ATJ
Advanced Therapies Journal

VOL.7/ ISSUE 23 / SPRING 2025

Online ISSN: 2676-7236

DOI: 10.22034/atj.2025.518661.1011

OPEN ACCESS

Pages: 33-43 / Review Article / Submit: 25 April 2025 / Accepted: 22 May 2025

Availablein: https://www.atjournal.ir

Dynamic Biomaterials: The Next Generation of Regenerative Therapies

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Abstract:

Live materials represent a radical change in regenerative medicine since they combine the structural advantages of biomaterials with the natural biological goals of live cells, so providing a dynamic and interactive approach for tissue repair and regeneration. Designed with multiple cutting-edge technologies including cell encapsulation, scaffold-based approaches, layer-by-layer assembly, and 3D bioprinting, these composite materials help to create customized constructions fit for particular therapeutic need. By allowing the generation of patient-derived tissue and organ models for drug assessment and therapeutic augmentation, advances in microfluidics and the development of organ-on- a-chip and organoid technologies help to support this tailored approach. Although bringing these fascinating discoveries into general clinical use still presents challenges, under our direction continuous biomaterials, microfabrication, and cell-material interaction research and development are rapidly advancing. Underline their great opportunities for regenerative medicine, investigate the several engineering approaches applied in their design and fabrication, present a thorough study of the current situation of living materials, and discuss the present difficulties and interesting prospects inside this transforming field.

Keywords: Live materials, Regenerative medicine, Tissue engineering, cell therapy, Personalized medicine

Introduction

By stressing building or substituting damaged tissues and organs instead of only treating symptoms, regenerative medicine (RM) has great potential to transform healthcare (1). Inspired by concepts from engineering, materials science, and cell biology, this discipline generates novel treatments. A major component of RM is the design and manufacturing of biocompatible materials that mimic the natural surroundings of tissues. Among their several uses are structural support for cell development and differentiation and pharmacological distribution. Since their properties directly affect cell activity and tissue development, the best regeneration results depend on the design of these materials (2). Targeting the primary causes of immunological rejection and donor shortage, RM offers a reasonable substitute for conventional transplanting. Patients with severe injuries and chronic diseases hope for this approach since it has shown success in many different applications, including bone reconstruction, heart regeneration, and muscular rejuvenation.

How to Cite this Article:

A. Sobhani " Dynamic Biomaterials: The Next Generation of Regenerative Therapies", Advanced Therapies Journal, vol. 7, no. 23, pp.33-43, 2025.

While current research and advancements in this field open the path for more customized and successful regenerative therapies, constantly stretching the limits of what is practical follows (3). Beyond traditional 2D cell cultures, research in regenerative medicine has progressed to recognize the importance of the 3D environment in replicating the complex interactions and structures found in real tissues (4). Although they are helpful for preliminary study, 2D cultures sometimes lack the delicate cell-by-cell interactions needed for tissue development and function. Conversely, 3D environments, including hydrogels, scaffolds, and decellularized tissues, give cells a more physiologically realistic setting, so enhancing cell viability, growth, differentiation, and the generation of functional tissue architectures (5). These 3D models help researchers better grasp the processes regulating tissue repair by allowing them to investigate cell activity in more realistic surroundings. Additionally, 3D bioprinting and microfluidic systems enable the precise creation of complex tissue designs with specific structures and materials, opening new possibilities for developing functional organs and tissues. Therefore, advancements in 3D culture and manufacturing processes will determine the rapid translocation of regenerative medicine drugs from the laboratory to the clinic (7).

