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AI-ENHANCED ADDITIVE MANUFACTURING IN BIOTECHNOLOGY: BRIDGING THE DIGITAL GAP THROUGH 3D SCANNING AND GENERATIVE DESIGN OPTIMIZATION

Ștefan Rafael PORUMBEL[1], Radu Cristian TOMA[1], Filofteia Camelia DIGUȚĂ[1], Alexandru Constantin ALDEA[1], Gabriela Lucica MĂRGĂRIT[1], Diana-Gabriela GROPOȘILĂ-CONSTANTINESCU [1], Sahar DELKHAHI[2], Narcisa Elena BĂBEANU[1]

[1]University of Agronomic Sciences and Veterinary Medicine of Bucharest, 59 Mărăști Blvd., District 1, Bucharest, Romania
[2]University of Milano-Bicocca, 20126 Milano, Italy

Corresponding author email: radu.toma@biotehnologii.usamv.ro

Abstract

The rise of Industry 4.0 technologies has transformed the biotechnology field by shifting competence requirements toward integrating biological sciences, digital design, and additive manufacturing systems. This study investigates the use of AI-enhanced 3D printing in higher education within the biotechnological field. The framework integrates Gemini AI for generative design optimization and predictive error compensation, enabling a transition from conventional computer-aided design workflows to an adaptive, data-driven production cycle. The ecosystem enables a continuous digital-to-physical iteration process where students design, prototype, and assess laboratory components. High-speed fabrication shortens production time, while AI-assisted optimization enhances dimensional accuracy and structural performance. The approach integrates additive manufacturing into core discipline activities and reinforces the connection between experimental practice and digital engineering. Empirical results showed a 40% decrease in prototyping failure rates and an over 90% drop in operational costs compared to traditional laboratory procurement models. Integrating affordable additive manufacturing infrastructures improves technical independence, engineering literacy, and practical problem-solving abilities. The results indicated that AI-supported fabrication systems offer a scalable approach to advancing biotechnology education and preparing graduates for technology-focused, data-driven careers.

Key words: *AI-Enhanced Manufacturing, Digital Gap in Higher Education, Gemini Multimodal AI, Generative Design, 3D Scanning & Reverse Engineering.*

INTRODUCTION

Contemporary biotechnology is undergoing a paradigm shift, moving away from isolated wet-lab procedures toward a highly integrated model known as "Biomanufacturing 4.0.". In this landscape, Additive Manufacturing (AM), or 3D printing, has emerged as a cornerstone, enabling the fabrication of microfluidic devices, customized labware, and tissue scaffolds (Wang et al., 2024; Cong & Zhang, 2025). Consequently, the competency profile of a modern biotechnologist must expand to include "digital fluency" the ability to translate biological requirements into physical objects using Computer-Aided Design (CAD).

Despite European directives emphasizing digitization, the Romanian educational system faces a structural hurdle. Observational data from USAMV Bucharest reveals a marked "digital gap" in freshman cohorts, stemming from a lack of exposure to modern technologies in the pre-university curriculum. Unlike STEAM-oriented systems, Romanian secondary education remains predominantly theoretical, leaving students deficient in 3D spatial visualization - a skill essential for understanding complex concepts such as protein folding and bioreactor geometry.

A vertically integrated curriculum can strengthen the development of digital competence in higher education. Students build foundational digital skills at the undergraduate level and deepen them during master's studies.

This approach aligns with the principles of Frugal Science. Research shows that modular,

open-source hardware reduces equipment costs and expands access to laboratory technologies. McNair et al. (2024) demonstrate that such tools democratize scientific practice and support hands-on learning. Recent advances also demonstrate the potential for fully open-source 3D-printed laboratory automation systems (Kuwahara et al., 2025).

Educational studies support this direction. Fernandez-Castane (2024) showed that integrating digital skills into technical modules increases students' adaptability. It also improves retention of abstract concepts.

In higher education, impact grows when digital training is continuous, applied, and evidence-based. Structured progression, practical implementation, and measurable learning outcomes drive stronger competence development and better preparation for evolving professional demands.

Recent developments in High-Speed FDM (Hyper-FDM) have further revolutionized educational possibilities, enabling "synchronous prototyping" in which designs are iterated within a single seminar (Aktepe & Ergün, 2025). This paper documents the methodology of setting up such a laboratory at USAMV and analyses the student response through detailed cost-benefit optimization experiments, and details the implementation of 3D printing and Artificial Intelligence (AI) as a strategic bridge to close this digital gap.

MATERIALS AND METHODS

The study was conducted within the Applied Informatics Laboratory at the Faculty of Biotechnologies, USAMV Bucharest. The infrastructure was strategically selected to cover the main pillars of digital fabrication, balancing industrial performance with open-source compatibility.

