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Article

# Implementing 3D Printing in Engineering Education: Development and Assessment of an Integrated Lecture–Laboratory Course

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## Abstract

Additive manufacturing (AM), commonly known as 3D printing, has rapidly transformed modern manufacturing, creating a growing demand for engineers with both theoretical knowledge and practical skills. Despite its increasing relevance, AM is often incorporated into engineering curricula as a supplementary tool rather than a fully integrated subject, limiting students' understanding of fundamental material–process–performance relationships. This study presents the development, implementation, and assessment of an integrated lecture–laboratory framework for AM education at the New Jersey Institute of Technology (NJIT). Two complementary courses were developed: an undergraduate course (Introduction to 3D Printing, CHE 415) and a graduate course (Additive Manufacturing and Applications, CHE 722). The curriculum integrates instruction in AM technologies, materials, and digital workflows with hands-on design challenges, team-based projects, and structured literature review, enabling students to engage in the complete design-to-fabrication process. Student learning outcomes were evaluated over multiple academic years using ABET-aligned assessments, grade distributions, and student self-assessments. Results demonstrate consistently high levels of student proficiency and engagement, with strong performance in design, problem-solving, and communication skills. The courses also attracted students from diverse disciplines, underscoring the interdisciplinary nature of AM education. While limitations remain in providing hands-on exposure to a broader range of AM technologies, ongoing expansion of laboratory infrastructure is expected to address these challenges. Overall, this work demonstrates that an integrated, project-based approach effectively bridges theory and practice and provides a scalable model for incorporating AM into engineering curricula.

**Keywords:** additive manufacturing; 3D printing; engineering education; project-based learning; lecture–laboratory integration; student learning outcomes

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## 1. Introduction

Three-dimensional (3D) printing, or additive manufacturing (AM), has emerged as one of the most transformative advanced manufacturing technologies, with applications spanning construction (Al Rashid et al., 2020; El-Sayegh et al., 2020; M. A. Hossain et al., 2020), electronics (Espera et al., 2019; Goh et al., 2021; Rao et al., 2022), aerospace and automotive (Goh et al., 2021; Jovanović et al., 2023; Lim et al., 2016), consumer products (Wu et al., 2022; Xiao & Kan, 2022), healthcare (Abaci et al., 2023; Liaw & Guvendiren, 2017), military (Chaari, 2024; K. R. Hossain et al., 2023), pharmaceuticals (Abaci et al., 2021; Jayabal et al., 2025), and even food industry (Liu et al., 2017). Its rapid adoption is driven by several key advantages, including unparalleled design flexibility, the ability to fabricate complex geometries, reduced material waste and cost, on-demand manufacturing, and rapid prototyping (Rayna & Striukova, 2016). Furthermore, multi-material printing enables the

fabrication of compositionally graded structures, adding material complexity to architectural design (House et al., 2023; Lopes et al., 2018; Zhu et al., 2024). As a result, many industries have integrated 3D printing into their operations, and universities and government laboratories have launched AM initiatives to remain at the forefront of this technological shift (Ford & Minshall, 2019; Motyl & Filippi, 2021). However, this rapid growth has also created a significant skills gap, increasing demand for educational programs that effectively integrate 3D printing. While accessibility and enthusiasm for the technology continue to grow, implementing it as a cohesive and innovative learning tool remains challenging (Nemorin & Selwyn, 2017; Perna & Wiedmer, 2020; L. Wang et al., 2020).

3D printing relies on a digital workflow in which a 3D design—typically created using computer-aided design (CAD) software and exported in STL (stereolithography) format—is converted into G-code (geometric code) through slicing software. This G-code contains critical information, including build geometry and process parameters such as layer height, temperature, and print speed (Manoj Prabhakar et al., 2021; Zhen et al., 2023). These parameters are highly dependent on the material and printing technology and directly influence the final properties and functionality of the printed object (Liaw et al., 2021). Broadly, 3D printing technologies can be categorized into material extrusion-, droplet-, light-, and powder-based printing. Material extrusion systems, such as fused filament fabrication (FFF), are widely adopted in educational settings due to their low cost, ease of use, and accessibility, and commonly utilize thermoplastic polymers such as polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS). Direct ink writing (DIW), another extrusion-based technique, enables the printing of a wide range of materials, including polymers, hydrogels, solutions, and particle-laden slurries, as well as composite systems, making it particularly attractive for advanced materials and bioprinting applications (Kumar et al., 2026). Light-based systems, including stereolithography (SLA) and digital light processing (DLP), use photocurable resins but require additional post-processing and safety considerations (Kitos Vasconcelos et al., 2025). Droplet-based systems, such as inkjet printing, require low-viscosity inks that can be cured thermally or via light exposure (Gudapati et al., 2016), while powder-based systems rely on high-energy sources to sinter or melt powders, often necessitating more stringent safety protocols (Shanthar et al., 2023). Due to these interdependencies between design, materials, and processing, it is difficult to treat these components independently, posing challenges for their cohesive integration into engineering education.

When examining how 3D printing is incorporated into education, it is most commonly used as a tool to enhance learning experiences rather than as a fully integrated subject (Anđić et al., 2023; Bai et al., 2021; Ford & Minshall, 2019; Lin et al., 2018). 3D printing offers significant advantages in teaching by enabling students to design and create solutions to real-world problems and iteratively refine their designs based on performance (Vo, 2024). It also supports development of spatial literacy—the ability to visualize and manipulate 3D objects—such as interpreting a 2D sketch and mentally constructing the corresponding 3D form, which is essential for effective design and engineering problem-solving (Munir et al., 2025; To et al., 2025). In K–12 education and outreach activities, 3D printing is frequently used to create physical models that enhance visualization and engagement. These efforts are often facilitated through libraries and makerspaces, where 3D printing serves primarily as a demonstration and prototyping tool. Additionally, it has emerged as an assistive technology for visually impaired students, enabling tactile learning experiences (Awang Zainal et al., 2026). In higher education, a similar approach is widely adopted, where 3D-printed models are incorporated into existing courses to enhance student understanding (Awang Zainal et al., 2026; Bonorden & Papenbrock, 2022; Diao et al., 2026; A. Pikkarainen & Piili, 2021; Szukala et al., 2026). Early examples include the use of 3D-printed atomic and molecular models (Paukstelis, 2018; Rossi et al., 2015; Scalfani & Vaid, 2014; Scalfani et al., 2016), as well as anatomical models that complement traditional teaching methods such as dissection-based learning (Cai et al., 2019; Kazoka et al., 2021; McMenemy et al., 2014; Smith et al., 2018). Another common strategy involves integrating 3D printing into engineering design education by combining CAD training with fabrication, typically

within laboratory courses, design courses, or capstone projects (Ari Pikkarainen et al., 2017; Ullah et al., 2020).

Beyond course integration, some institutions offer workshops, short courses, and certificate programs focused specifically on AM technologies. A pioneering example is the 3D Bioprinting Open-Source Workshop developed at Carnegie Mellon University. More recently, several universities have introduced multi-course sequences in AM to provide comprehensive training in areas such as 3D printing techniques, material selection, design for AM, and post-processing methods. These programs help students develop skills in prototyping, and process optimization, while also exposing them to tools such as CAD software, slicing programs, and various 3D printing technologies. The growing presence of university makerspaces has further supported these efforts by providing hands-on learning environments that foster creativity, innovation, and interdisciplinary collaboration (Chekurov et al., 2020; Kantaros et al., 2021).