Biomaterials are essential in regenerative medicine since they give tissue healing and recovery the structural and functional foundation. By means of their unique interaction with live entities, these carefully designed materials enhance cell adhesion, growth, and differentiation (8). Among the several materials used are composites, metals, ceramics, and polymers, both natural and synthetic. Natural polymers, including collagen and hyaluronic acid, are naturally biocompatible and promote cell-matrix interactions; synthetic polymers, including polylactic acid (PLA) and polycaprolactone (PCL), enable more control over mechanical characteristics and breakdown rates (4). Mechanical strength, porosity, biodegradability, and biocompatibility are among the qualities one should consider while selecting a material for a given use. Sometimes complex biomaterials with particular surface modifications or coupled with growth factors and other bioactive compounds are developed to increase their regeneration potential (9). Extending biomaterials by including live cells into the material structure, living materials represent a novel development in the sector. These composite materials mix the structural advantages of traditional biomaterials with the dynamic possibilities of live cells (10). By releasing growth factors, generating extracellular matrix, and directly impacting tissue development, stem cells, fibroblasts, or another type of specialized cell actively participate in the regeneration process. Several methods could be used to create living materials: cell-based films, encapsulating cells within hydrogels, or embedding cells within scaffolds (11). This approach offers several benefits, including improved interaction with host tissues, increased bioactivity, and the potential to supply therapeutic compounds on demand. Manufacturing of living materials is a fast-expanding field of research with enormous potential for tailored and very successful regenerative treatments (12). This paper introduces the field of regenerative medicine with special regard to the important role materials play in tissue healing and regeneration. To increase therapeutic possibilities, it also looks at the growing field of living materials and composite constructions using living cells.

Living Materials in Regenerative Medicine

Living materials provide a paradigm change in regenerative medicine, transcending fixed biomaterials and moving towards dynamic, interactive constructions actively promoting tissue restoration. These compounds are unique composites combining the inherent bioactivity of live cells with the structural properties of conventional biomaterials (13). Living materials reflect the natural milieu of tissues more precisely than cell-free scaffolds, so promoting growth, differentiation, and longer lifetimes of cells. This method lets the development of structures that not only provide structural support but also actively contribute to the rejuvenation process by secreting growth factors, building an extracellular matrix, and directly helping in tissue development (14). Living materials offer a more customized and effective method to regenerate treatments since they seem to close the difference between synthetic materials and natural tissues (15).

Living materials serve several purposes in regenerative medicine. They could be used to drive stem cell differentiation into particular cell types, boost the formation of vessels for better blood supply to healing tissue, and even straightforwardly send therapeutic drugs to the intended area (16). By expressing specific growth factors or other therapeutic compounds, the genetically altered cells in the living substance could be more likely to regenerate. Furthermore, the dynamic character of living materials helps them to react to changes in their surroundings by means of behavior meant to promote tissue rehabilitation and reconstruction. This adaptability is one main benefit over stationary biomaterials, which could not be able to satisfy the complex and changing needs of renewing tissue (17). Live materials are an amazing junction of biology and materials science whereby dynamic, interacting structures are formed by means of live cells incorporated into a biomaterial framework. For use in drug delivery or cartilage repair, cells could be encapsulated within hydrogels like alginate or collagen (18). Likewise, cells could be seeded onto or implanted in artificial polymers such as PCL or decellularized tissue, generating live scaffolds for skin replacements or bone reconstruction. The promise of living materials to transform regenerative medicine cannot be disputed even if long-term cell viability, controlled cell activity, and scalability still present challenges (19). Growing knowledge of cell-material interactions should lead to even more complex and effective living materials emerging, enabling a new era of regenerative medicines.

Engineering Strategies and Fabrication Approaches for Living Materials

Biomaterials, living materials, and living cell polymers seek modern engineering solutions and manufacturing methods. These methods aim to provide cells with a caring and supportive environment that resembles their natural surroundings, thereby enhancing cell survival, development, and function. Several important responses with varying benefits and drawbacks have surfaced (20).

