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COMMENTARY

The future of 3D bioprinting: From functional tissues to standardized manufacturing and clinical translation

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Abstract

Three-dimensional (3D) bioprinting has evolved from demonstrating the feasibility of fabricating complex tissue architectures to engineering increasingly functional biological constructs. However, advances in biological functionality have not been matched by comparable progress in standardized evaluation, manufacturing consistency, and clinical translation. Here, we propose a Bioprinting 1.0 to 5.0 evolutionary framework that describes the progression of the field from engineering feasibility and biological compatibility to biological functionality, standardized manufacturing, and clinical translation. We discuss emerging standardization efforts across extrusion-, jetting-, and vat photopolymerization–based bioprinting and highlight the need for quantitative, reproducible benchmarks spanning bio-ink properties, printing performance, construct quality, and biological function. We further examine the manufacturing, safety, regulatory, and clinical requirements needed to translate functional bioprinted tissues into therapeutic products. This framework provides a roadmap for advancing 3D bioprinting from laboratory-scale demonstrations toward reproducible and clinically translatable tissue engineering.

Keywords: 3D bioprinting; Biofabrication; Bio-inks; Tissue engineering; Standardization; Clinical translation

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1. Introduction

Three-dimensional (3D) bioprinting has evolved from fabricating anatomically relevant tissue constructs toward engineering increasingly functional tissues and organs for regenerative medicine, disease modeling, and personalized healthcare.[1-5] Advances in extrusion-, jetting-, and vat photopolymerization–based bioprinting have expanded the achievable resolution, structural complexity, and material diversity of printed constructs, while developments in printing systems,[6-13] bio-ink design[14-23] and bioprinting strategies[24-30] have further improved printing precision, cell viability, and biological performance.

Despite these advances, the translation of bioprinted constructs from laboratory research to clinical applications remains limited.[31] Engineering metrics such as printability,[32-34] shape fidelity,[35,36] and post-printing cell viability[37-40] continue to serve as

common benchmarks of bioprinting performance, whereas biological functionality, reproducibility, standardized evaluation, manufacturing readiness, and regulatory requirements receive comparatively less attention. This disparity highlights a fundamental challenge for the field: technological advances in fabrication do not necessarily translate into functional, reproducible, and clinically deployable tissue products.

As 3D bioprinting enters a new phase of development, its progress should therefore be evaluated against broader biological, manufacturing, and clinical objectives. In this Commentary, we propose a five-stage evolutionary framework spanning *Bioprinting 1.0 (Engineering Feasibility)* to *Bioprinting 5.0 (Clinical Translation)*, reflecting the changing scientific priorities and performance benchmarks of the field. We further discuss how standardized characterization and evaluation, guided by emerging international standards and clinically relevant performance criteria, can improve reproducibility, support regulatory assessment, and facilitate the translation of bioprinted tissues into clinical practice.

2. Evolutionary framework of 3D bioprinting

Since its emergence, 3D bioprinting has evolved through successive shifts in scientific priorities, progressing from engineering feasibility toward biological functionality, standardized manufacturing, and clinical translation. Early efforts established the engineering foundations of 3D bioprinting, demonstrating that complex tissue architectures could be fabricated with high shape fidelity.[41] As the field advanced, the emphasis expanded from structural fabrication to cell compatibility, biological functionality, manufacturing reproducibility, and clinical applicability. We propose a five-stage evolutionary framework in which successive generations of 3D bioprinting are defined by their primary scientific priorities and corresponding evaluation benchmarks: *Bioprinting 1.0 (Engineering Feasibility)*, *Bioprinting 2.0 (Biological Compatibility)*, *Bioprinting 3.0 (Biological Functionality)*, *Bioprinting 4.0 (Standardized Manufacturing)*, and *Bioprinting 5.0 (Clinical Translation)* (Figure 1). Each stage represents a shift in the primary benchmark used to evaluate progress, reflecting the increasing technological, biological, manufacturing, and clinical maturity of the field.

