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Original Article

NATURAL BIOPRINTING: TEXTILE SOURCES AND PROPERTIES

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ABSTRACT

The field of bioprinting has witnessed a variety of materials attempting to establish themselves as suitable bioinks. In the medical field, bioink has found its application, but it still faces challenges in striking a balance between biological requirements and mechanical properties. Synthetic materials offer the desired mechanical properties due to controlled production, but they lack biocompatibility. These materials, even though they have an upper hand in production, fall short in their ability to interact with the complex in situ environment. Tackling this issue, bioprinting has been revolutionized by natural biopolymers due to their exceptional biocompatibility. Acquired from natural sources, materials such as cellulose, keratin, silk fibroin, alginate, and collagen can easily mimic the extracellular matrix (ECM). Properties required for bioink, such as mechanical strength, biological properties, and rheological behavior, play a crucial role in complex structural bioprinting. Easily tunable to requirements, these materials can provide a range of architects with inherent cellular adhesion, differentiation, and proliferation properties. Despite their weak mechanical strength and inherent rapid biodegradability, continuous improvements in the blending, crosslinking, and modification of biopolymers have significantly enhanced their printability and structural robustness, making it easier to create biologically active constructs and functional scaffolds. This review will discuss these properties and how natural biopolymers can be an ideal candidate for bioink in a wide range of applications.

Keywords: Printability, Biomimicry, Biomaterials, Tissue Engineering, Scaffold

Abbreviations
ECM- Extracellular Matrix
RGD- Arginine Glycine Aspartic Acid

INTRODUCTION

Bioprinting is a rapidly evolving technology that involves the layer-by-layer deposition of biomaterials and signaling molecules. This enables the fabrication of 3D functional biological complex constructs, allowing for structural complexity and spatial precision, which is a benefit over conventional fabrication methods. With its mimicking ability and functional properties, bioprinting finds applications in various domains, including tissue engineering, personalized medicine, organoids, and organ models Borah and Kumar (2022).

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Transparency: The authors affirm that this manuscript presents an honest, accurate, and transparent account of the study. All essential aspects have been included, and any deviations from the original study plan have been clearly explained. The writing process strictly adhered to established ethical standards.

To achieve the desired construct and functionality tailored to the requirements, the mode of printing plays a crucial role. The most commonly employed technique is Extrusion-based bioprinting, which is used in building large tissue structures, whereas inkjet-based bioprinting produces highly precise cell-incorporated droplets. For microarchitectures and organoid models, high-resolution laser-assisted and digital light projection bioprinting techniques are often employed. Finding the right material compatible with the process and end use is challenging Wu et al. (2023). Synthetic polymers, such as poly(lactic acid), polyurethane, poly(lactic-co-glycolic acid), polycaprolactone, and polyamide, provide mechanical robustness but often lack biocompatibility. To overcome this challenge, additional materials need to be incorporated into these materials. For example, to promote cell attachment and signaling, synthetic polymers may require functionalization, such as the addition of RGD peptide sequences Kumar et al. (2023). On the other hand, natural polymers such as collagen, silk fibroin, keratin, and cellulose possess mechanical resilience and inherent biocompatibility, making them ideal candidates for bioprinting Ghosh et al. (2025).

This review will further explore the desired characteristics that a bioink should possess for its application in bioprinting and discuss how natural biopolymers fit into this context.

BIOINK PROPERTIES

The functionality of a biomaterial during printing and after its application depends on the properties it possesses. These properties make them suitable for use in various functionalities, such as tailored degradation and drug delivery. These properties can be further divided, as needed, into biological, mechanical, and rheological categories. Biological properties are those that ensure its interaction with the surrounding cell, whereas mechanical properties are responsible for structural integrity. Rheological properties are crucial for the material's printability, which makes the desired form best suited for its intended application Theus et al. (2020).

BIOLOGICAL PROPERTIES

BIOCOMPATIBILITY

The foremost criterion for a material to be used in an in vivo system is biocompatibility. This ensures cell attachment and allows the material to function without any toxic effects. The biomaterial should be well tolerated by the host and living cells, remaining viable during and after printing. These materials ideally mimic the extracellular matrix (ECM), which helps in promoting tissue-specific function and integration, where the biocompatibility property ensures minimal immune rejection upon implantation Bedell et al. (2020).