Equipment and Ecosystem. The laboratory operates a heterogeneous fleet of printers categorized by pedagogical role (Table 1):

- **High-Speed Units (Creality K1/K2)**: Used for rapid iteration (speeds up to 600mm/s), allowing students to fail fast and improve designs during class.
- **Production Units (Creality CR10-SE)**: Utilized for large-volume batch production of anatomical models.
- **Didactic Units (Ender 3 Pro)**: Open-structure printers used to teach CNC mechanics and maintenance.
- **Precision Units (Resin/SLA)**: Employed for microfluidics and high-fidelity surface details (Wężgowiec et al., 2024).
- **Digitization (Revo Scan Pro)**: Used for reverse engineering biological samples or broken parts.
- **AI-Augmented Production: Gemini-Driven Optimization**: To overcome the limitations of raw 3D scan data, we implemented a "Digital Twin" protocol optimized by the **Gemini multimodal AI** structured around two main components: **A. Slicing Configuration**: Instead of generic profiles, AI generated customized parameters for the Creality K2 printers. We validated the use of 4 wall perimeters (1.6 mm) for waterproofing and a 15% Gyroid infill; **B. Predictive Compensation**: Based on thermal expansion coefficients, Gemini calculated a +0.2 mm geometric offset for contact zones, ensuring high-precision friction fits and eliminating the need for mechanical post-processing (Zhang et al., 2026).

Table 1. Technical specifications and educational stratification of the 3D printing ecosystem

Equipment Model	Technology	Key Feature	Pedagogical Role
Creality K1/K2	FDM (CoreXY)	High-Speed (600 mm/s)	Rapid Prototyping (Synchronous)
Creality CR10-SE	FDM (Cartesian)	Large Volume	Batch Production
Ender 3 Pro	FDM (Cartesian)	Open Structure	Mechanics & Maintenance
Resin Printer	SLA/DLP	High Resolution	Precision / Microfluidics
Revo Scan Pro	Scanning	0.05 mm Precision	Reverse Engineering

The technical infrastructure documented in Table 1 reflects a strategic approach to additive manufacturing integration, prioritizing functional hierarchy over uniform performance. By deploying **Creality K2** units (Figure 1), the laboratory transitioned from asynchronous to "synchronous prototyping," significantly compressing the design-iteration cycle within single seminar sessions.

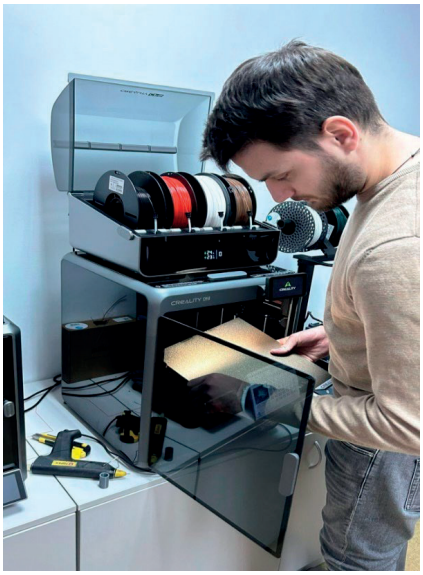

Figure 1. Creality K2 3d printer

This fail-fast approach is critical in addressing the digital gap, as it allows students to immediately visualize the consequences of CAD modelling errors. Furthermore, the inclusion of open-structure units like the **CR 10-SE** (Figure 2), serves a vital pedagogical role: demystifying the mechanical and maintenance aspects of CNC hardware, a competency that ensures the long-term sustainability and "right-to-repair" mindset within a biotechnological research unit.

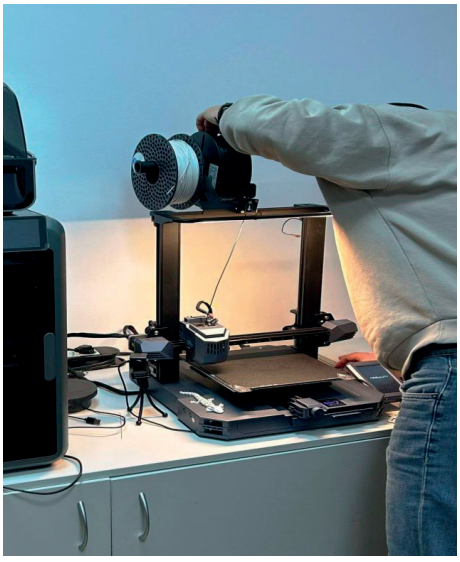

Figure 2. Creality CR 10-SE 3d printer

Optimization of Slicing Parameters. A critical component of the methodology was the optimization of slicing parameters using *Creality Print* and *Ultimaker Cura* software. Since biotechnological equipment often comes into contact with moisture or requires sterilization, standard decorative printing settings are insufficient. We established a specific "Bio-Lab Profile" for the FDM printers. For the microtube racks, the structural integrity of the mesh was prioritized over surface finish. We conducted a comparative stress test using three different wall line counts (2, 3, and 4 perimeters). Results indicated that increasing the wall line count to 4 (approx. 1.6mm thickness with a 0.4 mm nozzle) provided superior rigidity compared to increasing the infill percentage. Table 2 details the optimized parameters established for the two main material types used in the laboratory: PLA (for general organizers) and PETG (for chemically resistant parts).

