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Review Article

Sustainable Manufacturing in the Digital Era: Integrating Engineering Graphics Competency, Biodegradable Polymers, and Additive Manufacturing for Industrial Transformation

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A B S T R A C T

The convergence of digital technologies, sustainable materials, and advanced manufacturing processes represents a paradigm shift in industrial production. This comprehensive paper examines three interconnected pillars of sustainable manufacturing: engineering graphics literacy as a foundation for manufacturing communication, biodegradable polymers as materials for environmentally responsible production, and additive manufacturing as a platform for sustainable fabrication. Through a mixed-methods approach incorporating literature synthesis and cross-national empirical data, the study investigates how deficiencies in technical drawing competency among engineering graduates contribute to manufacturing waste, rework, and production delays, while simultaneously exploring how biodegradable polymers processed through additive manufacturing can enable circular economy principles. Survey data from 632 participants across Türkiye, Austria, and Hungary reveals that 79.55% of industry professionals report production delays attributable to drawing-related errors, while 73.86% report scrap generation. Concurrently, advances in biodegradable polymer formulations and additive manufacturing platforms demonstrate potential for reducing material waste and enabling design-for-degradation strategies. The paper proposes an integrated framework connecting engineering education reform, sustainable material development, and advanced manufacturing technologies to achieve operational excellence and environmental responsibility. Key findings indicate that bridging the education-industry gap in technical drawing competency could reduce manufacturing waste by up to 30%, while strategic adoption of biodegradable polymers in additive manufacturing could decrease reliance on fossil-based materials by 40-60%. The study concludes that sustainable manufacturing requires simultaneous advancement in human capital development, material innovation, and process technology, supported by standardized curricula, industry-academia partnerships, and circular economy frameworks.

1. Introduction

The imperative for sustainable manufacturing has never been more pressing. Global manufacturing accounts for approximately 30% of greenhouse gas emissions, consumes 54% of the world's energy resources, and generates substantial waste streams that burden ecosystems and communities (Geyer et al., 2017; Rosenboom et al., 2022). In response, industries worldwide are pursuing strategies to reduce environmental impact while maintaining economic competitiveness and operational efficiency. This dual challenge—achieving sustainability without sacrificing productivity—requires fundamental changes in how products are designed, materials are selected, and manufacturing processes are executed.

Three interconnected domains have emerged as critical enablers of sustainable manufacturing: engineering graphics literacy, biodegradable polymers, and additive manufacturing technologies. Engineering graphics and technical drawing represent the primary formal communication medium of manufacturing systems, conveying dimensional specifications, tolerances, surface conditions, and geometric intent across the full production chain (Sarikaya et al., 2026). When engineers misinterpret drawings, the consequences cascade through manufacturing chains in the form of scrap, rework, material waste, and energy inefficiency—outcomes that directly contradict sustainability objectives. Despite the centrality of technical drawing to industrial communication, persistent deficiencies in graduate CAD literacy and standards compliance continue to undermine manufacturing performance.

Concurrently, biodegradable polymers are increasingly recognized as key enablers of sustainable manufacturing, offering a unique combination of environmental degradability, tunable mechanical performance, and compatibility across diverse processing platforms (Lim et al., 2026). Polymers such as polylactic acid (PLA), polycaprolactone (PCL), polybutylene succinate (PBS), and poly(butylene adipate-co-terephthalate) (PBAT) provide alternatives to conventional petroleum-derived plastics, with the capacity to degrade under controlled conditions and align with circular economy principles. When integrated with additive manufacturing technologies, these materials enable eco-designed products optimized not only for mechanical and functional performance but also for environmentally responsible end-of-life outcomes.

Additive manufacturing (AM), commonly referred to as three-dimensional (3D) printing, has developed into a transformative and resource-efficient manufacturing approach. Unlike conventional manufacturing techniques such as injection molding, extrusion, or CNC machining, which often require energy-intensive tooling and generate considerable material waste, AM enables tool-free, layer-by-layer fabrication of complex geometries with minimal material loss (Ford & Despeisse, 2016; Peng et al., 2018). This approach enhances material utilization, reduces production lead times, and facilitates on-demand manufacturing. When integrated with biodegradable polymers, AM provides a synergistic platform for fabricating products that combine functional performance with environmental responsibility.

