Little S., Dunne N.J., Levingstone T.J. Translational Application of 3D Bioprinting for Cartilage Tissue Engineering. Bioengineering. 2021;8:144. doi: 10.3390/bioengineering8100144. [DOI] [PMC free article] [PubMed] [Google Scholar]
52. 9.Albanna M., Binder K.W., Murphy S.V., Kim J., Qasem S.A., Zhao W., Tan J., El-Amin I.B., Dice D.D., Marco J., et al. In Situ Bioprinting of Autologous Skin Cells Accelerates Wound Healing of Extensive Excisional Full-Thickness Wounds. Sci. Rep. 2019;9:1856. doi: 10.1038/s41598-018-38366-w. [DOI] [PMC free article] [PubMed] [Google Scholar]
53. 10.Tan S.H., Ngo Z.H., Sci D.B., Leavesley D., Liang K. Recent Advances in the Design of Three-Dimensional and Bioprinted Scaffolds for Full-Thickness Wound Healing. Tissue Eng.-Part B Rev. 2022;28:160–181. doi: 10.1089/ten.teb.2020.0339. [DOI] [PubMed] [Google Scholar]
54. 11.Wu Y., Ravnic D.J., Ozbolat I.T. Intraoperative Bioprinting: Repairing Tissues and Organs in a Surgical Setting. Trends Biotechnol. 2020;38:594–605. doi: 10.1016/j.tibtech.2020.01.004. [DOI] [PMC free article] [PubMed] [Google Scholar]
55. 12.Tan S.H., Chua D.A.C., Tang J.R.J., Bonnard C., Leavesley D., Liang K. Design of

hydrogel-based scaffolds for in vitro three-dimensional human skin model reconstruction. Acta Biomater. 2022;153:13–37. doi: 10.1016/j.actbio.2022.09.068. [DOI] [PubMed] [Google Scholar]

56. 13.Levato R., Jungst T., Scheuring R.G., Blunk T., Groll J., Malda J. From Shape to Function: The Next Step in Bioprinting. Adv. Mater. 2020;32:e1906423. doi: 10.1002/adma.201906423. [DOI] [PMC free article] [PubMed] [Google Scholar]
57. Hauser P.V., Chang H.-M., Nishikawa M., Kimura H., Yanagawa N., Hamon M. Bioprinting Scaffolds for Vascular Tissues and Tissue Vascularization. Bioengineering. 2021;8:178. doi: 10.3390/bioengineering8110178. [DOI] [PMC free article] [PubMed] [Google Scholar]
58. 21.Böttcher B., Pflieger A., Schumacher J., Jungnickel B., Feller K.-H. 3D Bioprinting of Prevascularized Full-Thickness Gelatin-Alginate Structures with Embedded Co-Cultures. Bioengineering. 2022;9:242. doi: 10.3390/bioengineering9060242. [DOI] [PMC free article] [PubMed] [Google Scholar]
59. Mirshafiei M, Rashedi H, Yazdian F, Rahdar A, Baino F. Advancements in tissue and organ 3D bioprinting: Current techniques, applications, and future perspectives. Materials & Design. 2024 Apr 1;240:112853.
60. Kirillova, A., Bushev, S., Abubakirov, A., & Sukikh, G. (2020). Bioethical and legal issues in 3D bioprinting. International Journal of Bioprinting, 6(3).
61. Hollinger, J. O., Brekke, J., Gruskin, E., and Lee, D. (1996). Role of bone substitutes. Clin. Orthop. Relat. Res. 324, 55–65. doi:10.1097/00003086-199603000-00008
62. Huan Fang, Jie Xu, Hailin Ma, Jiaqi Liu, Erpai Xing, Yuen Yee Cheng, et al. Functional materials of 3D bioprinting for wound dressings and skin tissue engineering applications: A review. Int J Bioprinting. 2023; 9: 757.
63. Konstantinos Loukelis, Nikos Koutsomarkos, Antonios G Mikos, Maria Chatzinikolaidou, et al. Advances in 3D bioprinting for regenerative medicine applications. Regen Biomater. 2024; 11: rbae033.
64. Khajehmohammadi M, Azizi Tafti R, Nikukar H. Effect of porosity on mechanical and biological properties of bioprinted scaffolds. J Biomed Mater Res A. 2023; 111: 245-260.
65. Yue Kang, Jie Xu, Ling'ao Meng, Ya Su, Huan Fang, Jiaqi Liu, et al. 3D bioprinting of dECM/Gel/QCS/nHAp hybrid scaffolds laden with mesenchymal stem cell-derived exosomes to improve angiogenesis and osteogenesis. Biofabrication. 2023; 15.
66. Francesca K Lewns, Olga Tsigkou, Liam R Cox, Ricky D Wildman, Liam M Grover, Gowsihan Poologasundarampillai. Hydrogels and Bioprinting in Bone Tissue Engineering: Creating Artificial Stem-Cell Niches for In Vitro Models. Adv Mater. 2023; 35.
67. Shumin Pang, Dongwei Wu, Franz Kamutzki, Jens Kurreck, Aleksander Gurlo, Dorian AH, Hanaor, et al. High performing additively manufactured bone scaffolds based on copper substituted diopside. 2022; 215: 110480.
68. Yuan Ma, Yilin Wang, Danni Chen, Ting Su, Qiang Chang A, Wenhua Huang, et al. 3D bioprinting of a gradient stiffened gelatin-alginate hydrogel with adipose-derived stem cells for full-thickness skin regeneration. J Mater Chem. 2023; 11: 2989-3000.
69. Yordan Sbirkov, Murad Redzheb, Nico Forraz, Colin McGuckin, Victoria Sarafian. High Hopes for the Biofabrication of Articular Cartilage-What Lies beyond the Horizon of Tissue Engineering and 3D Bioprinting?. Biomed. 2024; 12: 665.