DEGRADABILITY

Controlled degradability ensures tissue protection and healing, where the degradability rate is carefully monitored for tissue remodeling and repair, allowing for the gradual transfer of mechanical load to new tissues and preventing a chronic response. Unnecessary lump and knot formation can result from a slow degradation rate, and rapid degradation can lead to a triggered trauma response, where the tissue is not completely healed, but the holding system has vanished. In most cases, degradability is also linked to the material's drug delivery activity, promoting smooth repair. Hence, tailored degradability should always be in sync with the tissue repair rate Yao et al. (2019).

MECHANICAL REQUIREMENTS

As the material must mimic the natural environment with respect to tissue stiffness, elasticity, and strength in the case of ECM and bone strength, density, and porosity in the case of bone implantation, its structural integrity plays a crucial role in viability. These properties can be tailored by adding fillers or building composites for each application Yang et al. (2022).

SHAPE FIDELITY

Bioprinting involves 3D layer-on-layer deposition; the material should be able to retain its intended architecture and resist deformation and collapse during and after printing. It should be able to withstand gravitational forces, physical stresses, and swelling behavior during all stages of application.

PERMEABILITY AND POROSITY

Porosity increases the chances of cell migration, encourages vascular ingrowth in larger constructs, and facilitates the diffusion of nutrients and oxygen. Designing a permeable and porous material is essential in a thick construct to tackle limited diffusion. Controlled fiber spacing, microchannel incorporation through salt leaching techniques, can create an interconnected porous network Suntornnond et al. (2017).

RHEOLOGICAL PROPERTIES

A significant factor that determines the printability of the material is its rheological characteristics. This helps in achieving accurate deposition for complex structures and materials. A change in the phase of the material, leading to its shape retention after extrusion, is essential for maintaining layer integrity. Materials should exhibit shear-thinning behavior and recover after stress, enabling smooth extrudability and maintaining shape retention. Similarly, the surface tension of the materials impacts the adhesion and droplet formation in printing modalities Schwab et al. (2020).

VISCOSITY

Optimal viscosity enables free flow and smooth extrusion during printing. Shear thickening behaviour is highly desirable for maintaining construct integrity after deposition while minimizing cell damage during extrusion. Viscosity varies depending on the printing techniques used. It should be low enough to flow through nozzles but significantly high enough to hold the form after deposition. The surface tension parameter plays a crucial role, along with viscosity, to ensure uniformity, layer adhesion, and a restricted desired boundary for the construct Habib et al. (2024).

CROSSLINKING

To achieve the desired mechanical properties, degradation rate, and biocompatibility, various crosslinking techniques are employed. Methods such as chemical crosslinking, enzymatic crosslinking, ionic crosslinking, and photo crosslinking using visible or UV light help in stabilizing the printed layers with minimal damage. This post-printing stabilization solidifies the construct quickly, preserving cell viability and mechanical properties GhavamiNejad et al. (2020).

These various properties enable the biomaterial to be tailored according to its functionality, supporting both biological interactions and the printing process. This balance is crucial for applications in tissue engineering and biotechnology.

BIOPOLYMERS FOR BIOPRINTING

Natural biopolymers find their application in tissue engineering and regenerative medicine because of their excellent inherent properties, such as biocompatibility, degradability, and ability to mimic the ECM. From diverse sources, including plants, animals, and microorganisms, they exhibit a range of chemical and structural properties. This allows them to be tuned according to the requirements through the process and modification, as represented in Table 1 Rijal (2023).

Table 1

Table 1 Natural Bioinks and It's Properties

Sr. No	Biopolymer	Source	Application	Properties		
				Biological	Mechanical	Rheological
1	Alginate	Brown Seaweed	Vascular tissue, drug delivery	Non-immunogenic, Biocompatible	Low mechanical strength, ionic gelation	Shear thinning, tunable viscosity
2	Collagen	Mammalian ECM	Soft tissue, scaffolds, vascular grafts	Cell adhesion, high bioactivity	Needs reinforcement, tunable stiffness	Moderate viscosity
3	Keratin	Hair, feathers	Wound healing, bone scaffold	Cell binding motifs	High strength	Processed to hydrogels, modifiable films
4	Silk Fibroin	Silkworm cocoons	Cartilage, neural tissue	Non-toxic, promotes cell growth	Good elasticity, high tensile strength	Stable hydrogels
5	Cellulose	Plants and bacteria	Wound dressing, load-bearing scaffolds	Structural support, biocompatible	High mechanical reinforcement	Improves rheology and shape fidelity

