

Bioprinting: 3D Printing of Tissues and Organs, Role in Bio Modelling and Medical Research

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Abstract. This research investigates the capabilities and applications of bioprinting technology in tissue engineering and medical research through a comprehensive analysis of various printing methods and outcomes. The study examined data from 30 research facilities implementing different bioprinting technologies, including extrusion-based, inkjet-based, and laser-assisted systems. Statistical analysis revealed strong correlations between printing parameters and tissue outcomes, with significant relationships between printing speed and structural integrity ($r = 0.78$, $p < 0.001$) and material viscosity and cell viability ($r = 0.82$, $p < 0.001$). Extrusion-based systems achieved printing speeds of 10-15 mm/s while maintaining cell viability rates of 80-90%, whereas laser-assisted systems demonstrated superior precision with resolution down to 10 micrometres. Tissue models showed varying success rates, with skin constructs achieving 85% appropriate structural organisation and cartilage models demonstrating mechanical properties reaching 60-80% of native tissue values. Implementing bioprinting technology reduced drug screening timelines by 40% while achieving 85% accuracy in predicting adverse reactions. These findings demonstrate significant potential for bioprinting applications in medical research, particularly in drug development and tissue engineering, while highlighting critical areas requiring further development, especially in vascularisation strategies for larger tissue constructs.

Keywords: Bioprinting; Tissue Engineering; Drug Development; Cell Viability; Printing Parameters; Medical Research; Technology Assessment; Statistical Analysis; Tissue Models; Vascularization

INTRODUCTION

Bioprinting technology has emerged as a transformative force in medical research and tissue engineering, offering unprecedented capabilities for creating functional tissue constructs. This advancement addresses critical challenges in medical research while opening new possibilities for drug development and therapeutic applications.

The economic implications of bioprinting technology have gained increasing attention in recent years. Authors [1] identify significant potential for cost reduction in drug development through bioprinted tissue models. While initial technology investment remains substantial, the long-term benefits in research efficiency and reduced animal testing requirements suggest favourable

economic outcomes for research institutions implementing these systems.

International collaboration has emerged as a crucial factor in advancing bioprinting technology. Authors [2] demonstrate how shared protocols and standardised approaches across different research facilities accelerate technological development. This collaborative approach has proven particularly valuable in addressing everyday challenges, such as vascularisation and tissue stability while enabling more rapid validation of new methods and materials.

The regulatory landscape surrounding bioprinting technology continues to evolve, reflecting growing recognition of its potential in medical research and therapeutic applications. Authors

[3] highlight the importance of establishing clear guidelines for quality control and validating bioprinted tissue models. This regulatory development supports the broader adoption of the technology while ensuring the maintenance of scientific rigour and research reliability. These considerations underscore the complex interplay between technological advancement, practical implementation, and regulatory compliance in bioprinting.

Current State of Bioprinting Technology. Modern bioprinting systems combine sophisticated engineering principles with biological understanding to create complex tissue structures. Authors [4] demonstrate how current technologies enable the precise placement of cells and materials in three-dimensional arrangements replicating natural tissue architecture. These systems now achieve resolution levels capable of recreating detailed cellular organisations while maintaining high cell viability rates.

The field has witnessed significant technological diversification, with three primary approaches dominating current applications. Extrusion-based systems offer versatility in handling various materials and creating larger constructs. Inkjet-based technologies provide high precision for detailed cellular patterning. Laser-assisted systems achieve exceptional resolution for specific applications. These complementary approaches enable researchers to address tissue engineering and medical research challenges.

Problem Statement. Despite remarkable advances, bioprinting technology faces several critical challenges that limit its broader implementation in medical research and potential therapeutic applications. The fundamental challenge lies in creating fully functional tissue constructs that maintain long-term viability and proper physiological function. Authors [5] identify vascularisation as a particular bottleneck, limiting the size and complexity of viable tissue constructs.

The field also confronts significant challenges in standardisation and reproducibility. Creating consistent, high-quality tissue constructs across different facilities and applications remains difficult. These challenges extend to material selection, with current bio-inks often struggling to meet the diverse requirements of various tissue types while maintaining printability and biological functionality.

Recent Developments (2021-2024). In recent years, substantial progress has been made in addressing these challenges. Authors [6] report significant improvements in printing resolution and cell viability through advanced control systems and material formulations. New bioink developments have enhanced printability and biological support capabilities, enabling the creation of more complex tissue structures.

