บทความฟื้นวิชา **Review Article**

ปัญญาประดิษฐ์ในการออกแบบและสร้างเนื้อเยื่อวิศวกรรม
Artificial Intelligence in the design and fabrication of tissue engineering scaffolds

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บทคัดย่อ

วิศวกรรมเนื้อเยื่อ (Tissue Engineering) ได้กลายเป็นสาขาที่มีการเปลี่ยนแปลงสำคัญในทางเวชศาสตร์ฟื้นฟู โดยการออกแบบโครงร่าง (Scaffold) มีบทบาทสำคัญในการสนับสนุนการเจริญเติบโตของเซลล์และการฟื้นฟูเนื้อเยื่อ อย่างไรก็ตามการจำลองสถาปัตยกรรมที่ซับซ้อนและคุณสมบัติทางกลของเนื้อเยื่อธรรมชาตินั้น ยังคงเป็นความท้าทายที่สำคัญ ความก้าวหน้าล่าสุดในด้านปัญญาประดิษฐ์ (Artificial intelligence: AI) ได้ปฏิวัติการพัฒนาโครงร่างโดยการปรับปรุงการออกแบบ และการผลิตโครงร่างวิศวกรรมเนื้อเยื่อเพื่อให้ได้คุณสมบัติเฉพาะ AI ช่วยในการทำนายคุณสมบัติของวัสดุชีวภาพ ปรับแต่งรูปทรงของโครงร่างและเพิ่มประสิทธิภาพในการผลิตผ่านการควบคุมกระบวนการแบบ Real time ซึ่งช่วยลดการพึ่งพาการทดลองผิดพลาดได้อย่างมาก การผลิตโครงร่างที่ใช้เทคโนโลยีการพิมพ์ 3 มิติ ที่มีการควบคุมด้วย AI ได้แสดงให้เห็นถึงความแม่นยำที่มากกว่าในการผลิตโครงร่างที่ปรับให้เหมาะกับผู้ป่วยมีความทนทานทางกล และมีความเข้ากันได้ทางชีวภาพ นอกจากนี้โมเดล AI ยังช่วยทำนายพฤติกรรมทางกลและโปรไฟล์การย่อยสลายของโครงร่างได้อย่างแม่นยำ ซึ่งเร่งกระบวนการพัฒนา Solution วิศวกรรมเนื้อเยื่อที่มีศักยภาพทางคลินิก ดังนั้นการศึกษานี้เน้นการผสมผสานของ AI ในทุกขั้นตอนของการพัฒนาโครงร่างและศักยภาพในการลดข้อจำกัดที่มีอยู่ ซึ่งการริเริ่มบำบัดฟื้นฟูที่เป็นส่วนตัวมีประสิทธิภาพและสามารถขยายได้มากยิ่งขึ้น

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Abstract

Tissue engineering has emerged as a transformative field in regenerative medicine, with scaffold design playing a critical role in supporting cell growth and tissue regeneration. However, replicating a complex architecture and mechanical properties of native tissues remains a significant challenge. Recent advancements in artificial intelligence (AI) have revolutionized scaffold development by enhancing a design and fabrication processes to achieve specific functional properties. AI-driven approaches enable the prediction of biomaterial properties, optimization of scaffold geometries, and real-time control of fabrication processes, significantly reducing the reliance on trial-and-error experimentation. AI-integrated additive manufacturing has demonstrated superior accuracy in producing patient-specific, mechanically robust, and biologically compatible scaffolds. Moreover, AI models facilitate precise prediction of scaffold mechanical behavior and degradation profiles, accelerating the development of clinically viable tissue engineering solutions. This review highlights the integration of AI across various stages of scaffold development and discusses its potential to overcome existing limitations, paving the way for more personalized, effective, and scalable regenerative therapies.

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Introduction

Tissue engineering represents a rapidly evolving domain within biomedical science, aiming to develop functional biological substitutes for replacement, or regeneration of damaged tissues and organs. This interdisciplinary field integrates principles from cell biology, materials science, and engineering to create constructs capable of restoring or enhancing physiological function. A fundamental component of tissue engineering strategies is the use of scaffolds-three-dimensional, biocompatible structures designed to replicate key aspects of the native extracellular matrix. These scaffolds provide essential physical support and biochemical cues that facilitate critical cellular processes such as adhesion, proliferation, migration, and differentiation.