Despite these advancements, most academic programs have yet to incorporate standalone 3D printing courses into their curricula (Chekurov et al., 2020). Instead, 3D printing is often relegated to workshops, minor components of existing courses, or isolated projects within capstone design courses (Abel & Ziman, 2024; Birtchnell et al., 2017; Borgianni et al., 2022; Chong et al., 2018; Hofmann et al., 2023; Kostova et al., 2024; Stern et al., 2019; Williams & Seepersad, 2012). This limited integration creates a significant knowledge gap: while many students gain practical experience operating basic filament-based printers, they often lack a deeper understanding of the underlying science and engineering principles of AM. In particular, students may be unfamiliar with the diversity of AM technologies, material-process relationships, performance considerations, and critical issues such as repeatability, quality control, sustainability, and future trends.

To address these gaps, this paper presents an approach to integrating 3D printing into engineering curriculum through the development and assessment of an integrated lecture–laboratory framework. This study focuses on two complementary courses developed at the New Jersey Institute of Technology (NJIT): *Introduction to 3D Printing* (CHE 415), designed for undergraduate students, and *Additive Manufacturing and Applications* (CHE 722), tailored for graduate students. The undergraduate course provides foundational knowledge and hands-on experience, while the graduate course builds on these principles to explore advanced applications, material–process interactions, and emerging trends in additive manufacturing. This paper outlines the design, implementation, and instructional strategies of these courses and evaluates their impact on student learning. The courses emphasize project-based learning, interdisciplinary collaboration, and the development of critical skills such as problem-solving, communication, and engineering judgment. Systematic assessment methods, including ABET-aligned outcomes, student self-evaluations, and performance metrics, demonstrate consistently high levels of student proficiency and engagement. The success of this integrated approach highlights the importance of incorporating structured 3D printing education into engineering curricula to better prepare students for the evolving demands of advanced manufacturing industries.

## 2. Materials and Methods

### 2.1. Course Design and Structure

Two complementary courses were developed and implemented at NJIT: *Introduction to 3D Printing* (CHE 415) for undergraduate students and *Additive Manufacturing and Applications* (CHE 722) for graduate students. Both courses are structured as 3-credit offerings, consisting of two hours of lecture and two hours of laboratory work per week. The course syllabi are provided in the **Supplementary Materials (CHE415 and CHE722)**. This integrated lecture–laboratory format allows students to directly connect theoretical concepts with practical implementation. Lecture sessions incorporate traditional instruction, analytical modeling, and student-led discussions, while laboratory sessions focus on hands-on activities, including CAD modeling, slicing, and fabrication

using 3D printing technologies. Printing workflows typically involve an initial setup phase, followed by supervised printing under the guidance of teaching assistants.

## 2.2. Instructional Content

The lecture component provides a comprehensive overview of AM technologies, materials, and applications. Topics include fundamentals and classification of AM technologies; digital workflows (CAD, STL generation, slicing, G-code); extrusion-based printing; vat photopolymerization; droplet-based printing; powder-based printing; 3D bioprinting and bioinks; emerging technologies (e.g., 4D printing, in situ AM, near-zero-gravity printing); and industry trends and applications. Detailed lecture topics and learning objectives are provided in the **Supplementary Materials (Section 1)**. The curriculum emphasizes the interdependence between materials, processing parameters, and final part performance.

## 2.3. Laboratory and Design Projects

The laboratory component consists of progressive design challenges and a final team-based project. Design challenges are biweekly assignments that increase in complexity, beginning with basic CAD modeling and progressing to multi-component functional designs. Students complete both individual and group-based projects, developing skills in: CAD design, slicing and process optimization, material selection, and prototype fabrication. The final design project requires teams to address an open-ended engineering problem, such as designing functional devices or bio-inspired structures. Students must design, fabricate, and evaluate their prototypes and present their findings through written reports and oral presentations. Detailed descriptions of the design challenges and final project, along with representative figures illustrating the designs, are provided in the **Supplementary Materials (Section 2)**.

## 2.4. Literature Review Component

Each student completes a critical review of a peer-reviewed article related to additive manufacturing. Students present their analysis in a structured format, followed by class discussions. Each student is assigned an individual paper and delivers a presentation, while 3–4 students (depending on class size) present in each session. Presentations with lecture topics so that the selected papers correspond to the printing technologies covered in prior lectures. Papers are initially selected by the instructors to ensure coverage of key topics; however, students are also encouraged to explore online library resources, journal platforms, and supplementary materials to identify related work. To promote active participation, each student is required to ask at least three questions during paper review sessions over the course of the semester. Additional participation is incentivized through extra credit.

## 2.5. Group Presentations and Peer-Engagement Activities

To complement the literature-based component, group presentations are implemented to assess students' understanding of the 3D printing industry. Student teams are assigned a company in the AM sector and prepare a 10-minute presentation covering its history, product portfolio, target markets, and future opportunities. All presentations are conducted within a single class session. A peer self-assessment component is incorporated, in which students evaluate both their own contributions and those of their teammates. Groups whose self-assessments closely align with the instructor's evaluation receive additional credit. Students also participate in class-wide evaluations of presentations, selecting categories such as best product portfolio, strongest future market opportunities, most versatile product line, and overall favorite company. In addition, for each design project, students vote to recognize the best printed design. Across these activities, instructional strategies are designed as active, collaborative, and authentic learning assessments incorporating peer evaluation and student-driven engagement.

## 2.6. Assessment Methods

Student learning outcomes were evaluated using a combination of quantitative and qualitative measures across multiple academic semesters (Fall 2017–Fall 2023). Assessment methods included: Course grades and assignment performance; ABET-aligned learning outcome evaluations; Student self-assessments; Survey-based feedback. Grades were mapped to a 1–4 proficiency scale aligned with ABET outcomes. The defined student learning outcomes and the corresponding grade-mapping framework are provided in the **Supplementary Materials (Table S1 and Table S2, respectively)**. Data were collected from institutional learning platforms (Moodle for 2017-2019 and Canvas for 2019 onward) and analyzed using Microsoft Excel and KaleidaGraph.

## 2.7. Generative Artificial Intelligence (GenAI) Use Disclosure

Generative artificial intelligence (GenAI) tools (e.g., ChatGPT) were used to assist with drafting and refining portions of the manuscript text, including improving clarity, grammar, and overall readability. All content was reviewed, edited, and validated by the author to ensure accuracy, originality, and alignment with the study's objectives. No GenAI tools were used for data generation, analysis, or interpretation.