Computational integration represents another significant recent advancement. Authors [7] demonstrate how artificial intelligence and machine learning now support optimising printing parameters and predicting tissue development outcomes. These technological integrations have improved both efficiency and reliability in bioprinting applications.

Research Objectives. This research evaluates bioprinting technologies' current capabilities and limitations in creating functional tissues for medical research applications. The investigation examines different printing approaches, assessing their effectiveness in producing accurate and reliable tissue models for drug testing and disease modelling.

The study also seeks to analyse the integration of bioprinting technology with existing medical research protocols and practices; this includes evaluating standardisation requirements and quality control measures necessary for consistent research outcomes. Additionally, the research examines the potential of bioprinting in developing personalised medical solutions and patient-specific tissue models.

Literature Review. Recent literature reveals significant advances in bioprinting capabilities and applications. Authors [8] document substantial improvements in material development, with new bioink formulations offering enhanced support for cell growth and tissue development. These advances have created more complex tissue structures while maintaining cellular functionality.

The integration of bioprinting with drug development processes has shown particular promise. Authors [9] demonstrate how bioprinted tissue models provide more accurate drug response predictions than traditional testing methods. These applications have accelerated drug screening processes while potentially reducing reliance on animal testing.

Advances in vascularisation strategies represent another significant development. Authors [10] show progress in creating functional blood vessel networks within printed tissues, though limitations remain in supporting larger tissue constructs. This area continues to receive focused research attention as a critical factor in advancing the field.

The evolution of quality control methods has enhanced reliability in bioprinting applications. Authors [11] describe improved protocols for maintaining consistency in tissue production, supporting the broader implementation of the technology in research settings. These developments have particularly benefited standardisation efforts across different facilities.

This comprehensive introduction establishes the context for a detailed examination of bioprinting technology and its applications in medical research. The following sections will present this investigation's methodology, results, and implications, providing insights to advance the field's development and implementation.

METHOD

This research employs a mixed-methods approach to examine bioprinting technologies and their applications in tissue engineering. The comprehensive methodology combines quantitative analysis of technical parameters with qualitative assessment of implementation practices across multiple research facilities.

Research Design. The study utilises a systematic research design that enables a thorough investigation of both technical and practical aspects of bioprinting technology. Authors [12] advocate this integrated approach for investigating complex biomedical technologies, as it provides a comprehensive understanding of measurable outcomes and implementation challenges.

The research design incorporates experimental components to evaluate specific aspects of bioprinting processes and outcomes. Systematic observation protocols enable detailed assessment of printing parameters and tissue development patterns. This approach allows precise technical performance measurement while maintaining practical relevance to research applications.

Population and Sampling. The study encompasses 30 research facilities actively engaged in bi-

oprinting research and development. The selection criteria focused on facilities with at least three years of active bioprinting experience, ensuring meaningful data collection about technology implementation and outcomes. The sample includes academic research institutions (40%), medical research centres (35%), and biotechnology companies (25%), providing balanced representation across different research contexts.

Geographical distribution received careful consideration in the sampling process, with facilities selected from North America (35%), Europe (40%), and Asia (25%). This international scope enables examining different approaches to bioprinting implementation while considering varying regulatory environments and research priorities.

Data Collection Methods. The research employs multiple data collection tools to ensure comprehensive bioprinting applications and outcomes coverage. Direct observation is fundamental, utilising standardised protocols to examine bioprinting processes and tissue development. Technical measurements capture specific printing parameters, including speed, resolution, and material properties.

Structured interviews with research facility personnel provide crucial insights into implementation challenges and solutions. The interview protocols focus on both technical aspects of bioprinting operations and practical considerations in research applications. This approach enables the collection of detailed information about operational experiences and outcomes.

Technical Measurements. The study implements systematic measurement protocols for evaluating printing performance and tissue outcomes. Key parameters include printing speed (measured in mm/s), resolution capabilities (in micrometres), and cell viability rates (through standardised assays). These measurements enable quantitative comparison of different printing technologies and approaches.

The research also examines material properties and their influence on printing outcomes. Measurements include viscosity analysis, mechanical strength testing, and structural integrity assessment in printed constructs. These technical evaluations provide objective data about printing performance and tissue development.

Statistical Analysis. The research employs comprehensive statistical analysis to evaluate rela-

tionships between printing parameters and tissue outcomes. Correlation analysis examines relationships between various technical parameters and printing success rates. Multiple regression models assess the influence of different factors on tissue construct quality.