Bioprinting 1.0 (Engineering Feasibility) established the technological foundation of 3D bioprinting. Research during this stage demonstrated that complex 3D architectures could be fabricated using extrusion-, jetting-, and vat photopolymerization–based bioprinting approaches. Printability, shape fidelity, dimensional accuracy, and structural stability became key engineering benchmarks for assessing fabrication feasibility. These advances established the technological basis for incorporating living cells and biologically active components into bioprinted constructs.

The incorporation of living cells marked the emergence of *Bioprinting 2.0 (Biological Compatibility)*. The focus expanded from fabricating biomaterial structures to producing cell-laden constructs while preserving cell viability, proliferation, and phenotypic stability during and after printing. Bio-ink development therefore emphasized cytocompatibility, shear protection, nutrient transport, and crosslinking strategies that support cellular survival. Post-printing cell viability became a widely used benchmark for evaluating bioprinted constructs. However, maintaining viable cells alone was insufficient to reproduce the structural organization and functional complexity of native tissues.

This limitation led to *Bioprinting 3.0 (Biological Functionality)*, where the objective expanded from maintaining cellular viability to directing tissue development and function. Bio-inks evolved into cell-instructive matrices that regulate cellular behaviour through biochemical, architectural, and metabolic cues, providing greater control over tissue development and maturation. Bio-inks evolved into cell-instructive matrices that regulate cellular behaviour through biochemical, architectural, and metabolic cues, providing greater control over tissue development and maturation.[42] Advances in bio-ink design, multicellular bioprinting, vascularization, and tissue-specific microenvironment engineering have enabled the fabrication of biomimetic tissue constructs with greater structural organization and biological complexity. Evaluation therefore expanded beyond cell viability to include tissue maturation, biomimetic organization, and tissue-specific function.

Today, most 3D bioprinting research remains within the *Bioprinting 3.0 (Biological Functionality)* stage, with substantial progress in cell-instructive bio-inks, biomimetic microenvironments, vascularized constructs and organotypic tissue models. The transition toward *Bioprinting 4.0 (Standardized Manufacturing)* and *Bioprinting 5.0 (Clinical Translation)* remains incomplete. Variations in experimental methodologies, material characterization, biological assessment, and reporting practices continue to limit interlaboratory reproducibility and the comparison of bioprinting outcomes. Moving beyond *Bioprinting 3.0 (Biological Functionality)* therefore requires a shift from demonstrating biological function toward establishing reproducible, measurable, and controllable manufacturing processes.