## 3. Results

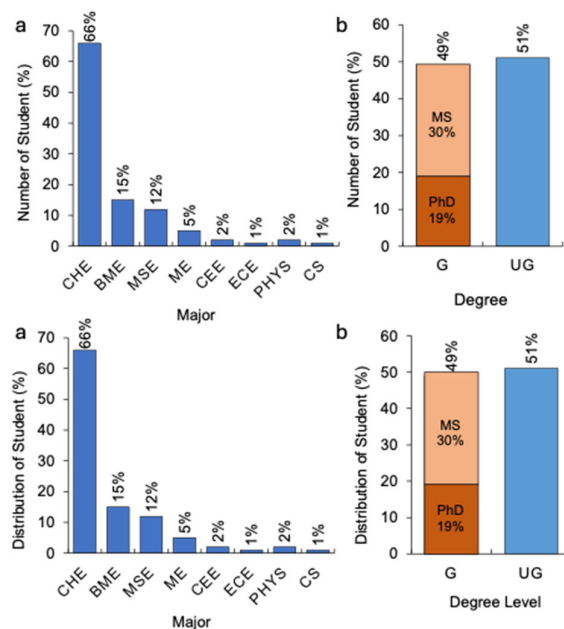
### 3.1. Course Design and Structure

This study is based on two complementary courses in AM: *Introduction to 3D Printing* (CHE 415) for undergraduate students and *Additive Manufacturing and Applications* (CHE 722) for graduate students. Both courses demonstrated consistently high enrollment across multiple years (**Table 1**). While CHE 415 was designed for chemical engineering students, enrollment data indicate significant participation from students in other disciplines, including biomedical engineering and science programs (**Figure 1**). This trend highlights the broad appeal of AM education and its interdisciplinary relevance.

**Table 1.** Course offerings at NJIT.

Year	Semester	Degree	Enrollment	Location
2017	Fall	UG	23 <sup>1</sup>	Satellite Lab
2018	Spring	G	30 <sup>2</sup>	NJIT Makerspace
2019	Spring	UG	24 <sup>1</sup>	CME 3DP Lab
2020	Spring	G	24 <sup>1</sup>	CME 3DP Lab
2021	Fall	G	11 <sup>1, 3</sup>	CME 3DP Lab
2023	Fall	UG	20 <sup>1</sup>	CME 3DP Lab
2025	Fall	UG	Scheduled	Renovated Lab

<sup>1</sup> Enrollment capped at 24 students. <sup>2</sup> Enrollment capped at 30 students. <sup>3</sup> Low graduate student enrollment attributed to the COVID-19 pandemic's impact on academic participation.



**Figure 1.** Student enrollment: a) Bar chart showing the percentage distribution of students by major, including Chemical Engineering (CHE), Biomedical Engineering (BME), Materials Science and Engineering (MSE), Mechanical Engineering (ME), Civil and Environmental Engineering (CEE), Electrical and Computer Engineering (ECE), Physics (PHYS), and Computer Science (CS). b) Bar chart illustrating the percentage distribution of students by degree level, divided into Graduate (G) and Undergraduate (UG) students. The total number of students is 132.

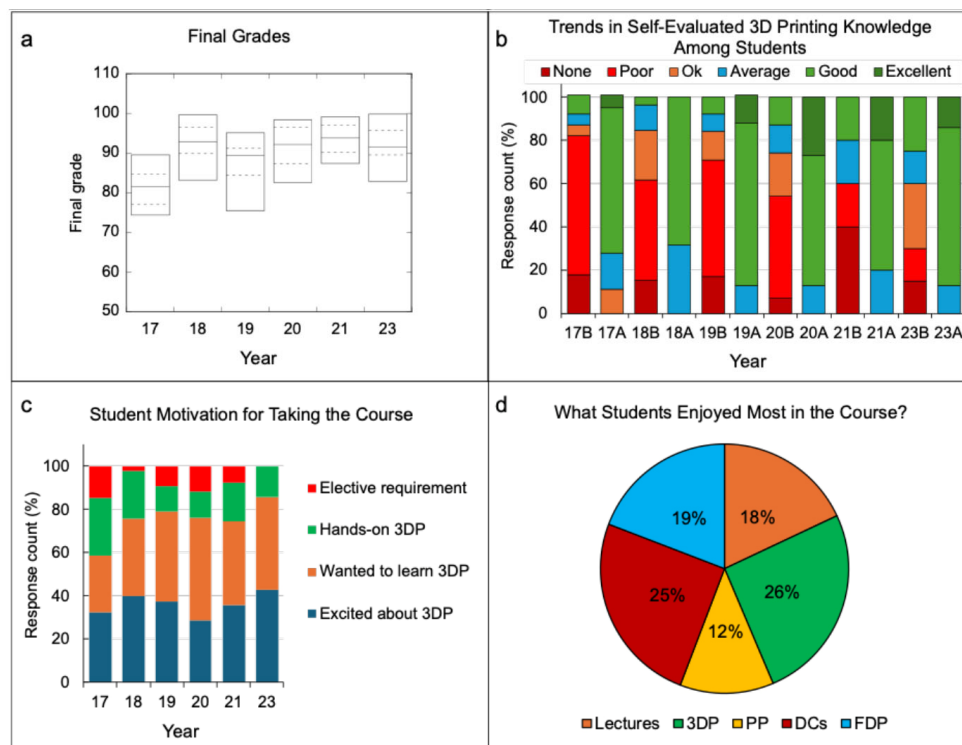
### 3.2. Student Learning Outcomes

Assessment results indicate consistently high student proficiency across ABET-aligned learning outcomes (**Supplementary Materials Table S1-S3**). Most outcomes achieved average scores above 3.5 on a 4.0 scale across multiple years. Several outcomes, including problem-solving, design, and communication skills, consistently achieved scores above 3.8, indicating strong competency. Certain outcomes demonstrated improvement over time, suggesting that iterative course refinements and instructional strategies contributed to enhanced student learning. Although minor variations were observed in some outcomes, overall performance remained stable, with relatively low standard deviations, indicating consistent learning experiences. These outcomes are further supported by engagement-based instructional activities described in *Section 3.6*, which promote active participation and application of concepts.

### 3.3. Academic Performance and Self-Evaluated Knowledge Gains

Student grade distributions (**Figure 2a**) show that the majority of students achieved high grades across multiple offerings of the course. The strong correlation between grades and learning outcome assessments suggests that academic performance reflects mastery of key competencies.

Student self-assessment data (**Figure 2b**) indicate significant increases in perceived knowledge of 3D printing technologies after completing the course. Prior to enrollment, many students reported limited or no experience with 3D printing. By the end of the course, most students rated their knowledge as “good” or “excellent.” Over time, incoming students demonstrated slightly higher baseline familiarity with 3D printing, reflecting increased exposure to the technology through NJIT makerspace and prior coursework.



**Figure 2.** a) Final grade distribution across multiple years. (b) Trends in self-evaluated 3D printing knowledge among students from 2017 to 2023, with B and A representing knowledge levels before and after the semester. c) Student motivation for enrolling in the course over the years. d) A pie chart illustrating the most enjoyed aspects of the course, including Lectures, 3D Printing (3DP), Paper Presentations (PP), Design Challenges (DCs), and the Final Design Project (FDP).