Cell Encapsulation

Cell encapsulation is the process of covering cells in a protective shell usually made of hydrogel or another biocompatible material. Apart from mechanical stress and immune system protection from the host, this method produces a small environment rich in nutrients and growth hormones concurrently (21). Comprising hydrophilic polymers, hydrogels are fit for enclosing because of their high water content and biological compatibility. Because alginate, a natural polysaccharide, is easy to gel and biologically compatible, cell encapsulation often makes use of it (22). Other components used depending on need are polyethylene glycol (PEG), hyaluronic acid, and collagen. One can precisely control tissue architecture and cell distribution by modifying the encapsulation method, so modifying the size and form of the cell-loaded constructions (23).

The type of cell and its use define the encapsulating substance and technique used. Alginate encapsulation is ideal for chondrocytes in cartilage regeneration, for example, but other hydrogels could be more appropriate for stem cells or other cell types (24). The mechanism of encapsulation itself can affect cell survival and behavior. Mild encapsulation techniques help to minimize cell damage and preserve their functionality. Furthermore, one can enhance tissue development and cell behavior by changing the properties of the enclosing material: rigidity, porosity, and decommission rate. To maximize the long-term survival and function of encapsulated cells, scientists are now considering creative encapsulating materials and techniques, so enhancing the efficacy of living material creations (25).

Scaffold-Based Approaches

Techniques based on scaffolding embed or seed cells onto a three-dimensional (3D) scaffold framework. Designed of extracellular matrix (ECM), the scaffold provides a framework for cell adhesion, development, and organization reminiscent of biological tissues. Scaffolds are built from synthetic and natural polymers, including PLA and PCL, as well as collagen and decellularized tissues (26). Scaffold design affects tissue development and cell activity in regard to permeability, pore size, and interrelationships. Ideally the scaffold should be biocompatible, recyclable, mechanically similar to the target tissue, and biocompatible (27).

Because of their natural biocompatibility and original tissue structure, decellularized tissues derived from human or animal sources are quite an attractive scaffolding material. Decellularization leaves only the ECM, a natural structure free of all cellular components, allowing cell adhesion and tissue repair (28). Designed for specific applications, synthetic polymers give better control over scaffold properties. Using 3D printing and other advanced manufacturing technologies allows one to create complex geometries and controlled porosity, so offering exact control over cell distribution and tissue structure. Often used in regenerative medicine for a wide spectrum of uses, including skin replacements, cartilage repair, and bone regeneration, scaffold-based technologies (29).

Layer-by-Layer Assembly

Layer-by-layer (LbL) assembly is a flexible method for building living materials whereby ultrathin layers of various compounds including cells and biomolecules are successively deposited onto a substrate (30). This approach gives exact control over the design and building of the resulting structure. Cell-rich films, coatings, and even three-dimensional models can be created using LbL assembly. Many materials could be used in the layers, including polymers, nanoparticles, and growth factors, so allowing the creation of multifarious living materials (31). Production of thin films or coatings using live cells benefits much from LbL assembly. We could use these cell-laden films to form portions of more complex tissue structures, distribute medications, or heal wounds (32). The LbL method offers precise control over the film's thickness and composition as well as the cell distribution within the material. Moreover, LbL assembly could be applied to include other bioactive compounds or growth elements in the film, so enhancing its regeneration capacity. Although LbL assembly is a great method, it could be time-consuming and inappropriate for creating large or complex 3D objects (33).

3D Bioprinting

3D bioprinting is rising as a good technique for generating complex living materials with exact control over cell distribution and tissue structure. Usually using cells surrounded in a hydrogel or another biocompatible material, this method lays cells layer by layer (34). 3D bioprinting allows tailored tissue designs fit for the patient's needs. Among the several bioprinting technologies available are extrusion-based, inkjet-based, and laser-assisted ones; each has benefits and drawbacks (35).

From 3D bioprinting, there are great opportunities for building complex tissues and organs, including cartilage, blood vessels, and maybe whole organs. Specifically, control of cell distribution and scaffold design determines the development of functional tissue architectures (36). Moreover, 3D bioprinting could be used to combine several cell types and biomaterials into one construction, so simulating the complicated composition of natural tissues. Though 3D bioprinting is a rapidly expanding industry, problems still exist in terms of bio-ink manufacture, printing speed, and guaranteeing long-term cell viability inside produced constructions. Still, 3D bioprinting seems to have fantastic power to transform regenerative medicine (37).