Bioprinting 4.0 (Standardized Manufacturing) addresses

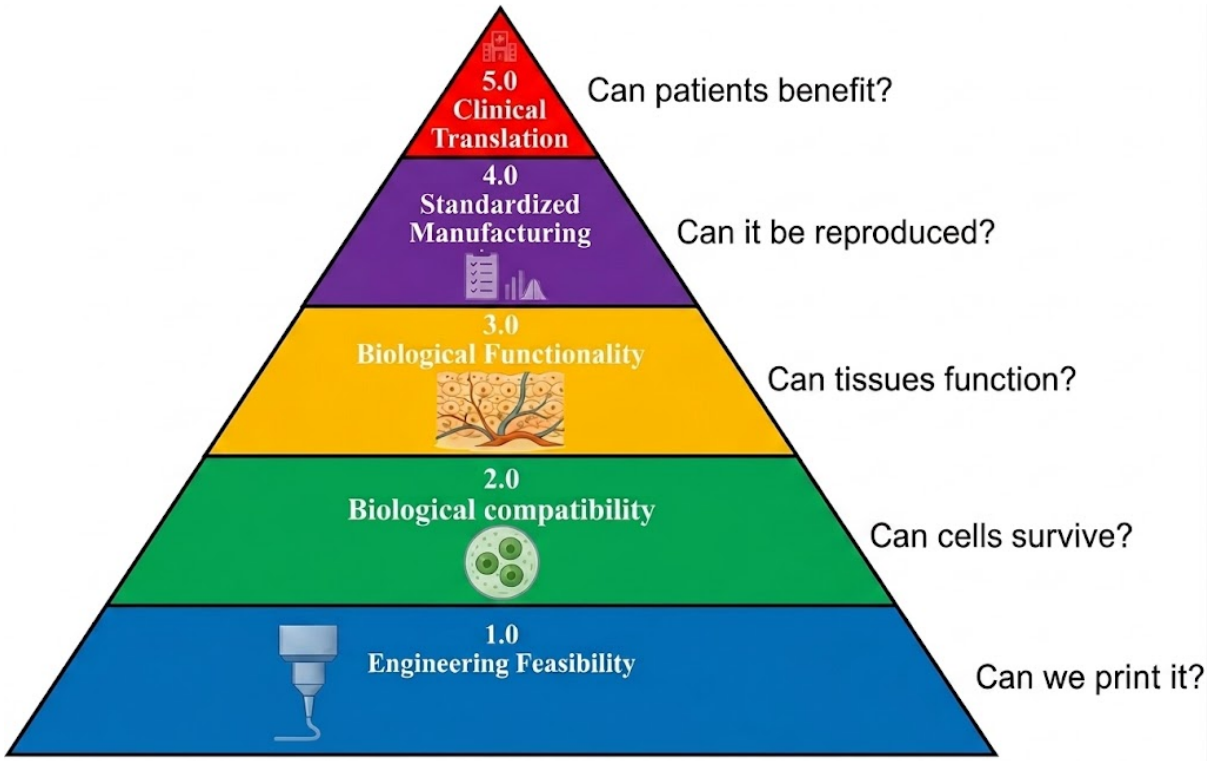


Figure 1. Evolutionary framework of 3D bioprinting from engineering feasibility to clinical translation. Proposed Bioprinting 1.0 to 5.0 framework illustrating the evolution of 3D bioprinting from proof-of-concept fabrication toward clinically translatable tissue-engineered products. *Bioprinting 1.0 (Engineering Feasibility)* established the technological foundation by demonstrating the fabrication of complex tissue architectures with high shape fidelity. *Bioprinting 2.0 (Biological Compatibility)* incorporated living cells into the fabrication process while emphasizing cell viability, proliferation, and phenotypic stability. *Bioprinting 3.0 (Biological Functionality)* shifted the focus toward engineering biomimetic tissues capable of tissue-specific function through cellular maturation and physiologically relevant microenvironments. *Bioprinting 4.0 (Standardized Manufacturing)* focuses on reproducible evaluation across bio-ink characterization, printing performance, structural fidelity, cellular function, long-term construct stability, and manufacturing consistency, establishing common benchmarks while retaining modality-specific requirements. *Bioprinting 5.0 (Clinical Translation)* extends this foundation toward clinically relevant products through product design, bio-ink formulation, standardized manufacturing, autonomous process control, preclinical validation and regulatory approval, and clinical assessment. Together, these stages describe the progression of 3D bioprinting from demonstrating fabrication feasibility to establishing reproducible manufacturing and ultimately generating safe, functional tissues with meaningful patient benefit.

this challenge by establishing common evaluation and reporting frameworks across the bioprinting workflow. Standardization should encompass bio-ink characterization, printing performance, structural fidelity, cellular function, long-term construct stability, and manufacturing consistency, while retaining evaluation criteria specific to different printing modalities. These domains provide a common basis for comparing materials, printing systems, and bioprinted constructs across laboratories and for identifying sources of process and biological variability. Standardized evaluation provides the measurement foundation for subsequent manufacturing control, quality assessment, and regulatory evaluation.

Bioprinting 5.0 (Clinical Translation) represents the progression from standardized tissue manufacturing toward clinically translatable products. This stage extends beyond fabrication and biological performance to encompass product design, bio-ink formulation, standardized manufacturing, autonomous process control, preclinical validation and regulatory approval, and clinical assessment. Progress will require bioprinted tissues to demonstrate reproducible quality, safety, functional performance, and meaningful patient benefit within appropriate manufacturing and regulatory frameworks. Patient-specific tissue design, automated process control, qualified materials and cells, and clinically compliant manufacturing workflows may further support the integration of bioprinted tissues into clinical practice.