### 3.4. Student Motivation and Course Experience

Survey data (**Figure 2c**) indicate that most students enrolled in the course due to intrinsic interest in 3D printing rather than as a requirement. This suggests strong student motivation and engagement. Student feedback (**Figure 2d**) highlights hands-on activities, including 3D printing and design challenges, as the most valued components of the course. Lectures, final projects, and paper presentations were also positively received, though to a lesser extent. Overall student satisfaction remained consistently high across all years, with majority of the students indicating that they would recommend the course to others. Overall student satisfaction remained consistently high across all years, with the majority of students indicating that they would recommend the course to others. Activities such as paper presentations, peer discussions, and design-based evaluations were frequently cited as valuable components of the course experience.

### 3.4. Student Engagement and Active Learning Outcomes

Student engagement was supported through structured activities including paper presentations, peer questioning, group-based industry analysis, and class-wide voting (**Table 2**). Participation in paper review sessions was consistently high, with all students meeting or exceeding the minimum requirement for asking questions, and many exceeding this threshold. Peer evaluation and voting activities—including selection of best paper presentation, best product portfolio, and best printed design—were completed by the majority of students, indicating strong participation in peer assessment processes. Survey responses further indicate that these activities contributed positively to the overall course experience, with paper presentations and discussions identified as valuable learning components (**Figure 2d**).

**Table 2.** Summary of engagement-based activities and participation

Activity	Description	Participation Level	Assessment Method
Paper Presentations	Individual critical review aligned with lecture topics	100%	Presentation + Q&A
Question Participation	Minimum 3 questions per student	100% (many exceeded)	Participation tracking
Industry Presentations	Group-based company analysis	100%	Peer + instructor evaluation
Peer Assessment	Self and team evaluation	100%	Alignment-based bonus
Voting Activities	Best paper, design, company	100%	Class Voting
Design Competitions	Best printed design per project	100%	Peer Voting

## 4. Discussion

### 4.1. Effectiveness of Integrated Lecture–Laboratory Approach

The results demonstrate that the integrated lecture–laboratory structure is highly effective in supporting student learning in AM. The consistently high performance across ABET-aligned outcomes and strong student engagement suggest that combining theoretical instruction with hands-on experience enables students to develop both conceptual understanding and practical skills. In particular, the laboratory component, which emphasizes iterative design and fabrication, appears to play a central role in reinforcing learning. Student feedback further supports this, as hands-on activities such as 3D printing and design challenges were consistently identified as the most valuable aspects of the course.

This finding aligns with broader trends in engineering education, where experiential and project-based learning approaches have been shown to enhance student engagement, retention, and skill development (Chang et al., 2024; Rehman et al., 2024; Sánchez-García & Reyes-de-Cózar, 2025; Zhang & Ma, 2023). The ability to design, fabricate, test, and refine prototypes provides a direct link between theory and application, which is especially critical in AM due to the strong interdependence between materials, processing, and performance.

### 4.2. Interdisciplinary Appeal and Accessibility

One of the notable outcomes of this study is the strong interdisciplinary participation in the undergraduate course. Although originally designed for chemical engineering students, the course attracted students from multiple disciplines, indicating that AM serves as a unifying platform across engineering and science fields. This interdisciplinary engagement enhances peer learning and exposes students to diverse perspectives and problem-solving approaches (Chen et al., 2024; Medupin et al., 2025).

The broad appeal of the course is partly attributed to the accessibility of material extrusion technologies, such as FFF. These systems have a relatively low barrier to entry, require minimal prior expertise, and are widely available in educational settings and makerspaces. This accessibility enables students from diverse academic backgrounds to quickly engage in hands-on design and fabrication activities. In addition, AM offers versatile solutions across a wide range of fields, including biomedical engineering, materials science, mechanical design, and product development (Zhou et al., 2024). As a result, students from different disciplines are motivated to learn AM for distinct purposes aligned with their academic and career interests. This diversity in motivation further enriches the learning environment by fostering cross-disciplinary collaboration and application-driven problem solving. At the same time, introducing more advanced technologies such as direct ink writing (DIW), vat photopolymerization, and bioprinting allows students to gain exposure to a broader range of

materials and applications, effectively bridging the gap between entry-level prototyping and advanced manufacturing (Rehberg & Brem, 2025).

#### 4.3. Development of Core Engineering Skills

The course structure supports the development of several key engineering competencies, including problem-solving, design thinking, communication, and teamwork. The progressive design challenges and final project require students to engage in iterative design processes, manage constraints, and make informed decisions about materials and process parameters. These activities closely mirror real-world engineering workflows (C.-C. Wang, 2024).

The literature review component further strengthens critical thinking and technical communication skills by requiring students to analyze and present peer-reviewed research. Beyond traditional literature review, the structured implementation of paper-based discussions and industry-focused assessments further enhanced these competencies. Students demonstrated a stronger ability to connect foundational concepts to real-world applications, particularly when analyzing research papers aligned with lecture topics. For example, concepts such as working curves in vat-based photopolymerization and process maps in powder-based printing were more effectively understood when encountered in current literature. Student feedback further supports this outcome, with one noting: "I understand better why we learned all these equations and why they are important."

The industry-focused group presentations complemented the literature-based approach by exposing students to real companies, product portfolios, and market considerations. This broadened students' perspectives beyond technical content to include commercialization and application contexts. The use of peer self-assessment, particularly when aligned with instructor evaluation, further encouraged thoughtful participation and awareness of individual contributions within teams. The structured requirement for students to actively engage—by asking questions during peer presentations—fostered a more interactive classroom environment and encouraged critical thinking. Similarly, incorporating peer evaluation and student voting mechanisms (e.g., best paper presentation, best product portfolio, and best printed design) increased motivation and accountability, while also promoting reflection on quality and innovation (Nielsen et al., 2012).

Overall, these activities functioned as active, collaborative, and authentic learning assessments incorporating peer evaluation and student-driven engagement. Together, they created a balanced learning environment that integrates technical knowledge with essential professional skills. Importantly, improvements observed in certain learning outcomes over time suggest that iterative refinement of course content and structure has contributed to enhanced student performance. This highlights the value of continuous assessment and course evolution in engineering education (Paloposki et al., 2025).

#### 4.4. Addressing Gaps in Additive Manufacturing Education

Despite the growing importance of AM in industry, many academic programs continue to treat 3D printing as a supplementary tool rather than a core subject. This often limits student exposure to basic operation of entry-level printers without developing a deeper understanding of material-process relationships, performance considerations, and advanced technologies. The courses presented in this study address this gap by providing a structured and comprehensive framework that integrates fundamentals, advanced topics, and hands-on experience. By exposing students to multiple AM technologies—including extrusion-based systems, vat photopolymerization, and emerging applications such as bioprinting—the curriculum moves beyond basic prototyping toward a more holistic understanding of AM.