Despite substantial progress over recent decades, the design and fabrication of scaffolds continue to present considerable challenges. The inherent complexity and heterogeneity of biological tissues, combined with the constraints of traditional experimental approaches, often limit the development of optimal scaffold architectures and functionalities. In this context, artificial intelligence (AI) has emerged as a promising tool to overcome existing limitations and accelerate innovation in scaffold design. By leveraging machine learning (ML) and deep learning (DL) algorithms, AI enables the analysis of large, high-dimensional datasets to identify patterns, predict scaffold performance, and guide the design of advanced biomaterials with improved efficacy.

This review highlights recent advancements in the integration of AI methodologies within the tissue engineering landscape, with a particular emphasis on scaffold development. It examines how AI-driven techniques are reshaping conventional paradigms by enhancing design efficiency, enabling the creation of patient-specific solutions, and facilitating the discovery of novel material compositions and architectural features, thereby advancing the broader objectives of regenerative medicine.

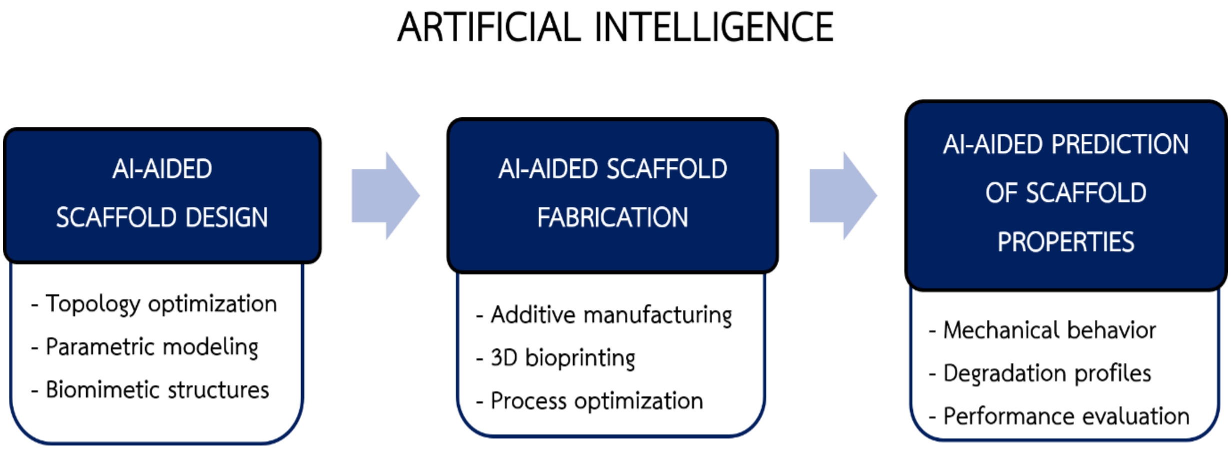

Figure 1 Integration of Artificial Intelligence in Tissue Engineering Scaffold Development.

A flowchart illustrating the contribution of artificial intelligence (AI) to three core stages of scaffold development: design, fabrication, and property prediction. AI enhances these stages through techniques such as topology optimization, additive manufacturing, and mechanical behavior modelling, thereby supporting the development of personalized and efficient tissue-engineered scaffolds.

Methodology

This review synthesizes recent literature on the application of artificial intelligence (AI) in tissue engineering scaffold design, fabrication, and property prediction. A structured search was conducted using databases including PubMed, ScienceDirect, and Google Scholar for articles published between 2010 and 2025, with a particular emphasis on studies from 2022 onward. Keywords used in the search included *"AI," "machine learning," "3D bioprinting," "scaffold design,"* and *"tissue engineering."*

The inclusion criteria focused on peer-reviewed studies that demonstrated the integration of AI into scaffold-related processes. The selected articles were analyzed and categorized into three main themes: technological advancements, practical applications, and emerging challenges, to provide a comprehensive overview of the current landscape.