The proposed *Bioprinting 1.0 to 5.0* framework provides a conceptual roadmap for the continued development of 3D bioprinting. *Bioprinting 1.0 to 3.0* established the engineering and biological foundations for fabricating

increasingly functional tissues, while *Bioprinting 4.0 (Standardized Manufacturing)* addresses the standardization and reproducibility required for controlled manufacturing and *Bioprinting 5.0 (Clinical Translation)* extends these foundations toward regulatory evaluation and clinical application. The progression is therefore not defined solely by increasing structural or biological complexity, but by the evolution of the benchmarks used to establish fabrication feasibility, biological functionality, manufacturing reproducibility, and ultimately clinical value.

3. Standardization: Establishing reproducible bioprinting benchmarks

The transition from *Bioprinting 3.0 (Biological Functionality)* to *Bioprinting 4.0 (Standardized Manufacturing)* requires a fundamental shift in how bioprinted constructs are evaluated. Although substantial progress has been achieved across extrusion-, jetting-, and vat photopolymerization–based platforms, characterization of bio-inks, printing performance, structural fidelity, and biological outcomes remains highly variable. Differences in bio-ink composition, printer configuration, processing conditions, and evaluation protocols can generate substantial interlaboratory variation, limiting reproducibility and meaningful comparison. Standardization is therefore needed across the bioprinting workflow, while recognizing that common cross-platform requirements must be complemented by modality-specific evaluation criteria.

To translate the concept of standardized manufacturing into measurable criteria, we propose a framework spanning six evaluation domains: bio-ink characterization, printing performance, structural fidelity, cellular function, long-term construct stability, and manufacturing consistency (Table 1). These domains build upon emerging bioprinting-specific standardization efforts, including ASTM F3659-24 and ISO/WD 26013, while recognizing the need to align with broader medical-device frameworks as bioprinted products progress toward clinical translation. ASTM F3659-24 provides a bioprinting-specific framework organized around pre-printing, printing, and post-printing considerations, including bio-ink properties, cellular components, crosslinking, printability, stabilization, cytocompatibility, structural fidelity, and post-print cell viability and function.[42] Its primary focus is extrusion-based bioprinting, providing an important foundation for modality-specific standardization. In parallel, ISO/WD 26013 is being developed to establish requirements and test methods for cell-containing 3D bioprinting across different stages of the printing process, with specific considerations for stereolithography, microextrusion, and drop-on-demand inkjet systems.[43] Together, these initiatives provide an emerging basis for moving from descriptive reporting toward harmonized quantitative evaluation, although important gaps remain.

For bio-ink characterization, standardization should extend beyond reporting individual rheological properties toward defined material specifications and reproducible test conditions. Rheological behavior, crosslinking kinetics, surface tension, optical properties, degradation behaviour, chemical composition, and cytocompatibility can influence both printing performance and cellular response. ASTM F3659-24 provides a foundation for characterizing bio-inks and their suitability for bioprinting,[42] while ISO/WD 26013 further supports standardized evaluation of material and process characteristics within cell-containing bioprinting workflows.[43] For clinical translation, material characterization should also align with the broader ISO 10993 framework for biological evaluation.[44] In particular, ISO 10993-1:2025 establishes a risk-based framework for evaluating biological safety, providing a complementary framework to bioprinting-specific characterization.[44] Thus, future standards should link bio-ink composition and material properties to printing performance, biological response, and clinically relevant safety considerations, rather than treating printability and biocompatibility as independent endpoints.

For extrusion-based bioprinting, standardization can build on the relatively mature understanding of bio-ink rheology and process-material interactions.[45] Printing performance is influenced by bio-ink viscosity and viscoelasticity, flow rate, nozzle diameter, extrusion pressure, temperature, and crosslinking kinetics, which affect deposition fidelity and the mechanical stresses experienced by encapsulated cells. ASTM WK92859, currently under development, specifically addresses printability of bio-inks and material inks used in laminar-flow extrusion bioprinting.[46] Quantitative assessment of single-line deposition, multilayer lattices, and upright cylindrical structures against their corresponding CAD geometries could provide reproducible measures for comparing bio-inks and printing systems.[46] Nevertheless, structural fidelity alone cannot fully capture extrusion performance because filament continuity, spreading, collapse, interlayer bonding, and dimensional deviation may respond differently to material and process parameters. Standardized extrusion assessment should therefore combine structural outcomes with defined material and process measurements, allowing variations in construct architecture to be related to measurable changes in bio-ink behavior and operating conditions.