Analysis of variance (ANOVA) enables performance comparison across different printing technologies and applications. The statistical analysis includes examining the main and interaction effects of various parameters. This approach provides robust evidence for identifying significant factors in bioprinting success.

Validity and Reliability. The study implements multiple measures to ensure research validity and reliability. Expert review of research protocols and instruments supports content validity, while systematic measurement procedures enhance reliability. Regular calibration of measurement instruments and standardisation of observation protocols maintain consistency across different research settings.

Inter-rater reliability receives particular attention through regular assessment of observational data coding. Multiple researchers independently analyse data samples to ensure consistent interpretation. This approach supports the reliability of qualitative findings while maintaining research rigour.

Ethical Considerations. The research adheres to strict ethical guidelines governing biomedical technology research. All participating facilities provided informed consent and maintained the right to withdraw from the study at any stage. Confidentiality protection extends to facility identities, proprietary information, and research data throughout all stages of the investigation.

The study obtained necessary institutional review board approvals before commencing research activities. Environmental responsibility formed another crucial ethical consideration, with the research implementing measures to minimise environmental impact while maintaining research quality.

This comprehensive methodology enables a thorough investigation of bioprinting applications while maintaining scientific rigour and practical relevance. Combining different research approaches provides a robust foundation for understanding technical capabilities and practical implementation challenges in bioprinting technology.

The methodology also incorporates quality control measures throughout the data collection and analysis. Detailed documentation protocols track all experimental procedures, technical measurements, and observational data. This systematic approach ensures data integrity while enabling verification of research findings through clear audit trails. Regular quality checks throughout the research period maintain consistency in data collection and analysis procedures.

Data management follows strict protocols to protect sensitive information while ensuring accessibility for analysis. The research implements secure digital storage systems with appropriate access controls and backup procedures. This comprehensive data management approach supports research security and analytical effectiveness, enabling thorough examination of complex datasets while maintaining the confidentiality of proprietary information.

Timeline management forms another crucial aspect of the research methodology. The study implements structured data collection and analysis schedules to ensure comprehensive coverage of seasonal variations and technological developments. This temporal consideration proves particularly important in examining long-term outcomes and technological evolution in bioprinting applications while maintaining practical feasibility for participating research facilities.

RESULTS AND DISCUSSION

The analysis of bioprinting technologies and their applications reveals significant variations in performance characteristics and outcomes across different printing methods and tissue types. This comprehensive evaluation examines technical capabilities, tissue development patterns, and implementation success rates.

The economic analysis of implementation outcomes reveals significant variations in cost-effectiveness across different applications. Initial investment requirements range from £50,000 for basic extrusion systems to £500,000 for advanced laser-assisted platforms. However, facilities report average cost reductions of 40% in drug screening processes compared to traditional methods, suggesting favourable long-term economic benefits despite substantial initial investments. Operational costs show similar variations, with maintenance requirements ranging

from every 150 to 400 hours, depending on the technology type.

Quality assessment outcomes demonstrate the importance of standardised protocols in achieving consistent results. Facilities implementing comprehensive quality control measures achieve 85% consistency in basic tissue applications, while those without standardised procedures show more significant variability in outcomes. These findings highlight the critical role of systematic quality management in successful bioprinting implementation, particularly in research settings requiring reproducible results for drug development and disease modelling applications.

Analysis of Bioprinting Technologies. Extrusion-based bioprinting systems demonstrate robust performance in creating larger tissue constructs, achieving printing speeds of 10-15 mm/s while maintaining cell viability rates of 80-90%. These systems handle materials with higher viscosities, ranging from 30 to 6×10^7 mPa·s, enabling the creation of structurally stable tissue constructs. The technology proves particularly effective for applications requiring high cell density and larger tissue volumes.

Table 1 – Comparative Analysis of Bioprinting Technologies

| Performance Parameter | Extrusion-based | Inkjet-based | Laser-assisted |
|-----------------------|---------------------------|---------------|----------------|
| Resolution Range | 100-200 μ m | 20-50 μ m | 10-20 μ m |
| Printing Speed | 10-15 mm/s | 8-12 mm/s | 2-5 mm/s |
| Material Viscosity | 30- 6×10^7 mPa·s | 3.5-12 mPa·s | 1-300 mPa·s |
| Cell Viability | 80-90% | 85-95% | 90-95% |
| Cost Efficiency | High | Medium | Low |
| Scalability | High | Medium | Low |

Inkjet-based systems show superior performance in applications requiring high precision, achieving resolution capabilities between 20-50 micrometres. These systems maintain excellent cell viability rates of 85-95% while enabling precise control over cell and material deposition. The technology demonstrates particular effectiveness in creating detailed tissue structures, though material viscosity limitations restrict their application range.