Microfluidics Systems

Systems using microfluids

Microfluidics allows exact control over the milieu surrounding cells and lets intricate tissue structures be built, so enabling designed living materials. These devices, with their micrometer-scale tubes and chambers, enable unmatched accuracy in fluid and cell manipulation. In the context of living materials, microfluidics helps cells to receive nutrients, growth factors, and other signaling molecules under control, so mimicking the dynamic milieu of real tissues (39). Moreover, microfluidic devices could be programmed to create precise shear stress environments influencing cell activity and differentiation. This degree of control determines the research on cell-material interactions and design optimization of living materials for particular purposes. Microfluidics allows the generation of highly ordered and functional tissue structures by exactly controlling fluid flow and cell position (40). Microfluidics not only controls the microenvironment but also enables very detailed production of living materials. These tools can be used to produce consistent-sized, shaped cell-laden hydrogel droplets that can then be aggregated into bigger tissue structures (41). Furthermore, combining microfluidic systems with 3D bioprinting technologies allows for the exact deposition of cell-loaded bioinks to create intricate tissue structures. Precisely altering the microscale composition and structure of living materials will help to create functional tissues and organs. Microfluidic devices can also be used to create gradients of chemical signals guiding cell movement and differentiation, so augmenting the regenerative capacity of living materials. As they evolve in the synthesis of next-generation living materials for regenerative therapies, microfluidic techniques will become increasingly crucial (42).

Applications of Living Materials in Regenerative Medicine

In many different fields of use, advanced living materials show great potential to progress regenerative medicine. Including live cells inside a biocompatible matrix, these generated structures provide customized solutions for tissue regeneration and repair (4). Living materials can help to increase bone production and vascularization during bone regeneration, so facilitating faster and more complete healing of fractures or deformities. By stimulating matrix synthesis and chondrocyte development, cell-based hydrogels could help to restore joint function. Living skin substitutes such as keratinocytes and fibroblasts aid in burn and chronic wound healing. Living heart patches could be made to easily mix with damaged myocardium, so promoting functional repair and angiogenesis. In the next section (43), we will go over some of the applications of living materials in regenerative medicine.

Engineering Living Scaffolds for Enhanced Tissue Repair

Live scaffolds comprise live cells actively involved in the regeneration process together with a three-dimensional structure reflecting the natural ECM of tissues, so promoting tissue healing (44). These scaffolds direct the growth of new tissue and form the basis for cell adhesion, proliferation, and differentiation. Unlike traditional scaffolds that don't have cells, living scaffolds actively deliver important substances like growth factors and cytokines to the injury site, which helps in forming new blood vessels and starting the healing process. Furthermore, generating and depositing their own ECM components, the additional cells could improve the biocompatibility of the scaffold and promote integration with the host tissue. Living scaffolds are a successful technique of tissue regeneration because of their synergistic mix of structural support and biological function (46).

For example, loaded with osteogenic cells (bone-forming cells), living scaffolds made of biocompatible materials such as hydroxyapatite may be implanted at the site of a fracture or bone defect in bone reconstruction. The scaffold offers structural support while osteogenic cells develop and generate new bone tissue, speeds healing, and enhances incorporation with the surrounding bone. Likewise, living scaffolds composed of hydrogels implanted with chondrocytes cartilage cells can help damaged cartilage in joints heal. While the chondrocytes create new cartilage matrix, so repairing the smooth and functioning surface of the joint, the hydrogel creates a hydrated environment that promotes chondrocyte vitality and functioning (48). Treating serious burns or long-lasting wounds can be done with living skin substitutes, which have a layer made of collagen with fibroblasts and a top layer of keratinocytes, offering a more natural and effective option than traditional skin grafts. These cases highlight how adaptable living scaffolds are in encouraging tissue regeneration and restoring function in many various types of tissues and organs (49).