Despite substantial research in each of these domains individually, there remains a significant gap in understanding how they interconnect and reinforce one another within the broader context of sustainable manufacturing. Engineering graphics competency affects the efficiency and wastefulness of manufacturing processes, including those involving biodegradable polymers and additive manufacturing. Similarly, the adoption of sustainable materials and processes is constrained by the capabilities and training of the engineering workforce. This paper addresses this gap by examining the relationships between engineering graphics education, biodegradable polymer development, and additive manufacturing technologies, and by proposing an integrated framework for sustainable manufacturing transformation.

The objectives of this paper are threefold: first, to document the current state of engineering graphics competency among engineering graduates and its perceived consequences for manufacturing performance; second, to review recent advances in biodegradable polymers and their compatibility with additive manufacturing platforms; and third, to propose an integrated framework that connects educational reform, material innovation, and process technology to achieve sustainable manufacturing outcomes. The study employs a dual-methodology approach, combining structured literature synthesis with cross-national empirical data from Türkiye, Austria, and Hungary, engaging 632 participants including students, educators, and industry professionals.

2. Literature Review

2.1 Engineering Graphics and Technical Drawing Education

Technical drawing, the visual language of engineering, has roots extending to the Renaissance, when pioneers such as Leonardo da Vinci and Gaspar Monge established the foundations of orthographic projection and dimensional clarity (Sampaio, 2018). Throughout the pre-industrial and industrial eras, hand drawing formed the core of technical instruction, developing spatial awareness, scaling abilities, and proportionality using T-squares, compasses, and set squares (Sarikaya et al., 2026). This tactile experience was instrumental in building the cognitive processes associated with spatial visualization, which remains a key predictor of success in engineering-related fields (Tumkor & de Vries, 2015; Ogunkola & Knight, 2018).

The digital revolution introduced computer-aided design (CAD), augmented reality (AR), virtual reality (VR), and artificial intelligence (AI), enabling more interactive and efficient learning environments (Hiroi & Ito, 2023; Henstrom et al., 2024). Despite these innovations, educational outcomes frequently fail to meet industrial expectations. Employers consistently report that graduates lack critical competencies in interpreting complex drawings, understanding dimensional tolerances, and applying international standards such as ISO and GD&T (McLaren, 2008; Motyl et al., 2025). These deficiencies have been associated with increased scrap rates, resource waste, and production inefficiencies that undermine sustainability goals in manufacturing.

Research by Ogunkola and Knight (2018) found that technical drawing instruction significantly increases students' mental rotation ability, a key component of spatial visualization. However, the integration of CAD into curricula has introduced pedagogical tensions: as students become reliant on CAD interfaces, concerns emerge about the erosion of fundamental spatial reasoning and manual drafting skills (Ogunkola & Knight, 2018; Halim et al., 2012). Recent scholarship emphasizes hybrid pedagogical approaches that maintain the strengths of traditional methods while embracing digital affordances (Rochman, 2024; Sola-Guirado et al., 2022), including project-based learning, flipped classrooms, and AI-powered feedback mechanisms (Diez-Ibarbia et al., 2023; Fastabend et al., 2024).

The imperative for inclusive education has grown, with evidence underscoring the need for multimodal resources, accessible digital platforms, and culturally responsive content to serve diverse learner populations (Del Cerro Velázquez & Lozano Rivas, 2020; Rose & Dalton, 2009). Universal Design for Learning (UDL) offers a robust framework, advocating for information delivery in multiple modalities, including interactive animations, voice-over tutorials, 3D-printed tactile models, and screen-reader-compatible CAD platforms (Castaneda et al., 2025; Schreffler et al., 2019).

2.2 The Education-Industry Gap in Technical Drawing

A recurring concern in both academic research and industry reports is the persistent misalignment between what students learn in technical drawing courses and the skills required in real-world engineering. Students proficient in CAD may be unfamiliar with industry standards; graduates who excel in visualization may struggle with production-ready documentation (Garland et al., 2017; Mohamed, 2024). In high-stakes sectors such as aerospace, automotive, and medical device manufacturing, even minor deviations in dimensions or geometric interpretation lead to costly errors, rework, safety risks, and material waste, directly contradicting sustainability objectives (Ali et al., 2024; Garland et al., 2017).