#### 4.5. Limitations

While the course demonstrates strong student engagement and learning outcomes, several limitations should be acknowledged. A key limitation identified through student feedback is the

limited hands-on exposure to a broader range of AM technologies beyond filament printers (FFF) and vat photopolymerization (Form 1, Formlabs). Although the curriculum includes comprehensive coverage of droplet-based, light-based, and powder-based processes, practical experience has primarily been focused on extrusion-based printing due to accessibility and logistical constraints. To address this gap, instructional strategies initially included the use of videos and demonstrations to illustrate advanced manufacturing processes. However, students consistently expressed a desire for direct interaction with these technologies. Recent improvements in institutional infrastructure have begun to mitigate this limitation. NJIT's expanded additive manufacturing facilities now provide access to a wider range of equipment, including a direct metal laser sintering (DMLS) system (EOS M 280), a selective laser sintering (SLS) polymer printer (Fuse 1), and several other vat photopolymerization systems. These resources offer opportunities for students to gain exposure to industrial-grade technologies that extend beyond entry-level platforms. Despite these advancements, challenges remain in integrating these systems fully into coursework. Constraints related to equipment availability, safety requirements, and training needs limit the extent of hands-on access for all students. As a result, providing equitable and consistent experiential learning across multiple technologies remains an ongoing challenge.

#### 4.5. Future Directions

To further expand AM education at NJIT, a dedicated 3D printing laboratory has recently been established, equipped with ten Bambu Lab printers and an expanding bioprinting infrastructure. The laboratory currently includes two bioprinters, with plans to increase this capacity to four, along with the addition of two large biosafety cabinets to support sterile cell-based work. Student engagement during the bioprinting lecture and laboratory demonstrations has been particularly strong. Demonstrations involving cell-laden, vascularized hydrogel constructs (Ji et al., 2019a), bone allograft-based scaffolds (Gharacheh & Guvendiren, 2022; Truong et al., 2025a), biodegradable tissue engineering scaffolds (Abaci & Guvendiren, 2024; Gharacheh et al., 2025; Ji et al., 2019b), as well as emerging topics such as 4D printing (Liaw et al., 2022) and pharmaceutical applications (e.g., chewable tablets (Liaw et al., 2022; Truong et al., 2025b)), generated significant interest among students. These observations highlight the growing demand for deeper exposure to biofabrication and advanced AM applications. To address this interest, future course development will include expanded hands-on bioprinting laboratory sessions within the existing curriculum. In addition, there are plans to develop a standalone bioprinting course that will provide focused training in bioink design, cell handling, and tissue engineering applications. These efforts aim to further bridge the gap between foundational AM education and emerging research and industry needs in biofabrication.

#### 4.6. Implications for Engineering Education

The findings of this study underscore the importance of integrating additive manufacturing into engineering curricula through structured, hands-on, and interdisciplinary approaches. The demonstrated success of these courses suggests that additive manufacturing can serve as an effective platform for teaching design, materials science, and manufacturing principles simultaneously. As the demand for AM expertise continues to grow, educational programs must evolve to provide students with both foundational knowledge and practical skills. The framework presented here offers a scalable model for institutions seeking to incorporate 3D printing into their curricula and better prepare students for careers in advanced manufacturing.

## 5. Conclusions

This study presents the development, implementation, and assessment of an integrated lecture-laboratory framework for additive manufacturing education at the undergraduate and graduate levels. The results demonstrate that combining theoretical instruction with hands-on design and fabrication activities provides an effective approach for teaching 3D printing technologies. Students

not only gained foundational knowledge of AM but also developed critical engineering skills, including problem-solving, design thinking, communication, and teamwork.

The interdisciplinary participation observed in the courses highlights the broad relevance of AM across engineering and science disciplines. The strong student engagement, high levels of performance across ABET-aligned outcomes, and positive feedback emphasize the value of experiential and project-based learning in this context. Importantly, the course structure enables students to connect material selection, processing parameters, and functional performance—an essential aspect of additive manufacturing that is often difficult to convey through traditional instruction alone.

Despite these successes, the study also identifies key challenges, including limitations in providing hands-on exposure to a full range of AM technologies. Ongoing investments in infrastructure, including expanded access to industrial-grade printing systems and bioprinting capabilities, are expected to address these limitations and further enhance the educational experience.

Overall, this work demonstrates that a structured, integrated approach to additive manufacturing education can effectively bridge the gap between theory and practice while preparing students for the evolving demands of advanced manufacturing industries. The framework presented here offers a scalable model for incorporating 3D printing into engineering curricula and can be adapted by other institutions seeking to expand their educational offerings in this rapidly growing field.

**Supplementary Materials:** The following supporting information can be downloaded at the website of this paper posted on Preprints.org, Course syllabi files (CHE415 and CHE722); Supplementary Materials file.

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## References

- Abaci, A., Camci-Unal, G., Guvendiren, M., & Guest, E. (2023). Three-dimensional bioprinting for medical applications. *MRS Bulletin*, 48(6), 624-631. <http://doi.org/10.1557/s43577-023-00546-z>.
- Abaci, A., Gedeon, C., Kuna, A., & Guvendiren, M. (2021). Additive Manufacturing of Oral Tablets: Technologies, Materials and Printed Tablets. *Pharmaceutics*, 13(2), 156. <https://doi.org/10.3390/pharmaceutics13020156>.
- Abaci, A., & Guvendiren, M. (2024). 3D bioprinting of dense cellular structures within hydrogels with spatially controlled heterogeneity. *Biofabrication*, 16(3), 035027. <http://doi.org/10.1088/1758-5090/ad52f1>.
- Abel, A., & Ziman, R. (2024). Learning Dogfish Shark Anatomy Using 3D-Printed Models: A Feasibility Study. *Education Sciences*, 14(1), 34. <https://doi.org/10.3390/educsci14010034>.
- Al Rashid, A., Khan, S. A., G. Al-Ghamdi, S., & Koç, M. (2020). Additive manufacturing: Technology, applications, markets, and opportunities for the built environment. *Automation in Construction*, 118, 103268. <http://doi.org/https://doi.org/10.1016/j.autcon.2020.103268>.
- Andić, B., Ulbrich, E., Dana-Picard, T., Cvjetičanin, S., Petrović, F., Lavicza, Z., & Maričić, M. (2023). A Phenomenography Study of STEM Teachers' Conceptions of Using Three-Dimensional Modeling and Printing (3DMP) in Teaching. *Journal of Science Education and Technology*, 32(1), 45-60. <http://doi.org/10.1007/s10956-022-10005-0>.
- Awang Zainal, A. Z., Md Yasir, A. S. H., Basri, A. Q., Latif, K., Nelfiyanti, N., Mohd Yusoo, M. Y., & Ishak, M. R. (2026). Exploring the use of assistive technology in special education: Issues and trends for student visual impairments: A systematic literature review. *Assist Technol*, 1-16. <http://doi.org/10.1080/10400435.2026.2636752>.
- Bai, W., Fang, H., Wang, Y., Zeng, Q., Hu, G., Bao, G., & Wan, Y. (2021). Academic insights and perspectives in 3d printing: A bibliometric review. *Applied Sciences (Switzerland)*, 11(18), Article 8298. <http://doi.org/10.3390/app11188298>.
- Birtchnell, T., Böhme, T., & Gorkin, R. (2017). 3D printing and the third mission: The university in the materialization of intellectual capital. *Technological Forecasting and Social Change*, 123, 240-249. <http://doi.org/https://doi.org/10.1016/j.techfore.2016.03.014>.
- Bonorden, M., & Papenbrock, J. (2022). Evidence-Based Optimization of Classroom Teaching Units Using 3D Printers for Designing Models—From the 2D Picture to the 3D Flower Model. *Education Sciences*, 12(11), 831.
- Borgianni, Y., Pradel, P., Berni, A., Obi, M., & Bibb, R. (2022). An investigation into the current state of education in Design for Additive Manufacturing. *Journal of Engineering Design*, 33(7), 461-490. <http://doi.org/10.1080/09544828.2022.2102893>.
- Cai, B., Rajendran, K., Bay, B. H., Lee, J., & Yen, C. C. (2019). The Effects of a Functional Three-dimensional (3D) Printed Knee Joint Simulator in Improving Anatomical Spatial Knowledge. *Anat Sci Educ*, 12(6), 610-618. <http://doi.org/10.1002/ase.1847>.
- Chaari, M. Z. (2024, 11-13 Nov. 2024). *The Impact of 3D Printing on the Defense Industry*. 2024 IEEE International Workshop on Technologies for Defense and Security (TechDefense).
- Chang, Y., Choi, J., & Şen-Akbulut, M. (2024). Undergraduate Students' Engagement in Project-Based Learning with an Authentic Context. *Education Sciences*, 14(2), 168. <https://doi.org/10.3390/educsci14020168>.
- Chekurov, S., Wang, M., Salmi, M., & Partanen, J. (2020). Development, Implementation, and Assessment of a Creative Additive Manufacturing Design Assignment: Interpreting Improvements in Student Performance. *Education Sciences*, 10(6), 156. <https://doi.org/10.3390/educsci10060156>.
- Chen, S., Ma, L., & Ma, Y. (2024). Chinese Doctoral Students Involved in Interdisciplinary Learning Score Higher on Scientific Creativity: The Roles of Teamwork Skills and Collaborative Behaviors. *Behavioral Sciences*, 14(11), 1046. <https://doi.org/10.3390/bs14111046>.
- Chong, S., Pan, G.-T., Chin, J., Show, P. L., Yang, T. C. K., & Huang, C.-M. (2018). Integration of 3D Printing and Industry 4.0 into Engineering Teaching. *Sustainability*, 10(11), 3960.
- Diao, K., Duff, S. M. G., & Li, H. (2026). An Idea to Explore: Enhancing the Teaching of Genome Editing Through 3D Printed Models of CRISPR-Cas9 Technology. *Biochemistry and Molecular Biology Education*, 1-5. <http://doi.org/10.1002/bmb.70047>.