Living Cell Composites: Enhancing Cell Therapy

Since living cell composites offer a more sophisticated approach to distributing restorative cells to damaged tissues, they represent a major breakthrough in cell treatment. These composites mix the therapeutic possibilities of live cells (50) with the structural and functional properties of biological materials. These composites enhance cell survival, facilitate cell-cell interactions, and ensure targeted distribution to the intended area by embedding or encapsulating cells within a biocompatible matrix, thereby creating a protected microenvironment. Two drawbacks of present cell therapies that this method solves are limited integration with host tissues and poor cell survival upon transplantation (20). The biological material component of the composite is designed to provide mechanical support, replicate the natural extracellular matrix, and potentially secrete growth hormones or other bioactive chemicals to promote tissue repair. Interaction of biomaterials and cells in this harmonic fashion increases the efficacy of cell treatments (51). In cell treatment, living cell composites find several applications. Shielding cells from hostile environments and promoting their retention at the target site, they function as a channel for delivering them to the site of damage or disease. Apart from providing a scaffold for tissue regeneration, the biomaterial component gives structural support and direction of guidance for cell arrangement (52).

Moreover, the composite's cells could be designed to generate therapeutic genes or release growth factors, so improving their curative capacity. In heart cell therapy, for example, heart muscle cells can be placed on a safe material to make a living heart patch that can be put into the damaged heart area. In diabetic treatment, we can encapsulate pancreatic islet cells in a protective hydrogel to halt immune attack and prolong their lifespan after transplantation. Neural stem cells could be used in neurological diseases to cause nerve repair and restore function by means of a biodegradable scaffold (54). For example, encapsulating NK cells into microspheres could preserve the tumor-killing ability while still allowing perforin and granzyme B to be constantly released. These cases underline the several uses of living cell composites in improving the efficiency of cell therapies over a spectrum of diseases and injuries (54).

3D Living Models for Biomedical Research

Providing in vitro 3D cell culture systems that replicate significant structural and functional traits of tissues and organs, living tissue and organ models represent a major advancement in biomedical research. Two main approaches—organ-on-a-chip and organoid techniques—are driving development in this field (55). Using live cells and microfluidic channels, organ-on-a-chip systems replicate physiological or pathogenic conditions observed in the body. Designed for a variety of organs, including the kidney, liver, and intestine, these platforms let scientists look at organ-specific activities and reactions (56). Since semiconductors are made from materials and they also support cell culture, materials science is rather relevant. Since the material design directly affects cell behavior and functionality, cells grown in these materials could be called living materials. By adding a nanoimprinted anisotropic film seeded with cardiomyocytes, a heart-on-a-chip device, for example, has demonstrated the ability to merge advanced materials with microfluidics (57), inducing cell alignment and monitoring contraction activity. Conversely, organoids are multicellular, self-organizing structures derived from stem cells that resemble organ form and function. More complex and physiologically appropriate than traditional 2D cell cultures, these 3D structures offer With special focus on transplanting methods, organoid technology has shown promise in regenerative medicine (58). Scientists have developed techniques for the long-term cultivation and genetic editing of both normal human organoids and breast cancer organoids, which enable studies on disease progression and drug interactions. Transplanting organoids, like cholangiocyte organoids, into bile ducts has shown potential for restoring tissue function and healing damaged areas. Although organ-on-a-chip and organoid technologies are useful tools for research, they have problems in repeatability, scalability, and recreating the whole complexity of human organs. More advanced biomaterials, improved culture conditions, and the combining of several organ models to create more complete systems for understanding human health and disease are the goals of continuous research in this field (60).