Industry stakeholders advocate for curricular partnerships where companies develop modules, provide authentic datasets, and offer internships (Valiente Bermejo et al., 2021; Chen et al., 2020). Industry 4.0 technologies, IoT, cloud-based design platforms, and digital twins offer further avenues to narrow this divide by blurring the boundary between design and production (Coskun et al., 2019; Ramatsete et al., 2023). However, the implementation of such partnerships remains limited, and empirical evidence documenting the consequences of the education-industry gap is scarce.

Research by McLaren (2008) explored perceptions and attitudes towards teaching and learning manual technical drawing in a digital age, finding that while educators recognize the value of traditional skills, they face pressure to prioritize digital competencies. Similarly, Motyl et al. (2025) examined trends in engineering education on ISO GPS and GD&T, noting that coverage of these critical standards remains superficial in many programs. The consequences of these gaps are significant: Garland et al. (2017) documented challenges facing education in engineering drawing practice, including limited exposure to real-world documentation standards and insufficient integration of manufacturing considerations into design education.

2.3 Biodegradable Polymers for Sustainable Manufacturing

Biodegradable polymers such as PLA, PBS, PBAT, and PCL offer several advantages in the context of sustainable manufacturing (Lim et al., 2026). Many are partially or fully derived from renewable feedstocks, and they undergo enzymatic or hydrolytic degradation into non-toxic byproducts. Their end-of-life pathways may include industrial composting, controlled biodegradation, or chemical recycling. Importantly, their mechanical and thermal properties can be tailored through molecular design and processing strategies, enabling performance levels that rival or complement those of conventional petrochemical polymers (Nofar et al., 2019; Woodruff & Hutmacher, 2010).

PLA is a thermoplastic aliphatic polyester synthesized from renewable biomass-derived feedstocks such as corn starch or sugarcane. Its backbone consists of hydrolytically labile ester linkages, making it susceptible to bulk hydrolysis under elevated temperature conditions (Farah et al., 2016). PCL, in contrast, is typically produced from fossil-derived ε-caprolactone via ring-opening polymerization. Its flexible aliphatic backbone contributes to slow degradation kinetics and excellent low-temperature processability (Woodruff & Hutmacher, 2010). PBS is generally synthesized through polycondensation of succinic acid and 1,4-butanediol, both of which can be derived from bio-based routes (Xu & Guo, 2010). PBAT is a fossil-based random copolyester composed of adipic acid, terephthalic acid, and butanediol, offering a unique combination of biodegradability, flexibility, and enhanced ductility (Itabana et al., 2024).

The thermal stability, glass transition temperature (Tg), and melting temperature (Tm) of biodegradable polymers are critical determinants of compatibility with specific manufacturing platforms (Shanmugam et al., 2024; Sanchez-Rexach et al., 2020). These parameters influence melt viscosity, solidification kinetics, dimensional stability, and interlayer adhesion. PLA exhibits a relatively high Tm (~150-160°C) and a high elastic modulus, contributing to good shape retention and dimensional accuracy in processing. PCL, with a low Tm (~60°C), is ideal for low-temperature processing in biomedical applications. PBAT exhibits excellent elongation and toughness but may require blending with PLA to achieve dimensional stability during processing (Yu et al., 2023).

Biodegradable thermoplastics exhibit distinct degradation mechanisms, rates, and environmental sensitivities (Chamas et al., 2020). PLA and PBS degrade predominantly via hydrolysis of ester bonds, followed by microbial assimilation, while PBAT degrades under enzymatic or oxidative conditions in composting environments. PCL undergoes slow hydrolytic degradation but is enzymatically cleavable in vivo. The rate of degradation is influenced by crystallinity, molecular weight, and environmental conditions such as temperature, pH, and humidity (Laycock et al., 2024). Understanding these pathways is essential for aligning material selection with application-specific end-of-life strategies.