- El-Sayegh, S., Romdhane, L., & Manjikian, S. (2020). A critical review of 3D printing in construction: benefits, challenges, and risks. *Archives of Civil and Mechanical Engineering*, 20(2), 34. <http://doi.org/10.1007/s43452-020-00038-w>.
- Espera, A. H., Dizon, J. R. C., Chen, Q., & Advincula, R. C. (2019). 3D-printing and advanced manufacturing for electronics. *Progress in Additive Manufacturing*, 4(3), 245-267. <http://doi.org/10.1007/s40964-019-00077-7>.
- Ford, S., & Minshall, T. (2019). Invited review article: Where and how 3D printing is used in teaching and education. *Additive Manufacturing*, 25, 131-150. <http://doi.org/https://doi.org/10.1016/j.addma.2018.10.028>.
- Gharacheh, H., Abaci, A., Alkhoury, K., Choudhury, E., Liaw, C.-Y., Chester, S. A., & Guvendiren, M. (2025). Comparative evaluation of melt- vs. solution-printed poly( $\epsilon$ -caprolactone)/hydroxyapatite scaffolds for bone tissue engineering applications. *Soft Matter*, 21(5), 844-854. <http://doi.org/10.1039/D4SM01197J>.
- Gharacheh, H., & Guvendiren, M. (2022). Cell-Laden Composite Hydrogel Bioinks with Human Bone Allograft Particles to Enhance Stem Cell Osteogenesis. *Polymers*, 14(18), 3788. <https://doi.org/10.3390/polym14183788>.
- Goh, G. L., Zhang, H., Chong, T. H., & Yeong, W. Y. (2021). 3D Printing of Multilayered and Multimaterial Electronics: A Review. *Advanced Electronic Materials*, 7(10), 2100445. <http://doi.org/https://doi.org/10.1002/aelm.202100445>.
- Gudapati, H., Dey, M., & Ozbolat, I. (2016). A comprehensive review on droplet-based bioprinting: Past, present and future. *Biomaterials*, 102, 20-42. <http://doi.org/https://doi.org/10.1016/j.biomaterials.2016.06.012>.
- Hofmann, U., Ferchow, J., & Meboldt, M. (2023). Enhancing design for additive manufacturing education through a performance-based design challenge. *Procedia CIRP*, 119, 728-733. <http://doi.org/https://doi.org/10.1016/j.procir.2023.02.163>.
- Hossain, K. R., Shishir, M. M. A., Rashid, S., Ahmed, M. H., Basher, A., Risad, R. H., & Paul, A. C. (2023). Application of 3D printing technology in the military. *Journal of Chemistry Letters*, 4(2), 103-116. <http://doi.org/10.22034/jchemlett.2023.395069.1113>.
- Hossain, M. A., Zhumabekova, A., Paul, S. C., & Kim, J. R. (2020). A Review of 3D Printing in Construction and its Impact on the Labor Market. *Sustainability*, 12(20), 8492.
- House, A., Kuna, A., Hastings, D., Rodriguez, N., Schoenitz, M., Dreizin, E. L., & Guvendiren, M. (2023). Effect of particle shape on rheology and printability of highly filled reactive inks for direct ink writing. *Progress in Additive Manufacturing*, 8(6), 1573-1585. <http://doi.org/10.1007/s40964-023-00422-x>.
- Jayabal, P., Gujar, S., Ostrovidov, S., Sesma, J. Z., del Burgo Martínez, L. S., Durrieu, M. C., Pedraz, J. L., Sivalingam, D., Bharath, G., Ramalingam, M., & Mathapati, S. (2025). Advances in 3D Printing for Personalized Pharmaceuticals. *Polymers for Advanced Technologies*, 36(12), Article e70478. <http://doi.org/10.1002/pat.70478>.
- Ji, S., Almeida, E., & Guvendiren, M. (2019a). 3D bioprinting of complex channels within cell-laden hydrogels. *Acta Biomaterialia*, 95, 214-224. <http://doi.org/https://doi.org/10.1016/j.actbio.2019.02.038>.
- Ji, S., Dube, K., Chesterman, J. P., Fung, S. L., Liaw, C.-Y., Kohn, J., & Guvendiren, M. (2019b). Polyester-based ink platform with tunable bioactivity for 3D printing of tissue engineering scaffolds. *Biomaterials Science*, 7(2), 560-570. <http://doi.org/10.1039/C8BM01269E>.
- Jovanović, M., Mateo Sanguino, T. d. J., Damjanović, M., Đukanović, M., & Thomopoulos, N. (2023). Driving Sustainability: Carbon Footprint, 3D Printing, and Legislation concerning Electric and Autonomous Vehicles. *Sensors*, 23(22), 9104. <https://doi.org/10.3390/s23229104>.
- Kantaros, A., Diegel, O., Piromalis, D., Tsaramirsis, G., Khadidos, A. O., Khadidos, A. O., Khan, F. Q., & Jan, S. (2021). 3D printing: Making an innovative technology widely accessible through makerspaces and outsourced services. *Materials Today: Proceedings*.
- Kazoka, D., Pilmane, M., & Edelmers, E. (2021). Facilitating Student Understanding through Incorporating Digital Images and 3D-Printed Models in a Human Anatomy Course. *Education Sciences*, 11(8), 380.
- Kitos Vasconcelos, A. P., Millik, S. C., Vazquez, A., Sadaba, N., Sateesh, S., Daily, S., Yu, S., Zhang, M., Manitsirisuk, N., & Nelson, A. (2025). Light-Based 3D Printing of Polymeric Materials. *Annual Review of Materials Research*, 55(Volume 55, 2025), 491-521. <http://doi.org/https://doi.org/10.1146/annurev-matsci-080423-123810>.