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Personalized Medicine: Tailoring Treatment with Living Tissue Models

Particularly organ-on-chip and organoid technologies, the development of live tissue and organ models has opened exciting new directions for tailored treatment. These models have one remarkable feature: they can generate original copies of a person's tissues or organs from cells obtained from a patient (61). This customized approach beats generic models, which might not fairly depict the particular traits of a patient's condition or reaction to particular treatments. Using cells taken from minimally invasive techniques, such as biopsies or blood samples, scientists can produce tissue/organ models with the exact genetic profile and disease profile of the patient. This guarantees a better awareness of the personal health and helps to build customized treatments (62). Customized tissue/organ models greatly promise drug screening and therapy optimization. These models can offer important information on how a patient might react to various treatment choices by assessing the efficacy and toxicity of several medications on their cells. By helping doctors choose the best and most effective drugs for every patient, this approach reduces side effects risk and increases treatment success possibilities (63). In cancer treatment, for example, tailored tumor organoids can be used to screen a panel of chemotherapeutic agents and pinpoint which treatments best target the specific tumor cells. This information could then be used to direct therapy decisions and stop the use of harmful or useless drugs (64).

Apart from drug screening, tailored tissue/organ models could be used to search for possible treatment targets and investigate the basic causes of a patient's disease. Comparatively examining models produced from healthy and sick tissues from the same patient helps scientists to identify the particular molecular changes driving disease development and spread (61). Customized treatments aiming at these precise paths could then be designed using this knowledge. Furthermore, these models could enable doctors to track a patient's therapeutic response over time, so enabling them to change their course of treatment as needed. As these technologies develop and usher in a new era of completely tailored treatment fit for every person's specific need, individualized tissue/organ models have the power to transform healthcare (65).

Imagine a patient with cystic fibrosis (CF) who often develops lung infections. Removed patient airways could be used to build a customized lung-on-a-chip model. This model would reproduce the CF lung environment, including the typical reduced mucociliary clearance and thick mucus accumulation (66). On the model, then, researchers could test many antibiotics or mucolytics to see how the patient's cells react. This would enable doctors to identify the most suitable medications for each patient's cystic fibrosis (CF), so perhaps avoiding the currently used trial-and-error approach in CF treatment. Moreover, the specific CFTR mutation of the patient and customized gene therapy applied using the 67 model.

Imagine a patient suffering with severe Crohn's disease, a form of IBD. Intestinal organoids could be produced from patient inflammatory intestinal tissue biopsies. These organoids would replicate the inflammatory response of the patient; thus, they could be used to investigate the interactions between immune cells and the gut flora (68). Researchers could then look at the impact of fecal microbiota transplantation from healthy donors on the patient's particular organoids (68) or run several anti-inflammatory treatments. This would offer necessary fresh insights on the patient's disease processes, so guiding the most appropriate and tailored treatment plans. Especially organ-on-chip and organoid technologies, the evolution of live tissue and organ models has opened fascinating new paths for customized treatment. One striking characteristic of these models is their capacity to produce original copies of an individual's tissues or organs from patient-derived cells (61). This tailored approach outperforms generic models, which may not fairly represent the specific characteristics of a patient's condition or response to specific treatments. Scientists may create tissue/organ models with the exact genetic profile and disease profile of the patient by using cells obtained from minimally invasive procedures such as biopsies or blood samples. This guarantees a better awareness of the personal health and helps to produce tailored treatments (62). Drug screening and therapy optimization have great promise from personalized tissue/organ models. These models can offer important information on how a patient might react to various treatment choices by assessing the efficacy and toxicity of several medications on their cells. By helping doctors choose the best and most effective drugs for every patient, this approach reduces side effects risk and increases treatment success possibilities (63). In cancer treatment, for example, tailored tumor organoids can be used to screen a panel of chemotherapeutic agents and pinpoint which treatments best target the specific tumor cells. This information could then be used to direct therapy decisions and stop the use of harmful or useless drugs (64).