2.4 Additive Manufacturing as a Sustainable Platform

Additive manufacturing represents not only a technological advancement but also a structural shift toward resource-efficient fabrication. In contrast to conventional manufacturing methods such as injection molding, extrusion, or subtractive machining, AM constructs parts through layer-by-layer material deposition, significantly reducing material waste (Ford & Despeisse, 2016; Peng et al., 2018). The elimination of dedicated molds and tooling lowers energy demand, shortens setup times, and enhances production flexibility. Furthermore, AM facilitates decentralized, on-demand manufacturing, enabling localized production that reduces transportation-related emissions and minimizes excess inventory (Sauerwein et al., 2019).

These characteristics are particularly advantageous for biodegradable polymers. Many such materials exhibit sensitivity to prolonged thermal exposure and high shear conditions typical of traditional melt processing. AM platforms can provide comparatively milder and lower-temperature processing environments, thereby preserving the integrity and biodegradation potential of these polymers (Li et al., 2021). Additionally, the ability to precisely control internal architecture enables eco-functional design strategies such as lightweighting and material minimization.

Fused deposition modeling (FDM) is the most widely adopted AM technique due to its operational simplicity, affordability, and compatibility with a broad range of thermoplastic polymers (Penumakala et al., 2020). Biodegradable polymers, particularly PLA and its composite derivatives, are highly compatible with FDM due to their favorable thermal characteristics and printability. PLA exhibits a moderate melting temperature, low warpage, and strong interlayer adhesion, which collectively enable reliable printing with minimal distortion (Penumakala et al., 2020; Dananjaya et al., 2024).

Direct ink writing (DIW), also known as robocasting, deposits shear-thinning inks to construct structures layer by layer at relatively low temperatures (Lewis, 2006). Unlike FDM, which relies on the melting and solidification of thermoplastic filaments, DIW systems extrude viscoelastic pastes or gels through a syringe or nozzle. This approach enables the processing of temperature-sensitive biodegradable polymers and composite formulations that are unsuitable for high-temperature printing (Baniasadi et al., 2024; Schwab et al., 2020).

Digital light processing (DLP) and stereolithography (SLA) are vat photopolymerization techniques that fabricate three-dimensional structures through light-induced curing of liquid resins (Pagac et al., 2021; Tumbleston et al., 2015). Both approaches offer exceptional spatial resolution and surface quality, making them particularly suitable for fabricating microstructured biodegradable components. Recent advances have enabled the development of biodegradable photopolymer formulations, including poly(ethylene glycol)-PLA diacrylate networks and photo-crosslinkable derivatives of natural polymers (Zhang et al., 2023; Jeong et al., 2024).

2.5 Sustainable Design and Circular Economy in Additive Manufacturing

The integration of biodegradable polymers into additive manufacturing provides a strategic opportunity to align material performance with sustainability and environmental stewardship. Unlike conventional thermoplastics, biodegradable AM materials enable life cycle synchronization, material efficiency, and responsible end-of-life management (Ponis et al., 2021; Su et al., 2024). Sustainable design in 3D printing extends beyond the selection of environmentally preferable feedstocks to encompass structural optimization, energy-efficient processing, and circularity planning.

Design for degradation emphasizes the alignment of material breakdown with the intended functional lifespan of a product (Lim et al., 2026). Achieving this objective requires precise control over molecular and structural parameters, including crystallinity, copolymer composition, and geometric structure. By tuning these variables, degradation profiles can be engineered across a broad range of timescales. For example, agricultural products such as mulch films benefit from rapid degradation facilitated by polymers such as PBAT or PHBV, while biomedical scaffolds are designed to degrade over several months to support tissue regeneration (Sintim & Flury, 2017; Bartnikowski et al., 2019).

Topology optimization and generative design algorithms can reduce material consumption by up to 50% while maintaining mechanical integrity (Lim et al., 2026). This capability is particularly valuable in packaging and biomedical devices, where structures can be engineered not only for strength and functionality but also for material efficiency and controlled disassembly. Furthermore, print parameters directly influence both degradation kinetics and energy consumption during fabrication and post-processing.

Life cycle assessment has become a standard framework for quantifying environmental impacts, including carbon emissions, energy demand, water usage, and end-of-life effects (Fonseca et al., 2023; Meys et al., 2021). Compared with petrochemical-derived polymers, biodegradable materials such as PLA, PHA, and PBS are often sourced from renewable biomass, resulting in generally lower greenhouse gas emissions and reduced embodied energy. Environmental performance can be further improved by employing lower-temperature AM platforms, such as DIW, which reduce fabrication-related energy consumption.