Jetting-based bioprinting requires a different set

of process parameters because material is deposited as discrete droplets rather than continuous filaments. Droplet formation and deposition depend on viscosity, surface tension, inertia, actuation conditions, nozzle geometry, substrate wettability, and cell concentration.[47] Dimensionless parameters such as the Ohnesorge (*Oh*) number and *Z*-number provide useful representations of the relative contributions of viscous, inertial, and surface-tension forces and can help identify stable jetting regimes. However, these parameters alone are insufficient as universal performance metrics because jetting systems use different actuation mechanisms and hardware configurations. Standardization should therefore prioritize transferable output measures, including droplet volume and velocity distributions, positional accuracy, satellite formation, deposition repeatability, and post-print cell viability. ISO/WD 26013 provides an important emerging framework by incorporating drop-on-demand inkjet printing within its proposed requirements,[43] but dedicated methods for linking droplet dynamics with deposition performance and cellular response are still required.

For vat photopolymerization–based bioprinting, printing performance is governed by the interaction between optical parameters, photopolymerization kinetics, material composition, and cellular response. Light wavelength and intensity, exposure duration, optical attenuation, photo-initiator and photo-absorber concentrations, and bio-ink composition can influence curing depth, dimensional accuracy, mechanical properties, and cell viability.[48,49] ASTM WK83109 provides process-specific design guidance for vat photopolymerization,[50] while ASTM WK78224 addresses mechanical characterization of lattice structures fabricated using vat photopolymerization.[51] Further standardization is needed for bio-ink-specific parameters, including optical attenuation, curing behavior, degree of conversion, residual photo-initiator or monomer content, and cellular responses to photopolymerization. Optical exposure should therefore be treated as a process variable with both structural and biological consequences, linking exposure conditions to curing depth, dimensional fidelity, mechanical properties, residual chemical species, and cell response.

Beyond modality-specific printing performance, standardized evaluation should address the quality and stability of the resulting construct. Structural fidelity should be quantified through consistent comparisons between designed and fabricated geometries, including dimensional deviation, filament or droplet placement accuracy, pore and channel fidelity, and structural defects. Cellular evaluation should extend beyond immediate post-print viability to include standardized measurements of morphology, phenotype, proliferation, differentiation, and tissue-specific function using application-relevant endpoints. Similarly, long-term construct stability requires defined testing conditions and time points for structural integrity, mechanical stability, swelling, degradation, and biological function. These aspects remain challenging because culture conditions, sampling time points, degradation protocols, and biological endpoints vary substantially between studies. Importantly, ISO/WD 26013 currently excludes the biological maturation phase and long-term, product-specific investigations from its scope, highlighting the need for complementary standards or application-specific qualification strategies.[43]

Importantly, standardized measurements do not automatically produce standardized outcomes. Reproducibility can remain limited by equipment calibration, operator-dependent variables, material variability, environmental conditions, and differences in process execution. This is particularly relevant to bioprinting because construct properties emerge from the interaction of material, machine, process, and biological variables. Standardization should therefore progress beyond individual test methods toward integrated evaluation frameworks that define material specifications, process windows, calibration requirements, in-process monitoring, reporting requirements, and acceptance criteria. The objective is not to impose identical operating conditions across different bioprinting modalities, but to establish sufficiently well-defined measurements and reporting practices that results generated across platforms can be interpreted within a common framework. Such standardized evaluation will provide the measurement foundation for *Bioprinting 4.0*, enabling reproducible manufacturing and generating the quality evidence required for the product-specific validation and regulatory considerations discussed in the next section.