70. Zhiyuan Kong, Xiaohong Wang. Bioprinting Technologies and Bioinks for Vascular Model Establishment. Int J MOI Sci. 2023; 24: 891.
71. Sasinan Bupphathong, Joshua Lim, Hsu-Wei Fang, Hsuan-Ya Tao, Chen-En Yeh, Tian-An Ku, et al. Enhanced Vascular-like Network Formation of Encapsulated HUVECs and ADSCs Coculture in Growth Factors Conjugated GelMA Hydrogels. ACS Biomater Sci Eng. 2024; 10: 3306-3315.
72. Hongjian Zhang, Chengtie Wu. 3D printing of biomaterials for vascularized and innervated tissue regeneration. Int J Bioprinting. 2023b; 9: 706.
73. Dominic Henn, Kellen Chen, Tobias Fehlmann, Artem A Trotsyuk, Dharshan Sivaraj, Zeshaan N Maan, et al. Xenogeneic skin transplantation promotes angiogenesis and tissue regeneration through activated Trem2 + macrophages. Sci Adv. 2021; 7: eabi4528.
74. Tânia Baltazar, Jonathan Merola, Carolina Catarino, Catherine B Xie, Nancy C Kirkiles-Smith, Vivian Lee, et al. Three Dimensional Bioprinting of a Vascularized and Perfusable Skin Graft Using Human Keratinocytes, Fibroblasts, Pericytes, and Endothelial Cells. Tissue engineering. Part A. 2020; 26: 227-238.
75. Hongjian Zhang, Chengtie Wu. 3D printing of biomaterials for vascularized and innervated tissue regeneration. Int J Bioprinting. 2023b; 9: 706.
76. Vito Antonio Baldassarro, Valentina Giraldi, Alessandro Giuliani, Marzia Moretti, Giorgia Pagnotta, Alessandra Flagelli, et al. Poly(l-lactic acid) Scaffold Releasing an α 4 β 1 Integrin Agonist Promotes Nonfibrotic Skin Wound Healing in Diabetic Mice. ACS Applied Bio Materials. 2023; 6: 296-308.
77. Alberto Pappalardo, David Alvarez Cespedes, Shuyang Fang, Abigail R Herschman, Eun Young Jeon, Kristin M Myers, et al. Engineering edgeless human skin with enhanced biomechanical properties. Sci Adv. 2023; 9: eade2514.
78. Soja Saghar Soman, Mano Govindraj, Noura Al Hashimi, Jiarui Zhou, Sanjairaj Vijayavenkataraman. Bioprinting of Human Neural Tissues Using a Sustainable Marine Tunicate-Derived Bioink for Translational Medicine Applications. Int J Bioprinting. 2022; 8: 604.
79. Danielle Warren, Eva Tomaskovic-Crook, Gordon G. Wallace, Jeremy Micah Crook. Engineering in vitro human neural tissue analogs by 3D bioprinting and electrostimulation. APL Bioeng. 2021; 5: 020901.
80. Sullivan MA, Lane S, Volkerling A, Engel M, Werry EL, Kassiou M. 3D Bioprinting of Stem Cell-Derived Central Nervous System Cells Enables Astrocyte Growth, Vasculogenesis and Enhances Neural Differentiation/Function. Biotechnol Bioeng. 2022; 120: 3079-3091.
81. Yongcheng Jin, Ellina Mikhailova, Ming Lei, Sally Cowley, Tianyi Sun, Xingyun Yang, et al. Functional Integration of 3D-Printed Cerebral Cortical Tissue into a Brain Lesion. 2022.
82. Kirillova A, Bushev S, Abubakirov A, Sukikh G. Bioethical and legal issues in 3D bioprinting. International Journal of Bioprinting. 2020 Apr 28;6(3):272.
83. Chawla S, Midha S, Sharma A, Ghosh S. Silk‐based bioinks for 3D bioprinting. Advanced healthcare materials. 2018 Apr;7(8):1701204.
84. Tripathi S, Mandal SS, Bauri S, Maiti P. 3D bioprinting and its innovative approach for biomedical applications. MedComm. 2023 Feb;4(1):e194.
85. Lee AR, Hudson AR, Shiwarski DJ, Tashman JW, Hinton TJ, Yerneni S, Bliley JM,