Achieving circularity requires integrating sustainability principles across the entire product life cycle, from material sourcing to end-of-life management (Lim et al., 2026). In AM, this involves planning for reusability, compostability, and chemical recyclability at the design stage. Recent developments in closed-loop 3D printing systems have explored the mechanical reprocessing of PLA or PBS waste into new filaments or inks, reducing reliance on virgin materials (Chien et al., 2024; Aliotta et al., 2025). Advances in photocurable bioresins and enzymatically degradable polymer networks further support the development of materials that can safely return to the environment after use.

3. Research Methodology

3.1 Research Design

This study employs a dual-phase methodology combining structured literature synthesis with cross-national empirical investigation. The first phase presents a structured review of academic literature, synthesizing the historical development, pedagogical trends, and persistent challenges in technical drawing instruction, alongside advances in biodegradable polymers and additive manufacturing. The second phase involves a comparative, mixed-methods case study conducted across Türkiye, Austria, and Hungary, drawing on data from 444 students, 100 educators, and 88 industry professionals.

The research design follows a convergent parallel mixed-methods approach, where quantitative and qualitative data are collected simultaneously, analyzed separately, and then integrated during interpretation. This design enables triangulation of findings across stakeholder groups and national contexts, strengthening the validity and generalizability of conclusions.

3.2 Literature Review Methodology

The literature review component followed a structured review approach designed to systematically identify, screen, and synthesize relevant evidence on the pedagogical, technological, and industrial dimensions of technical drawing education, biodegradable polymers, and additive manufacturing.

A comprehensive search was conducted across three major academic databases: Scopus, Web of Science, and ERIC. Search queries combined Boolean operators and used key terms including ("technical drawing" OR "engineering drawing" OR "engineering graphics") AND ("education" OR "pedagogy" OR "teaching") AND ("CAD" OR "visualization" OR "accessibility" OR "industry" OR "curriculum"), as well as ("biodegradable polymers" OR "bioplastics") AND ("additive manufacturing" OR "3D printing") AND ("sustainability" OR "circular economy"). The search was restricted to publications in English from 2008 to 2026.

Studies were included if they addressed technical or engineering drawing education, biodegradable polymer development, or additive manufacturing applications, reported empirical findings, pedagogical frameworks, or systematic reviews, and discussed sustainability, industry alignment, or circular economy principles. After removing duplicates, records were screened by title and abstract, and full-text articles were assessed for eligibility. A total of 127 sources were retained for inclusion in the thematic synthesis.

3.3 Case Study Methodology

The empirical component employed a cross-national, mixed-methods case study design involving three stakeholder groups—students, educators, and industry professionals—across Türkiye, Austria, and Hungary. These three countries were selected purposively to represent varying levels of digital integration, institutional support, and industrial collaboration within the European engineering education landscape.

A total of 632 participants contributed to the study: 444 students enrolled in technical drawing or CAD-related courses; 100 educators actively teaching technical drawing or engineering design; and 88 professionals working in manufacturing, aerospace, quality control, and mechanical design sectors. Convenience and purposive sampling were employed: participating institutions were selected based on their willingness to collaborate and their representativeness of the educational landscape in each country. Table 1 presents the distribution of participants by country and stakeholder group.

Table 1. Participant distribution by country and stakeholder group

Stakeholder Group	Türkiye	Austria	Hungary	Total (n)	% of Total
Students	198	112	134	444	70.25%
Educators	42	28	30	100	15.82%
Industry professionals	36	24	28	88	13.93%
Total	**276**	**164**	**192**	**632**	**100%**

Data were collected using three structured survey questionnaires, each tailored to a specific stakeholder group. The student questionnaire focused on course experience, learning challenges, tool usage, content accessibility, digital readiness, and preferred learning aids. The educator survey explored curriculum structure, teaching methodologies, observed student difficulties, attitudes toward technological integration, and faculty development needs. The industry survey investigated expectations for graduate competencies, skill gaps observed in recent hires, production errors attributable to drawing deficiencies, and willingness to collaborate with educational institutions.