4. Clinical translation: From standardized manufacturing to patient benefit

The transition from *Bioprinting 4.0 (Standardized Manufacturing)* to *Bioprinting 5.0 (Clinical Translation)* requires bioprinted constructs to progress from reproducible research outputs to well-characterized therapeutic products with defined quality, safety, and efficacy attributes. Figure 2 outlines a proposed translational pathway spanning product design, bio-ink formulation, standardized manufacturing, autonomous process control, clinical assessment, and regulatory approval. The regulatory pathway is not determined by the printing technology alone, but by the nature of the final product, its cellular and material components, intended

Table 1. Proposed framework for standardized evaluation of bioprinted tissue constructs

Evaluation domain	Current evaluation parameters	Future standardized benchmarks	Relevant standardization frameworks
Bio-ink characterization	Viscosity, viscoelasticity, shear-thinning behavior, gelation/crosslinking kinetics, surface tension, optical properties, cytocompatibility	Defined test conditions and reporting requirements; material specifications and acceptance ranges linked to printing modality and intended application	ASTM F3659-24; ISO/WD 26013; ISO 10993-1:2025
Printing performance	Flow rate, extrusion pressure, printing speed, droplet velocity, jetting stability, printability, deposition accuracy	Standardized operating conditions and quantitative measures of deposition stability, accuracy, repeatability, and process robustness	ASTM F3659-24; ISO/WD 26013; ASTM WK83109
Structural fidelity	Line width, pore size, dimensional accuracy, layer thickness, filament continuity, spreading, collapse, channel patency	Quantitative CAD-to-print comparison, dimensional deviation, filament/droplet placement accuracy, pore and channel fidelity, and defect frequency	ASTM F3659-24; ISO/WD 26013; ASTM WK83109
Cellular function	Viability, proliferation, morphology, phenotype, differentiation, tissue-specific function	Defined assay conditions, time points, controls, and application-specific functional endpoints; quantitative relationships between process conditions and cellular response	ASTM F3659-24; ISO/WD 26013; ISO 10993-1:2025
Long-term construct stability	Structural integrity, mechanical stability, swelling, degradation, cell viability and function over time	Defined culture conditions, sampling time points, mechanical and dimensional retention criteria, degradation rates, and biological stability endpoints	ASTM F3659-24; ISO/WD 26013; ASTM WK78224
Manufacturing consistency	Batch-to-batch variation, operator effects, equipment differences, material variability, environmental and process variability	Material specifications, equipment calibration, validated process windows, in-process monitoring, traceability, interlaboratory reproducibility, and predefined acceptance criteria	ASTM F3659-24; ISO/WD 26013

use, mechanism of action, and manufacturing process. Establishing the appropriate regulatory classification early in development is therefore an important component of *Bioprinting 5.0*.

Product design should consider the intended tissue function, anatomical requirements, and clinical use from the outset. Tissue architecture, cell organization, mechanical properties, degradation, and functional requirements should be defined alongside the intended therapeutic outcome. Bio-ink formulation must then balance printability, structural stability, cell compatibility, and biological function while providing consistent and controllable material properties.

Standardized manufacturing requires control of raw materials, cells, equipment, and printing parameters. Critical quality attributes (CQAs) should encompass material, structural, cellular, and functional properties. These may include bio-ink composition, degree of functionalization, crosslinking behavior, and endotoxin levels; tissue dimensions, architecture, mechanical properties, and degradation; and cell type, concentration, viability, and phenotype. Functional CQAs should reflect the intended functionality, such as matrix production in cartilage, barrier function in skin, or contractility in cardiac tissue.[38] The standardized evaluation framework described in Section 3 provides the measurement foundation for defining and monitoring these attributes across the bioprinting workflow. ASTM F3659-24 and ISO/WD 26013 provide broader frameworks for bio-ink and bioprinting process evaluation,[42,43] while modality-specific standards under development, including ASTM WK92859 for extrusion-based printability and fidelity,[46] ASTM WK83109 for vat photopolymerization,[50] and ASTM WK78224 for mechanical characterization of photopolymerized lattice structures, provide more specific approaches to process and construct assessment.[51] ISO/TS 21560:2020 further provides general requirements for tissue-engineered medical products covering materials, manufacturing, quality control, and biological effects, providing a useful foundation for bioprinted tissue quality control.[52]