- Kostova, B., Chavdarov, I., Georgieva-Tsaneva, G., Kostova, S., & Krastev, A. (2024, 26-28 Sept. 2024). *Integrating Creativity in a STEAM Physics Lesson by using 3D Printing and a Humanoid Robot NAO*. 2024 International Conference on Software, Telecommunications and Computer Networks (SoftCOM).
- Kumar, P., Ray, R., Kumar, S., Powar, S., & Doddamani, M. (2026). A review on direct ink writing 3D printing: Materials, properties, and future advancements. *Progress in Engineering Science*, 3(1), 100241. <http://doi.org/https://doi.org/10.1016/j.pes.2026.100241>.
- Liaw, C.-Y., & Guvendiren, M. (2017). Current and emerging applications of 3D printing in medicine. *Biofabrication*, 9(2), 024102. <http://doi.org/10.1088/1758-5090/aa7279>.
- Liaw, C.-Y., Pereyra, J., Abaci, A., Ji, S., & Guvendiren, M. (2022). 4D Printing of Surface Morphing Hydrogels. *Advanced Materials Technologies*, 7(6), 2101118. <http://doi.org/https://doi.org/10.1002/admt.202101118>.
- Liaw, C.-Y., Tolbert, J. W., Chow, L. W., & Guvendiren, M. (2021). Interlayer bonding strength of 3D printed PEEK specimens. *Soft Matter*, 17(18), 4775-4789. <http://doi.org/10.1039/D1SM00417D>.
- Lim, C. W. J., Le, K. Q., Lu, Q., & Wong, C. H. (2016). An Overview of 3-D Printing in Manufacturing, Aerospace, and Automotive Industries. *IEEE Potentials*, 35(4), 18-22. <http://doi.org/10.1109/MPOT.2016.2540098>.
- Lin, K.-Y., Hsiao, H.-S., Chang, Y.-S., Chien, Y.-H., & Wu, Y.-T. (2018). The effectiveness of using 3D printing technology in STEM project-based learning activities. *EURASIA Journal of Mathematics, Science and Technology Education*, 14(12), em1633.
- Liu, Z., Zhang, M., Bhandari, B., & Wang, Y. (2017). 3D printing: Printing precision and application in food sector. *Trends in Food Science & Technology*, 69, 83-94. <http://doi.org/https://doi.org/10.1016/j.tifs.2017.08.018>.
- Lopes, L. R., Silva, A. F., & Carneiro, O. S. (2018). Multi-material 3D printing: The relevance of materials affinity on the boundary interface performance. *Additive Manufacturing*, 23, 45-52. <http://doi.org/https://doi.org/10.1016/j.addma.2018.06.027>.
- Manoj Prabhakar, M., Saravanan, A. K., Haiter Lenin, A., Jerin leno, I., Mayandi, K., & Sethu Ramalingam, P. (2021). A short review on 3D printing methods, process parameters and materials. *Materials Today: Proceedings*, 45, 6108-6114. <http://doi.org/https://doi.org/10.1016/j.matpr.2020.10.225>.
- McMenamin, P. G., Quayle, M. R., McHenry, C. R., & Adams, J. W. (2014). The production of anatomical teaching resources using three-dimensional (3D) printing technology. *Anatomical Sciences Education*, 7(6), 479-486. <http://doi.org/10.1002/ase.1475>.
- Medupin, C., Regalado, C., & Burrows, M. (2025). Creating an Innovative Approach to Engagement, Connectivity, and Problem-Solving in Higher Education Institutions Using LEGO® Serious Play®. *Education Sciences*, 15(6), 663. <https://doi.org/10.3390/educsci15060663>.
- Motyl, B., & Filippi, S. (2021). Trends in engineering education for additive manufacturing in the industry 4.0 era: a systematic literature review. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 15(1), 103-106. <http://doi.org/10.1007/s12008-020-00733-1>.
- Munir, M. T., Jamwal, P. K., Li, B., Carter, S., & Hussain, S. (2025). Revolutionising engineering pedagogy: The role of 3D printing in modern engineering education. *Innovations in Education and Teaching International*, 62(2), 575-593. <http://doi.org/10.1080/14703297.2024.2346554>.
- Nemorin, S., & Selwyn, N. (2017). Making the best of it? Exploring the realities of 3D printing in school. *Research Papers in Education*, 32(5), 578-595. <http://doi.org/10.1080/02671522.2016.1225802>.
- Nielsen, K. L., Hansen-Nygaard, G., & Stav, J. B. (2012). Investigating Peer Instruction: How the Initial Voting Session Affects Students' Experiences of Group Discussion. *International Scholarly Research Notices*, 2012(1), 290157. <http://doi.org/https://doi.org/10.5402/2012/290157>.
- Paloposki, T., Virtanen, V., & Clavert, M. (2025). From a final exam to continuous assessment on a large Bachelor level engineering course. *European Journal of Engineering Education*, 50(1), 164-177. <http://doi.org/10.1080/03043797.2024.2334728>.
- Paukstelis, P. J. (2018). MolPrint3D: Enhanced 3D Printing of Ball-and-Stick Molecular Models. *Journal of Chemical Education*, 95, 169-172.
- Pernaa, J., & Wiedmer, S. (2020). A systematic review of 3D printing in chemistry education – analysis of earlier research and educational use through technological pedagogical content knowledge framework. *Chemistry Teacher International*, 2(2). <http://doi.org/doi:10.1515/cti-2019-0005>.