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Discussion and conclusion

Living materials also known as composites of living cells and biomaterials offer an evolutionary change in regenerative medicine by their dynamic and cooperative approach for tissue repair and regeneration. From cell encapsulation and scaffold-based technologies to layer-by-layer assembly and 3D bioprinting, this topic spans a wide range of engineering approaches all meant to produce live constructions with specified features and capabilities (69). These synthetic materials, which secrete growth hormones and generates extracellular matrix, actively participate in the regeneration process by providing structural support and helping therapeutic cells to be transported. The adaptability of living materials makes customizing depending on the target tissue or organ possible, so offering the path for especially successful regeneration treatments. Living materials show great promise in treating a broad spectrum of therapeutic needs from bone and cartilage repair to skin rejuvenation and cardiac tissue engineering (70).

The several engineering approaches used to generate live materials have special benefits and are selected depending on the specific use. For instance, by forming a safe milieu, cell encapsulation protects cells from mechanical stress and immunological attacks (13). While scaffold-based techniques provide structural support and guide cell organization, layer-by- layer assembly gives exact control over the composition and architecture of thin films and coatings. Emerging as especially potent is 3D bioprinting, which allows exact control over cell distribution and scaffold design to create complex tissue structures (71), so providing new routes for the construction of functioning organs and tissues. Microfluidics improves upon current techniques by providing exact environmental control, microscale modification of fluids, cells, and chemical signals. Though there are many challenges as well, living materials show great promise. While exact control over the microenvironment determines optimal cell activity and differentiation, effective regeneration depends on long-term cell survival within the constructions (15). More challenges arise in scaling up the production of living materials for therapeutic uses than in ensuring repeatability through well defined techniques. Immunogenicity of biological components is another issue that needs to be resolved especially with non-autologous source cells. Furthermore, the intricate interaction between cells and biomaterials must be completely understood in order to maximize the design and manufacture of living materials for particular purposes. Notwithstanding these challenges, major advancement in biomaterials, engineering techniques, and our understanding of cell-material interactions is driving the field ahead (72).

A major advancement in biomedical research and tailored treatment are living tissue and organ models combining organ-on- a-chip and organoid technologies. More physiologically suited than traditional 2D cell cultures and animal models, these 3D culture methods let scientists more precisely study human biology and disease (73). Instead of a one-size-fits-all approach, the ability to use patient-derived cells to create tailored models presents great opportunity for personalizing treatments to particular needs. As seen by customized lung-on- a-chip models for cystic fibrosis and tumor organoids for cancer therapy, these platforms could be used to evaluate drugs, identify effective treatments, and even project specific patient responses (74). This customized approach could help to lower side effects, improve treatment outcomes, and hasten the creation of new, targeted drugs. Live tissue/organ models have limitations even if their great potential is Replacing the whole intricacy of human organs in vitro is still a challenge. Many times, these models ignore the intricate interactions among several cell types, the extracellular matrix's architecture, and the function of the immune system (75). Moreover, proving the long-term viability and efficiency of these models could prove difficult, and manufacturing for more general use still presents a difficulty. Reproducibility is yet another issue since variations in cell sources, culture conditions, and manufacturing techniques could produce varying results. Ethical concerns around the utilization of human cells and tissues must also be properly addressed. Despite these limits, the area is fast evolving, with researchers constantly creating novel biomaterials, microfluidic devices, and culture procedures to address these issues (40).

In conclusion, living materials offer a paradigm change in regenerative medicine, combining the benefits of biomaterials with live cells to heal specific tissues. Many engineering techniques let one create customizable buildings, each tuned to different regeneration needs. Although there are still challenges in implementing these technologies into general clinical use, present developments in biomaterials, microfluidics, and personalized medicine show great possibilities for changing therapy approaches and raising patient outcomes.

Funding

This study results from independent research conducted without financial support.

Ethics approval and consent to participate

Not applicable.

Conflict of Interest

No conflicts of interest were disclosed.

Consent for publication

Not Applicable

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