Campbell PG, Feinberg AW. 3D bioprinting of collagen to rebuild components of the human heart. Science. 2019 Aug 2;365(6452):482-7.

86. 67. Cui X, Boland T, D'Lima DD, Lotz MK. Thermal inkjet printing in tissue engineering and regenerative medicine. Recent Pat Drug Deliv Formul 2012;6(2):149–155.
87. Banks J. Adding value in additive manufacturing: Researchers in the United Kingdom and Europe look to 3D printing for customization. IEEE Pulse 2013;4(6):22–26.
88. Hoy MB. 3D printing: making things at the library. Med Ref Serv Q 2013;32(1):94–99
89. Bartlett S. Printing organs on demand. Lancet Respir Med 2013;1(9):684.
90. Lipson H. New world of 3-D printing offers "completely new ways of thinking:" Q & A with author, engineer, and 3-D printing expert Hod Lipson. IEEE Pulse 2013;4(6):12–14.
91. P. Madhu Raghava, G. Jaya Chandra Reddy. A Review on 3D Printing Technology - Materials, Polymer Composites, Applications, Challenges, and Future Trends. Int J Eng Res Appl. 2023;13(4):91-94.
92. Tabassum T, Mir AA. A review of 3d printing technology-the future of sustainable construction. Materials Today: Proceedings. 2023 Jan 1;93:408-14.
93. Vasava M, Raval AD, Pitroda JR. A Future of Construction Industry: 3D Concrete Printing Technology. Int Res J Modernization Eng Technol Sci. 2021.

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