Laser-assisted bioprinting achieves exceptional precision with resolution down to 10 micrometres, maintaining the highest cell viability rates at 90-95%. However, these systems operate at slower printing speeds of 2-5 mm/s, limiting their application for larger tissue constructs. The technology excels in creating precise cellular arrangements for specialised applications.

Tissue Model Evaluations. The evaluation of tissue models reveals varying success rates across different tissue types. Skin tissue constructs achieve promising results, with 85% of samples showing appropriate structural organisation and barrier function development. These constructs demonstrate progressive improvement in transepithelial electrical resistance, reaching 800-1000 $\Omega \cdot \text{cm}^2$ after 14 days of culture.

Table 2 – Tissue Model Performance Metrics, %

| Tissue Type | Structural Success | Functional Achievement | Stability Period |
|-------------|--------------------|------------------------|------------------|
| Skin | 85 | 80 | 30+ days |
| Cartilage | 75 | 70 | 45+ days |
| Vascular | 70 | 65 | 14+ days |
| Bone | 65 | 60 | 35+ days |
| Cardiac | 60 | 55 | 21+ days |

Cartilage models demonstrate mechanical properties reaching 60-80% of native tissue values, successfully developing appropriate extracellular matrix composition. These constructs maintain structural stability throughout extended culture periods, showing minimal degradation over 60 days.

Vascular tissue constructs maintain patency in 70% of cases over 14-day culture periods, though achieving proper elastic response remains challenging. The constructs demonstrate appropriate cellular organisation but achieve only 60% of the compliance observed in native vessels.

Statistical Correlations. Statistical analysis reveals strong relationships between printing parameters and tissue outcomes. Correlation analysis demonstrates significant relationships between printing speed and structural integrity ($r = 0.78$, $p < 0.001$) and between material viscosity and cell viability ($r = 0.82$, $p < 0.001$). Multiple regression models explain 85% of the variance in tissue construct quality.

Factor analysis identifies three primary components influencing bioprinting success, accounting

for 78% of the observed variance in printing outcomes. Material properties contribute 32% of the variance, process parameters account for 28%, and environmental conditions explain 18%. Time series analysis reveals consistent patterns in tissue development, with exponential growth phases observed during the first 14 days, followed by plateau phases. These patterns show statistical significance ($p < 0.001$) across multiple tissue types.

Cluster analysis reveals distinct groups of optimal printing parameters for different applications, with three primary clusters corresponding to other tissue types and construct sizes. These clusters demonstrate significant internal consistency (Cronbach's $\alpha = 0.87$), suggesting reliable parameter groupings for specific applications. Power analysis confirms the statistical significance of observed effects, achieving power levels exceeding 0.90 for primary outcome measures, with effect sizes ranging from moderate to large (Cohen's $d = 0.65$ to 0.95).

Implementation Outcomes. The implementation of bioprinting technology demonstrates a significant impact on research efficiency and outcomes. Drug development applications show a 40% reduction in screening timelines while achieving 85% accuracy in predicting adverse reactions. Disease modelling applications successfully recreate pathological conditions in 75% of attempts, providing valuable platforms for therapeutic research.

These comprehensive results demonstrate the capabilities and limitations of current bioprinting technologies while highlighting specific areas requiring further development. The findings provide crucial guidance for technology selection and implementation in research applications.

The comprehensive analysis of bioprinting technologies reveals significant advances in tissue engineering capabilities while highlighting crucial areas requiring further development. The findings demonstrate the transformative potential of bioprinting technology in medical research and the challenges that influence its broader implementation.

Evaluating different printing technologies underscores the importance of matching specific approaches with intended applications. Extrusion-based systems prove particularly effective for creating larger tissue constructs, offering practical advantages in terms of material versatility

and cost-effectiveness. However, their limited resolution capabilities restrict applications requiring precise cellular patterning. In contrast, laser-assisted systems achieve exceptional precision but face scalability and processing speed limitations.

The successful development of functional tissue models, particularly in skin and cartilage applications, demonstrates the technology's capability to support medical research applications. The achievement of appropriate structural organisation and mechanical properties in these constructs provides valuable platforms for drug testing and disease modelling. However, the challenges observed in creating more complex tissues, particularly regarding vascularisation, indicate critical areas requiring focused development efforts.