- Pikkarainen, A., & Piili, H. (2021). Implementing 3d printing education through technical pedagogy and curriculum development. *International Journal of Engineering Pedagogy*, 10(6), 95-119. <http://doi.org/10.3991/IJEP.V10i6.14859>.
- Pikkarainen, A., Salminen, A., & Piili, H. (2017). Creating Learning Environment Connecting Engineering Design and 3D Printing. *Physics Procedia*, 89, 122-130. <http://doi.org/https://doi.org/10.1016/j.phpro.2017.08.020>.
- Rao, C. H., Avinash, K., Varaprasad, B. K. S. V. L., & Goel, S. (2022). A Review on Printed Electronics with Digital 3D Printing: Fabrication Techniques, Materials, Challenges and Future Opportunities. *Journal of Electronic Materials*, 51(6), 2747-2765. <http://doi.org/10.1007/s11664-022-09579-7>.
- Rayna, T., & Striukova, L. (2016). From rapid prototyping to home fabrication: How 3D printing is changing business model innovation. *Technological Forecasting and Social Change*, 102, 214-224. <http://doi.org/https://doi.org/10.1016/j.techfore.2015.07.023>.
- Rehberg, L., & Brem, A. (2025). Bridging the gap: Linking prototyping and technology readiness levels for integrative product development. *Creativity and Innovation Management*, 34(1), 237-252. <http://doi.org/https://doi.org/10.1111/caim.12633>.
- Rehman, N., Huang, X., Mahmood, A., AlGerafi, M. A. M., & Javed, S. (2024). Project-based learning as a catalyst for 21st-Century skills and student engagement in the math classroom. *Heliyon*, 10(23), e39988. <http://doi.org/https://doi.org/10.1016/j.heliyon.2024.e39988>.
- Rossi, S., Benaglia, M., Brenna, D., Porta, R., & Orlandi, M. (2015). Three Dimensional (3D) Printing: A Straightforward, User-Friendly Protocol To Convert Virtual Chemical Models to Real-Life Objects. *Journal of Chemical Education*, 92(8), 1398-1401. <http://doi.org/10.1021/acs.jchemed.5b00168>.
- Sánchez-García, R., & Reyes-de-Cózar, S. (2025). Enhancing Project-Based Learning: A Framework for Optimizing Structural Design and Implementation—A Systematic Review with a Sustainable Focus. *Sustainability*, 17(11), 4978. <https://doi.org/10.3390/su17114978>.
- Scalfani, V. F., & Vaid, T. P. (2014). 3D printed molecules and extended solid models for teaching symmetry and point groups. *Journal of Chemical Education*, 91(8), 1174-1180. <http://doi.org/10.1021/ed400887t>.
- Scalfani, V. F., Williams, A. J., Tkachenko, V., Karapetyan, K., Pshenichnov, A., Hanson, R. M., Liddie, J. M., & Bara, J. E. (2016). Programmatic conversion of crystal structures into 3D printable files using Jmol. *J Cheminform*, 8, 66. <http://doi.org/10.1186/s13321-016-0181-z>. PMID: PMC5122160.
- Shanthar, R., Chen, K., & Abeykoon, C. (2023). Powder-Based Additive Manufacturing: A Critical Review of Materials, Methods, Opportunities, and Challenges. *Advanced Engineering Materials*, 25(19), 2300375. <http://doi.org/https://doi.org/10.1002/adem.202300375>.
- Smith, C. F., Tollemache, N., Covill, D., & Johnston, M. (2018). Take away body parts! An investigation into the use of 3D-printed anatomical models in undergraduate anatomy education. *Anat Sci Educ*, 11(1), 44-53. <http://doi.org/10.1002/ase.1718>.
- Stern, A., Rosenthal, Y., Dresler, N., & Ashkenazi, D. (2019). Additive manufacturing: An education strategy for engineering students. *Additive Manufacturing*, 27, 503-514. <http://doi.org/https://doi.org/10.1016/j.addma.2019.04.001>.
- Szukala, J., Ishutov, S., Yildirim-Erbasli, S. N., & Taikh, A. (2026). Exploring the use of 3D-printed models, computer-aided designs, and 2D images in geoscience learning within a small-cohort introductory classroom. *Journal of Geoscience Education*, 1-13. <http://doi.org/10.1080/10899995.2026.2642391>.
- To, T. T., Al Mahmud, A., & Ranscombe, C. (2025). A framework for integrating additive manufacturing into engineering education: perspectives of students and educators. *European Journal of Engineering Education*, 50(2), 298-319. <http://doi.org/10.1080/03043797.2024.2358368>.
- Truong, H., Abaci, A., Gharacheh, H., & Guvendiren, M. (2025a). Embedded bioprinting of dense cellular constructs in bone allograft-enhanced hydrogel matrices for bone tissue engineering. *Biomaterials Science*, 13(12), 3213-3222. <http://doi.org/10.1039/D4BM01616E>.
- Truong, H., Rodriguez, N., Abaci, A., Guner, G., Young, J., Bilgili, E. A., & Guvendiren, M. (2025b). 3D Printing of chewable oral tablets using drug nanosuspension inks: an experimental and machine learning study. *Virtual and Physical Prototyping*, 20(1), e2517811. <http://doi.org/10.1080/17452759.2025.2517811>.
- Ullah, A. S., Tashi, Kubo, A., & Harib, K. H. (2020). Tutorials for Integrating 3D Printing in Engineering Curricula. *Education Sciences*, 10(8), 194.

- Vo, H. (2024). Design creativity in Industry 4.0: Gravity Sketch and 3D printing in a Luminaire design project. *Journal of Engineering, Design and Technology*, 22(5), 1413-1432. <http://doi.org/10.1108/JEDT-01-2022-0053>.
- Wang, C.-C. (2024). Using design thinking for interdisciplinary curriculum design and teaching: a case study in higher education. *Humanities and Social Sciences Communications*, 11(1), 307. <http://doi.org/10.1057/s41599-024-02813-z>.
- Wang, L., Jiang, S., & Zhang, S. (2020). Mapping technological trajectories and exploring knowledge sources: A case study of 3D printing technologies. *Technological Forecasting and Social Change*, 161, Article 120251. <http://doi.org/10.1016/j.techfore.2020.120251>.
- Williams, C. B., & Seepersad, C. C. (2012). *Design for additive manufacturing curriculum: A problem- and project-based approach*. 2012 International Solid Freeform Fabrication Symposium.
- Wu, S., Zeng, T., Liu, Z., Ma, G., Xiong, Z., Zuo, L., & Zhou, Z. (2022). 3D Printing Technology for Smart Clothing: A Topic Review. *Materials*, 15(20), 7391. <https://doi.org/10.3390/ma15207391>.
- Xiao, Y.-Q., & Kan, C.-W. (2022). Review on Development and Application of 3D-Printing Technology in Textile and Fashion Design. *Coatings*, 12(2), 267.
- Zhang, L., & Ma, Y. (2023). A study of the impact of project-based learning on student learning effects: a meta-analysis study. *Front Psychol*, 14, 1202728. <http://doi.org/10.3389/fpsyg.2023.1202728>. PMID: PMC10411581.
- Zhen, H., Zhao, B., Quan, L., & Fu, J. (2023). Effect of 3D Printing Process Parameters and Heat Treatment Conditions on the Mechanical Properties and Microstructure of PEEK Parts. *Polymers*, 15(9), 2209. <https://doi.org/10.3390/polym15092209>.
- Zhou, L., Miller, J., Vezza, J., Mayster, M., Raffay, M., Justice, Q., Al Tamimi, Z., Hansotte, G., Sunkara, L. D., & Bernat, J. (2024). Additive Manufacturing: A Comprehensive Review. *Sensors (Basel)*, 24(9). <http://doi.org/10.3390/s24092668>. PMID: PMC11085389.
- Zhu, C., Gameda, H. B., Duoss, E. B., & Spadaccini, C. M. (2024). Toward Multiscale, Multimaterial 3D Printing. *Advanced Materials*, 36(34), 2314204. <http://doi.org/https://doi.org/10.1002/adma.202314204>.

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