Literature Review

AI-aided scaffold design

One of the main challenges in tissue engineering is replicating the complex architecture of natural tissues, which includes organization, mechanical properties, vascular networks, and dynamic interactions between cells and the matrix. Designing scaffolds that mimic these features requires a comprehensive understanding of biological systems and precise control over key parameters such as geometry, porosity, mechanical strength, and degradation rate. Scaffold geometry plays a critical role, as it influences how well the scaffold integrates with bone, with pore size and shape affecting nutrient transport[1].

Traditional scaffold design methods often rely on trial and error or basic modeling, which can be inefficient and require skilled designers(2). These methods may not be suitable for personalized or large-scale production. Parametric design helps by allowing researchers to define adjustable geometric parameters to create various structures. However, this leads to many experiments to find the best designs, reducing efficiency. Topology optimization is another method that finds the best material distribution to maximize strength or minimize weight, resulting in robust and material-efficient scaffolds. However, it provides complexity and high cost when many variables are involved(3). When integrated with AI, topology optimization becomes more powerful. Deep learning models can create scaffold designs that mimic the intricate internal architectures of natural tissues. Parametric design, by adjusting input parameters such as pore size and orientation, enables the rapid development and analysis of many designs. When paired with AI or genetic algorithms, it allows real-time adaption to meet mechanical and biological needs.

Researchers introduced Machine Learning (ML) to optimize bone tissue engineering scaffolds by focusing on triply periodic minimal surface (TPMS) structures, which are known for their mechanical and properties. They generated a comprehensive dataset comprising over a thousand TPMS designs with measured properties such as density and stiffness. The ML models showed high predictive accuracy, achieving a median error of less than 3% and a correlation coefficient exceeding 0.89(1). This approach enabled the successful design of scaffolds that closely mimic the mechanical characteristics of natural bone.

The integration of AI, topology optimization, and parametric design has made scaffold development more predictive, personalized, and efficient. This approach reduces reliance on trial-and-error methods and facilitates the creation of scaffolds that are both mechanically robust and biologically compatible. As biomedical data and technologies continue to advance, the role of AI in scaffold design is expected to become increasingly pivotal in the field of regenerative medicine.

AI-aided scaffold fabrication

Scaffold fabrication plays a critical role in tissue engineering by providing structural frameworks that support biological function. Additive manufacturing (AM) enables the production of scaffolds with complex microarchitectures and offers design flexibility to accommodate diverse clinical requirements. The integration of AI further enhances the accuracy, efficiency, and customization of scaffold development, enabling the creation of patient-specific constructs for regenerative medicine.

In 3D bioprinting, precise control of printing parameters such as pressure and speed is essential. AI can optimize these parameters, leading to consistent scaffold quality and reduced fabrication time. Machine learning have demonstrated approximately 85% predictive accuracy in forecasting filament properties in extrusion-based bioprinting(4). Additionally, AI facilitates the development of high-throughput screening systems that identify ideal printing conditions and enhance the mechanical performance of hydrogel scaffolds(5).

Ning et al.[6] have shown integrating machine learning with 3D bioprinting enhances scaffold fabrication by optimizing formulations, predicting parameters, and real-time defect detection. This approach reduces the need for traditional trial-and-error methods, speeding up the discovery of optimal printing conditions. Gharibshahian et al.[7] incorporated ML into the scaffold fabrication process, highlighting its role in refining printing parameters, increasing precision, shortening fabrication time, and improving scaffold uniformity through real-time monitoring and defect identification. Additionally, they utilized ML to enhance bioink formulations, achieving a balance between cell viability and mechanical strength. Mohammadnabi et al.[8] showed how combining AM with AI can improve tissue engineering scaffold production. They used different techniques to create accurate scaffolds while AI optimized printing settings for better quality and efficiency. However, challenges in material choice and scaling production were noted, and clinical validation is still needed.

Overall, the integration of AI and AM has markedly enhanced the design and efficiency of tissue-engineered scaffolds. By making the process more predictive and less reliant on empirical trial-and-error, these technologies contribute significantly to the advancement of personalized regenerative therapies.

AI-aided scaffold property prediction

The mechanical properties are essential for ensuring that scaffolds effectively replicate the physical environment of native tissues. The primary properties include tensile and compressive strength, stiffness, elasticity, and toughness. These characteristics are crucial in determining the structural integrity of the scaffold and significantly influence cellular behavior[9].