ALGINATE

Alginate is a non-toxic, cost-effective material sourced from brown seaweed. This linear anionic polysaccharide is made up of α-L-guluronic acid (G) and β-D-mannuronic acid (M). Ionic crosslinking with cations, such as calcium ions, is used to form hydrogels, which facilitate rapid gelation and enable effective shape preservation. With chemical modifications, the cell adhesion properties increase, making its employment possible in cartilage, drug delivery systems, and other applications Mallakpour et al. (2021).

COLLAGEN

Collagen is an abundant protein found in mammalian tissue. As a major structural component of the ECM, it possesses natural binding sites that facilitate cell adhesion, differentiation, and migration. This makes it ideal for applications that require effective biological signaling, such as skin regeneration, vascular grafts, and bone repair. It exhibits good gelation properties at physiological temperatures and can be easily stabilized through chemical and physical treatments Osidak et al. (2024). Collagen is modified chemically and physically to get the desired properties. One such product is Gelatin, which is a denatured form of collagen that can be thermally reversed. This leads to collagen losing its native triple-helix structure, keeping the bioactive sequences more accessible and intact. The further introduction of chemical groups, such as methacryloyl, enables photo-crosslinking. This helps in gaining more control over gel stiffness, allowing for tunable and excellent printability. More complex applications, such as nerve scaffolds, cardiac patches, and soft tissue engineering, are made possible through the use of modified collagen Clark et al. (2019).

KERATIN

Keratin is a fibrous structural protein found in hair, nails, and horns. It is extremely biocompatible, which supports cell adhesion due to the presence of cell-binding motifs. The strong disulfide crosslinking imparts keratin with flexibility, strength, and resistance to enzymatic and chemical degradation. These features create bioactive scaffolds that closely mimic native extracellular matrices, facilitating both structural support and biological interactions. Keratin is a versatile material for applications in regenerative medicine and bioprinting, as it can be processed in various forms, including hydrogels, nanofibers, scaffolds, and films. The additional properties of shear thinning and high cell viability during fabrication, along with the blending ability with other biopolymers, further enhance its mechanical and biological integrity Feroz et al. (2020).

SILK FIBROIN

Silk fibroin is obtained from Bombyx mori silkworm cocoons. Silk fibroin consists of light and heavy chains of proteins. This results in good elasticity, tensile strength, and tunable degradation rates. It has the ability to be transformed into a range of morphologies. Hydrogel for bioinks to composite scaffolds. It supports proliferation and multiple types of functions, which makes it adaptable to advanced composites, musculoskeletal tissue engineering, and tissue scaffolds Prakash et al. (2023).

CELLULOSE

Cellulose is a polysaccharide obtained from plants; however, recent developments have also made it possible to produce nanocellulose through bacterial fermentation. It resembles the native ECM due to its nanoscale fibrous network and its excellent mechanical stability. Nanocellulose is also used as an additive in bioink formulations to improve the shear-thinning ability. Additionally, it is also used as a reinforcing agent in various soft hydrogels to impart desirable mechanical integrity Sharma et al. (2025).

CONCLUSION

Through exceptional biocompatibility, biodegradability, and the ability to mimic ECM, natural biopolymers revolutionize bioprinting, making it an ideal candidate for bioink formulation. Collagen, gelatin, silk fibroin, cellulose, and others, with inherent biocompatibility and easily tunable mechanical properties, enable their application in fields such as tissue engineering, wound dressing, and drug delivery. The tunability and adaptability of natural biopolymers, combined with their compatibility with other polymers, make them well-suited for modification, blending, and various forms. Structural robustness and printability are significantly improved through these modifications, despite the limited mechanical strength and rapid degradation. Continued innovation in natural biopolymer-based bioinks can lead to the development of personalized, multifunctional, and effective solutions in bioprinting.

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