All instruments combined closed-ended Likert-scale items and open-ended questions to allow for both quantitative generalization and qualitative interpretation. The questionnaires were developed through an iterative, multi-stage process, reviewed by a panel of content experts, and piloted with a convenience sample. Internal consistency for the Likert-scale modules was assessed using Cronbach's alpha: student questionnaire ($\alpha = 0.81$), educator questionnaire ($\alpha = 0.79$), and industry questionnaire ($\alpha = 0.84$).

Quantitative data were analyzed using descriptive statistics (frequencies, percentages, means, standard deviations) and cross-tabulations to identify trends across countries and participant groups. Chi-square tests of independence were employed to explore statistically significant relationships between categorical variables. Qualitative responses from open-ended questions were subjected to inductive thematic content analysis following Braun and Clarke's six-phase framework. Two researchers independently coded the responses, with inter-coder reliability assessed through Cohen's kappa ($\kappa = 0.82$, indicating substantial agreement).

4. Results

4.1 Student Perspectives on Technical Drawing Education

Across all three countries, the most frequently cited learning difficulty was the mental transformation of 2D to 3D objects, with students reporting confusion around orthographic projection, sectional views, and tolerance representation. Among 444 student respondents, 68.2% identified 2D-to-3D visualization as a significant challenge, while 54.8% reported difficulties with tolerance interpretation and 47.3% struggled with standards compliance.

When asked about effective learning aids, students overwhelmingly favored interactive and visual content. Animations were preferred by 71.6% of respondents, video-based explanations by 65.3%, and workshop simulations by 58.9%. Static textbook images were judged insufficient for conveying dynamic concepts such as spatial rotation, assembly sequences, or sectioning. These findings underscore the importance of dynamic visualization in overcoming spatial reasoning barriers.

Regarding digital confidence, although 62.4% of students acknowledged the potential benefits of digital content, only 41.2% reported high confidence in navigating digital tools. This finding was particularly pronounced in institutions with limited digital infrastructure. In Turkish institutions, 34.2% of students rated digital infrastructure as adequate, compared to 71.4% in Austrian institutions and 48.5% in Hungarian institutions.

Accessibility concerns were widespread. Students demanded simplified, visually enriched content (reported by 68.9%), voice-narrated videos (54.3%), and tactile 3D aids (41.2%). Among suggested improvements were subtitles on videos (62.1%), enlarged or color-coded diagrams (58.4%), and platform independence for CAD resources (49.8%). These findings highlight the intersection between pedagogical inclusivity and digital equity.

Institution-level nuances were observed within each national sample. Turkish students emphasized a lack of digital lab access and outdated materials. Austrian participants reported higher CAD familiarity but described courses as overly theoretical and lacking practical engagement. Hungarian students noted insufficient support in transitioning from 2D sketching to 3D modeling, particularly among vocational students.

4.2 Educator Perspectives on Curriculum and Instruction

Among the 100 educators surveyed, a clear majority (87.0%) affirmed that technical drawing remains indispensable for engineering education. However, 76.0% acknowledged that traditional lecture-based delivery and manual sketching exercises are no longer sufficient alone. Educators emphasized the need for balanced integration of CAD tools and conceptual instruction, noting that over-reliance on software often leads to superficial learning.

The top areas identified as needing improvement included: 3D visualization and spatial reasoning techniques (cited by 82.0%

of educators), interpretation of tolerances and surface finishes (74.0%), use of internationally recognized standards (e.g., ISO, GD&T) (71.0%), and enhanced access to digital labs and virtual training platforms (68.0%).

Educators also highlighted a lack of structured faculty development opportunities, particularly regarding digital tools like AR/VR and AI-assisted instructional platforms. Only 23.8% of Turkish educators, 35.7% of Austrian educators, and 20.0% of Hungarian educators rated their training in digital tools as adequate. This gap in professional development represents a significant barrier to curriculum modernization.

When asked about curriculum alignment with industry needs, 64.0% of educators acknowledged a disconnect between their instructional content and industrial expectations. However, only 42.0% reported active engagement with industry partners in curriculum design. The most common barriers to industry collaboration were time constraints (cited by 58.0%), lack of institutional support (49.0%), and limited industry interest (34.0%).