The autonomous process control pillar addresses

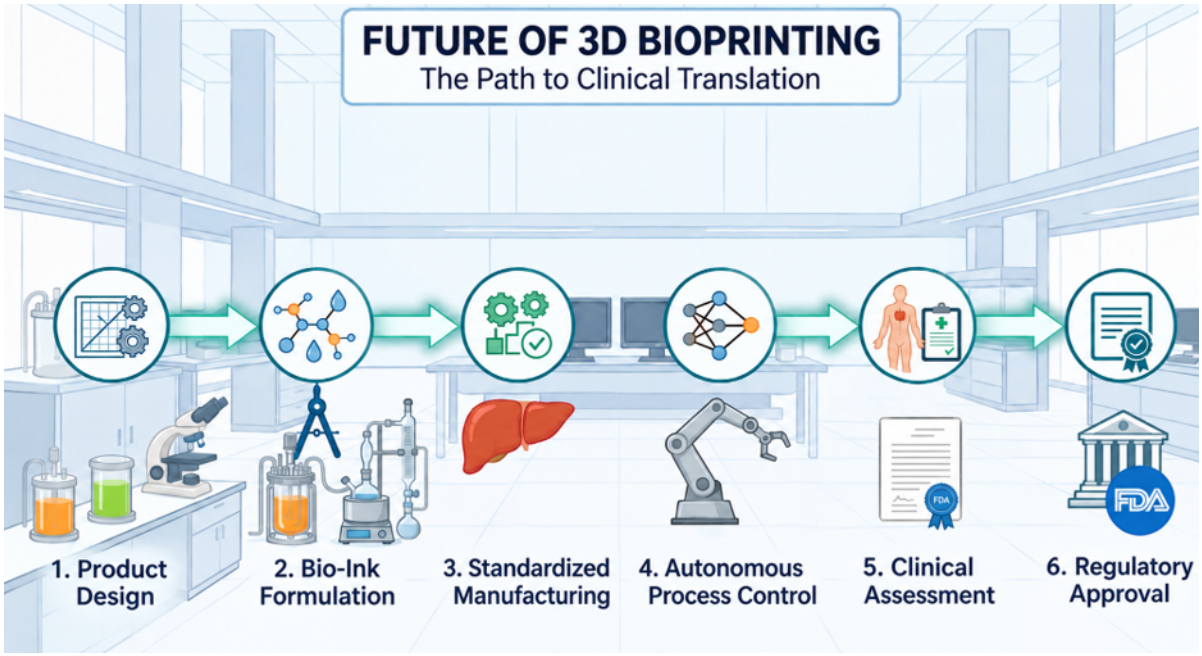


Figure 2. The future of 3D bioprinting: from functional tissues to clinical translation. Schematic pathway integrating product design, bio-ink formulation, standardized manufacturing, autonomous process control, clinical assessment, and regulatory approval. Clinical translation ultimately requires functional tissues to be manufactured reproducibly, meet defined quality and safety requirements, and demonstrate meaningful patient benefit.

variability during fabrication. Imaging and sensor-based systems could monitor filament or droplet formation, layer deposition, pressure, temperature, and optical exposure to detect process deviations and adjust printing parameters in real time using validated, closed-loop control.[53-57] The quantitative measurements and modality-specific benchmarks discussed in Section 3 could provide the reference conditions against which such process deviations are detected. For example, extrusion-based measures of filament continuity and dimensional fidelity, jetting-based measures of droplet volume and deposition accuracy, and vat photopolymerization-based measures of curing behavior and dimensional fidelity could be incorporated into in-process monitoring. Such systems should be linked to CQAs to demonstrate that process measurements provide meaningful indicators of final tissue quality.[58]

Together, the standardized manufacturing and autonomous process control pillars establish the consistency needed for preclinical and regulatory evaluation. However, the transition from a research prototype to a clinically manufactured tissue remains substantial. Research prototypes commonly rely on research-grade materials, manually optimized parameters, variable cell sources, and operator-dependent adjustments. Clinical manufacturing requires qualified and traceable raw materials, controlled cell sources, validated equipment and processes, defined acceptance criteria, and documented manufacturing procedures. Process changes must also be evaluated for their potential impact on product quality. These requirements are particularly important for naturally derived bio-inks and patient-derived cells, where material and biological variability can directly affect the final tissue.