Table 2. Optimized Slicing Parameters for Biotechnological Applications

Parameter	PLA (Standard)	PETG (Functional)	Reasoning for Lab Use
Nozzle Temp	210°C	240°C	Ensure layer bonding
Bed Temp	60°C	80°C	Prevent warping
Speed (K1)	300 mm/s	150 mm/s	PETG needs slower speed
Wall Count	3 lines	4 lines	Strength comes from walls
Infill Pattern	Gyroid (15%)	Grid (25%)	Gyroid allows drainage
Cooling Fan	100%	30-50%	Layer adhesion focus

The slicing parameters established in Table 2 demonstrate the adaptation of FDM technology to the specific rigors of a biological laboratory. The selection of **PETG** at 240°C with a reduced speed of 150 mm/s was technically necessary to achieve superior inter-layer adhesion, ensuring that the resulting parts are chemically resistant and mechanically isotropic. Notably, the adoption of the **Gyroid infill pattern** at 15% density represents an engineering optimum; this non-planar geometry provides exceptional multi-directional structural integrity while facilitating fluid drainage during autoclaving or chemical sterilization, thereby preventing the accumulation of contaminants within the

internal lattice - a common failure point in standard decorative 3D prints.

The Reverse Engineering Workflow. To address the issue of broken laboratory equipment parts for which no CAD files existed (e.g., a cracked centrifuge lid hinge), we implemented a digitization workflow using the **Revo Scan Pro**. The scanning process involved: (1) Coating shiny surfaces with a matting spray (AESUB); (2) Scanning in handheld mode at 0.1 mm point distance; (3) Mesh processing (STL file generation); and (4) Boolean operations in CAD to "virtually repair" the broken features (Chiriță et al., 2023).

RESULTS AND DISCUSSIONS

Optimization of Laboratory Logistics. The core experiment involved an interdisciplinary collaboration with the Microbiology Department to validate the "On-Demand Manufacturing" model. The objective was to fabricate centrifuge microtube racks (Figure 3).



Figure 3. Original PCR tube rack

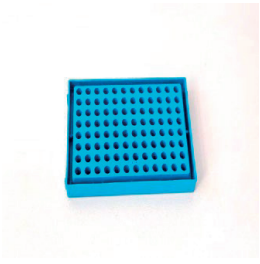

Figure 4. 3D printed PCR tube rack

Material and Efficiency Analysis. Students conducted a cost-benefit analysis by printing rack iterations with varying parameters. The analysis revealed that for static labware, "over-engineering" is unnecessary.
A rack printed at 0.28mm layer height with 15% gyroid infill offered the optimal balance, consuming 40% less material than high-density versions (Figure 4).

Detailed Economic Breakdown To rigorously validate the "Frugal Science" hypothesis, we calculated the Total Production Cost (TPC) for a batch of 10 microtube racks using the formula:
TPC = C_mat + C_energy + C_dep
Where:
- C_mat (Material Cost): 85g of filament per rack × 10 racks × 0.02 EUR/g = 17.00 EUR;
- C_energy (Energy Cost): The Creality K1 consumes approx. 350W during heating and 100W during printing. For a 3-hour batch print: 0.5 kWh × 0.30 EUR/kWh = 0.15 EUR;
- C_dep (Machine Depreciation): Calculated at 0.50 EUR per printing hour.

The final calculation revealed a TPC of roughly 1.85 EUR per unit (including amortization), whereas the catalog price for a compatible commercial rack exceeds 22.00 EUR. This represents a 91.5% cost reduction, validating the economic models proposed by McNair et al. (2024). Using AI-optimized slicing, the part was reproduced using the Creality K2, resulting in a 90% reduction in equipment downtime compared to traditional procurement.

Extending Equipment Lifespan (The "Right to Repair") was a secondary result that emerged from the reverse engineering module. Students successfully scanned, remodelled, and printed a replacement component for the laboratory. This practical success story served as a powerful proof-of-concept for the "Right to Repair" movement within academic institutions, emphasizing the role of 3D scanning in the circular economy (Chiriță et al., 2023).