Implications for Medical Research. The demonstrated reduction in drug screening timelines and improved prediction accuracy hold significant implications for pharmaceutical research. The ability to create reliable tissue models for drug testing suggests the potential for accelerating therapeutic development while reducing reliance on animal testing – these advantages position bioprinting technology as a valuable tool in advancing medical research efficiency and effectiveness.

The successful implementation of standardised protocols across different facilities demonstrates the potential for establishing reliable research platforms. The high consistency rates achieved through systematic quality control measures support the broader adoption of bioprinting technology in research settings. These findings particularly benefit institutions seeking to implement or expand bioprinting capabilities.

Technical and Practical Challenges. Vascularisation remains a critical challenge in advancing bioprinting capabilities, particularly for larger tissue constructs. The limitations in maintaining cell viability beyond specific tissue thicknesses highlight the need for improved strategies in creating functional blood vessel networks. This challenge requires focused research attention to expand the technology's potential for creating more complex tissue structures.

The economic considerations present both opportunities and challenges for technology implementation. While substantial initial investments create barriers to adoption, the demon-

strated cost reductions in research applications suggest favourable long-term economic outcomes. These findings support strategic planning for technology implementation while considering immediate costs and potential benefits.

Future Development Recommendations. Future development efforts should prioritise advancing vascularisation strategies for larger tissue constructs. Research should focus on creating hierarchical vessel networks that effectively support tissue survival across larger volumes. This development would significantly expand the potential applications of bioprinting technology in both research and therapeutic contexts.

The standardisation of bioprinting protocols requires continued attention to enhance reproducibility across different facilities. Developing comprehensive quality control measures and validation procedures will support broader technology adoption while maintaining research reliability. These efforts should include the establishment of industry-wide standards for both technical processes and outcome evaluation.

Research Limitations. The study faces limitations regarding long-term tissue construct stability and function evaluation. While the research demonstrates successful tissue development over several weeks, longer-term performance characteristics require further investigation. Additionally, the focus on research applications may not fully address considerations for potential therapeutic implementations.

While diverse, the geographical distribution of participating facilities may not fully represent all potential variations in bioprinting implementation. Cultural differences and varying regulatory environments could influence technology adoption and application patterns that are not fully captured in this study. Future research should consider broader geographical representation to enhance understanding of implementation factors across different contexts.

Technical limitations in current measurement capabilities may affect the precision of specific findings. While the study employs sophisticated analysis tools, some aspects of tissue functionality and cellular behaviour in bioprinted constructs remain challenging to quantify accurately. These measurement limitations mainly affect assessing complex tissue interactions and long-term functional characteristics.

Resource constraints limited the depth of investigation possible for each specific tissue type and application. While the study examines various bioprinting applications, practical limitations prevented exhaustive analysis of all potential tissue types and research scenarios. This constraint necessitated focusing on representative cases rather than comprehensively examining all possible applications.

CONCLUSIONS

Bioprinting technology demonstrates significant potential for advancing medical research capabilities while requiring continued development in specific areas. The successful creation of functional tissue models for drug testing and disease modelling supports the increased adoption of this technology in research settings. However, challenges in vascularisation and standardisation necessitate ongoing research attention to maximise the technology's potential impact on medical research and development.

The findings support the strategic implementation of bioprinting technology while emphasising the importance of matching specific approaches with intended applications. The demonstrated benefits in research efficiency and cost reduction justify continued investment in this technology, particularly when accompanied by comprehensive quality control measures and standardisation protocols. These conclusions provide valuable guidance for institutions considering or expanding bioprinting capabilities while highlighting promising directions for future technological development.

Integrating bioprinting technology with existing research practices demonstrates challenges and opportunities for advancing medical research capabilities. While technical hurdles persist, particularly in creating complex tissue structures, the successful implementation of this technology in drug development and disease modelling applications suggests significant potential for transforming medical research methodologies. The demonstrated improvements in research efficiency and accuracy support continued investment in developing and refining these capabilities.

The future of bioprinting technology appears promising, with ongoing developments in materials science, control systems, and biological understanding likely to address current limitations.

The field's evolution suggests increasing impact on medical research and potential therapeutic applications, mainly as solutions to vascularisation challenges emerge, and standardisation ef-

forts mature. These advancements will likely expand the technology's applications while improving accessibility and effectiveness across different research contexts.

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