The clinical assessment pillar builds on preclinical evidence of safety, integration, and functional performance and determines whether these attributes translate into meaningful clinical outcomes. For living tissues, high cell viability or structural fidelity alone does not establish therapeutic efficacy. Clinical studies should therefore evaluate safety and therapeutic performance using endpoints appropriate to the intended tissue function and mechanism of action. The design of these studies should also reflect the characteristics of the final manufactured product and the consistency demonstrated during development.

The final pillar, regulatory approval, presents additional challenges because bioprinted tissues integrate living cells and biomaterials within a single therapeutic product.[59] In the United States, cell-containing bioprinted tissues may be regulated under the HCT/P framework in 21 CFR Part 1271, depending on product characteristics, manufacturing processes, degree of manipulation, and intended use.[60] For bioprinted tissues, these interactions may include effects

of the biomaterial or scaffold on cell behavior, changes in material properties during cell culture or degradation, and the influence of manufacturing or processing methods on the final biological product. Consequently, safety and performance should be established for the integrated product, rather than inferred solely from the individual components. In the European Union, cell-containing bioprinted tissues may fall under the Advanced Therapy Medicinal Product (ATMP) framework, including tissue-engineered products (TEPs) and combined ATMPs under Regulation (EC) No 1394/2007.[61] EMA defines combined ATMPs as ATMPs containing one or more medical devices as an integral part, including examples in which cells are embedded in a biodegradable matrix or scaffold. These examples highlight why regulatory classification should be considered early, as cell source, bio-ink composition, tissue design, intended use, and manufacturing process can influence the applicable regulatory requirements.

Bioprinting 5.0 therefore extends beyond the fabrication of functional tissues to the demonstration that these tissues can be manufactured reproducibly, characterized using meaningful quality and potency attributes, evaluated clinically, and approved within an appropriate regulatory framework. Successful translation will require integration of standardized manufacturing, process control, product-specific release testing, clinical evidence, and regulatory assessment to demonstrate that bioprinted tissues are safe, functional, and capable of providing meaningful patient benefit.

5. Concluding remarks

3D bioprinting has progressed from demonstrating engineering feasibility to developing increasingly functional tissue constructs. The proposed *Bioprinting 1.0 to 5.0* framework captures this evolution from engineering feasibility and biological compatibility to biological functionality, standardized manufacturing, and clinical translation. While substantial progress has been achieved across the first three stages, broader implementation will require greater emphasis on standardized evaluation, manufacturing consistency, process control, and clinically relevant validation. *Bioprinting 4.0* establishes this foundation by defining common benchmarks for bio-ink characterization, printing performance, structural fidelity, cellular function, long-term construct stability, and manufacturing consistency, while accommodating modality-specific requirements. *Bioprinting 5.0* builds on this foundation by integrating product design, bio-ink formulation, standardized manufacturing, autonomous process control, clinical assessment, and regulatory approval. The future of 3D bioprinting will therefore depend not only on the ability to fabricate functional living tissues, but on demonstrating that these tissues can be manufactured reproducibly, meet defined quality and safety requirements, and provide meaningful clinical benefit. Achieving this goal will require closer integration of biomaterials science, bioprinting technologies, manufacturing engineering, standardization, regulatory science, and clinical research.

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Conflict of interest

Both Prof. Paulo Bartolo and Dr. Wei Long Ng serve as Editorial Board Members of this journal, but were not in any way involved in the editorial and peer-review process conducted for this paper, directly or indirectly. The authors declare they have no competing interests.

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Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

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Further disclosure

The authors take full responsibility for the integrity and accuracy of the scientific content presented. AI-assisted tools were used to improve Figure 2.

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