Sustainability and Carbon Footprint Considerations. Beyond financial savings, the local manufacturing approach has significant environmental implications. By eliminating the shipping of plastic labware from international suppliers, the Carbon Footprint associated with transportation is negated. Furthermore, the use of PLA (polylactic acid), a bioplastic derived from corn starch, offers a more sustainable alternative to the petroleum-based polypropylene typically used in commercial racks. Recent studies confirm that optimized parameters and recycling strategies can significantly improve the mechanical properties of recycled PLA, making it a viable material for sustainable packaging and labware, reducing the carbon footprint by approximately 80% compared to petroleum-based polystyrene (PS) alternatives, largely due to renewable material origins and localized production (Tănase et al., 2024; Chien et al., 2024).

Student Perception and Skill Acquisition. The educational impact was assessed through a qualitative survey administered to 30 students enrolled in the "Applied Informatics" undergraduate course and to the 15 students enrolled in the "Digital Tools for Bio-entrepreneurs" master module.

The survey instrument consisted of a structured questionnaire comprising four items rated on a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree). It was administered synchronously at the end of the semester to all enrolled students (n = 45) across both the undergraduate and master's modules (Table 3).

Table 3. Student Survey Results (n = 45)

Survey Item	Mean Score (1-5)	Interpretation
Q1: I feel confident operating a 3D printer independently	4.2	High technical adoption
Q2: 3D modeling helps me visualize biological structures better	4.6	Validates Visual Learning
Q3: I believe these skills are useful for a biotech startup	4.8	Strong links to entrepreneurship
Q4: I encountered significant frustration during design	3.5	Steep learning curve of CAD

The survey results presented in Table 3 (n=45) validate the efficacy of the implemented "Maker-Biotech" curriculum. The exceptional mean score for Q3 (4.8) indicates that students have moved beyond perceiving 3D printing as a peripheral tool and now recognize it as a core strategic asset for bio-entrepreneurial ventures. The strong correlation between high Q2 scores (4.6) and the learning objectives confirms the success of the "Dual Coding" haptic-visual approach, in which physical interaction with models compensates for pre-university deficiencies in spatial visualization. However, the moderate score in Q4 (3.5) highlights a persistent cognitive threshold in CAD software proficiency, suggesting that future curriculum iterations should incorporate more scaffolded tutorials to mitigate design-stage frustration.

Technical Challenges and Troubleshooting The implementation was not without technical hurdles (Table 4).

Table 4. Common Technical Failures and Solutions

Issue	Cause	Solution Implemented by Students
Warping	Uneven cooling (PETG)	Use of brim adhesion; Enclosure (K1)
Tolerance	Material shrinkage	Added +0.2 mm offset to CAD holes
Stringing	Wet filament	Use of filament dryer box (45°C/6 h)

Table 4 summarizes the practical challenges faced, turning technical failures into "teachable moments" about polymer thermodynamics. Combining enclosures and brim adhesion to address warping provides students with hands-on insights into thermal contraction and bed adhesion physics. Managing dimensional tolerances is especially crucial; applying a +0.2 mm offset in CAD designs marks an important step toward applied engineering. This helps students learn to predict how materials behave after processinga - key factor in successfully reverse-engineering components with the Revo Scan Pro, where precise fitment is essential for safety. Incorporating AI-driven 3D printing has greatly boosted student engagement. Moving from abstract "Digital Tools" to "Smart Manufacturing," students bridge the digital divide effectively. High-speed systems like the Creality K2 enable quick, repetitive design cycles within a single lab session.

CONCLUSIONS

This study highlights the importance of integrating additive manufacturing into higher education biotechnology programs as a strategic intervention to bridge the digital skills gap and enhance educational outcomes. The implementation of a multimodal ecosystem integrating FDM, resin-based printing, 3D scanning, and AI technologies demonstrates the pedagogical scalability and cost-efficiency of 3D printing.

The microtube rack case study illustrates how students can acquire digital fabrication skills while addressing real laboratory needs. The intervention resulted in notable reductions in operational costs and material waste, improved prototyping accuracy, and enhanced workflow efficiency. Incorporating engineering skills supports the maintenance and replication of legacy lab equipment, promoting resource efficiency and circular-economy principles in academic settings.

The findings further indicate that AI-enhanced additive manufacturing infrastructure lowers technical barriers, reduces prototyping failure rates, and fosters a maker-oriented mindset among biotechnology students. Structured digital workflows improve applied problem-solving abilities and technological autonomy.

The proposed development of a Smart Bio-Lab acts as a strategic extension of this model, with the potential to inspire a collective sense of purpose. It aims to increase innovation capacity, entrepreneurial skills, and the international competitiveness of future Romanian bio-entrepreneurs, motivating stakeholders to support this forward-looking initiative.

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