Traditionally, the accurate evaluation of Young's modulus and yield strength in lattice structures depends on comprehensive experimental testing and finite element method (FEM) simulations. Nevertheless, FEM frequently encounters challenges with complex scaffold geometries, especially those with high aspect ratios, intricate designs, or manufacturing imperfections, which can result in unreliable predictions[10].

To address these limitations, recent research has shown that artificial neural networks (ANNs) present a robust alternative. ANNs can learn complex relationships between scaffold design parameters and mechanical performance from extensive datasets, enabling rapid and accurate predictions of mechanical properties without the requirement for labor-intensive simulations. Bai et al.[3] indicated that ANN models could accurately predict the Young's modulus and yield strength of lattice structures with prediction errors below 5%, while significantly decreasing computational time in comparison to traditional FEM analysis. The implementation of ANN-based predictive models thus improves the efficiency of scaffold design processes, facilitating the development of mechanically optimized and clinically applicable tissue engineering scaffolds. Bermejillo Barrera et al.[10] presented an AI-driven methodology to anticipate the mechanical properties of tissue engineering scaffolds utilizing 3D convolutional neural networks (3D CNNs). By transforming CAD scaffold models into digital tomographies, the 3D CNNs were trained to predict properties such as young's modulus, shear modulus, and porosity. This approach provides a rapid and accurate alternative to conventional finite element simulations, especially for complex scaffold geometries. Omigbodun et al.[11] integrated ML to predict the mechanical properties of 3D-printed polylactic acid scaffolds reinforced with calcium hydroxyapatite. The models demonstrated high predictive accuracy for both compressive and tensile strengths.

The integration of AI has proven to be an effective approach for predicting the mechanical properties of scaffolds. This approach enhances the material design process and significantly reduces the need for extensive and costly experimental trials.

Challenges and Future Directions

Despite promising

Advancements, the integration of artificial intelligence (AI) into tissue engineering faces several key challenges. First, the quality and quantity of training data remain critical limitations. Most AI models rely on large, high-resolution datasets of scaffold designs and mechanical properties, which are often limited or inconsistently reported across studies. Improving standardization in data collection and sharing will be essential for the development of more robust and generalizable models.

Second, integration with current manufacturing systems, particularly 3D bioprinters and additive manufacturing platforms, presents technical and cost-related challenges. Many existing systems lack real-time data interfaces or adaptability to AI-driven optimization, which limits their widespread adoption in clinical settings.

Third, clinical validation and regulatory approval remain underexplored areas. While AI-assisted scaffolds show potential in preclinical models, few have progressed to human trials. Regulatory frameworks for AI-integrated biomaterials are still evolving and requiring interdisciplinary collaboration among engineers, clinicians, and regulatory agencies. Looking forward, future research should focus on:

- Developing multimodal datasets that combine mechanical, biological, and clinical performance data;
- Advancing explainable AI models to ensure transparency in decision-making;
- Exploring smart scaffold systems that adapt in response to biological feedback;
- Creating digital twin frameworks to simulate patient-specific tissue regeneration outcomes.

Additionally, fostering collaboration among material scientists, data scientists, and clinicians will be crucial to translate AI-driven innovations into safe, personalized, and scalable regenerative therapies.

Discussion

Artificial intelligence (AI) is rapidly transforming tissue engineering by advancing scaffold design, fabrication, and mechanical property prediction. AI enables the creation of complex, biomimetic structures through data-driven design tools such as topology optimization and parametric modeling. In fabrication, AI enhances precision and efficiency in additive manufacturing and 3D bioprinting by optimizing real-time printing parameters and improving scaffold uniformity. Moreover, machine learning models enable accurate prediction of mechanical behavior, thereby accelerating the development of clinically viable scaffolds.

Despite these advancements, several challenges still remain. These include the need for large, high-quality datasets, seamless integration with manufacturing platforms, and comprehensive clinical validation. Overcoming these barriers will require interdisciplinary collaboration, improved data infrastructure, and the development of explainable and scalable AI models.

In the future, the convergence of AI with smart biomaterials, digital twin modeling, and personalized medicine holds great promise for the development of next-generation scaffolds. With ongoing innovation, AI is poised to play a central role in advancing safe, effective, and patient-specific regenerative therapies.

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