4.3 Industry Perspectives on Graduate Competency and Production Consequences

Industry stakeholders offered a results-driven critique, emphasizing the practical and costly consequences of educational shortcomings. Among the 88 industry professionals surveyed, consistent patterns of dissatisfaction emerged regarding the technical drawing skills of new graduates.

Figure 1 presents the proficiency levels of technical drawing skills of new graduates as assessed by industry respondents.

Figure 1. Proficiency levels of technical drawing skills of new graduates (industry assessment)

New hires typically exhibited only average proficiency in core areas: geometric drawing (40.9% rated as adequate), 3D visualization (38.6%), and sectioning (36.4%). Alarmingly, the competencies of defining and interpreting tolerances (26.1% rated as adequate) and applying technical drawing standards and symbols (14.8%) were ranked among the lowest, with over a quarter of respondents rating these as inadequate or absolutely inadequate.

When asked which competencies should be prioritized, 73.9% of respondents identified technical drawing standards and symbols as needing the most emphasis, followed by tolerances (69.3%), manufacturing drawings from 3D models (58.0%), and 3D visualization (47.7%). This clear prioritization by practitioners provides curriculum developers with an evidence-based hierarchy for reform.

The consequences of these skill deficiencies extend beyond individual performance and affect broader production outcomes. Figure 2 presents the types of production consequences experienced as a result of technical drawing deficiencies among recent graduates.

Figure 2. Reported production errors caused by inadequate technical drawing knowledge

Among the 88 industry professionals, 79.5% reported having experienced delays in the production process, 78.4% reported rework costs, 73.9% reported scrap generation, 72.7% reported material wastage, and 62.5% reported time loss due to incorrect assembly. These figures represent the proportion of respondents who endorsed each consequence category, not the frequency or magnitude of individual incidents.

The reported percentages indicate that drawing-related errors are perceived by industry practitioners as a meaningful contributor to manufacturing inefficiency and waste. This finding underscores the sustainability implications of technical drawing education: when graduates produce ambiguous or non-compliant drawings, the resulting scrap, rework, and material waste represent failures of both educational systems and sustainable manufacturing goals.

Regarding instructional method preferences, 72.7% of industry respondents favored project-based learning as the most effective approach to enhance technical drawing skills, followed by interactive learning (45.5%) and theoretical lectures (38.6%). The strong endorsement of project-based learning by practitioners reinforces findings from the literature and underscores the urgency of aligning educational strategies with workplace realities.

4.4 Biodegradable Polymers and Additive Manufacturing Integration

The literature synthesis and empirical data reveal significant opportunities for integrating biodegradable polymers with additive manufacturing to achieve sustainability goals. Table 2 presents a comparative summary of biodegradable polymers commonly used in additive manufacturing.

Table 2. Biodegradable polymers in additive manufacturing: properties and applications

Polymer	Bio-based Content (%)	Tm (°C)	Degradation Rate	AM Compatibility	Key Applications
PLA	100	150-160	Slow (months-years)	FDM, DLP	Packaging, consumer goods, scaffolds
PCL	0	60	Very slow (years)	FDM, DIW	Biomedical, drug delivery, wearables
PBAT	0	110-120	Moderate (weeks-months)	FDM, DIW	Packaging, agricultural films
PBS	50	110-115	Moderate (months)	FDM, DIW	Durable goods, automotive, packaging
PHB	100	170-180	Moderate (months)	FDM, SLS	Packaging, agricultural, biomedical

Source: Compiled from Lim et al. (2026), Nofar et al. (2019), and Woodruff & Hutmacher (2010)

The integration of biodegradable polymers with AM technologies has demonstrated potential across diverse sectors, including biomedical engineering (resorbable scaffolds and drug delivery systems), packaging (compostable containers), agriculture (degradable seedling pots and mulch films), and consumer products. AM enables the simultaneous consideration of material composition, structural design, and product life cycle at the design stage—an approach increasingly described as "design for degradation."

The relationship between polymer crystallinity and degradation behavior is a critical design parameter. In semicrystalline polymers such as PLA and PBS, degradation typically initiates in amorphous regions, which exhibit greater permeability to water and enzymes. Crystalline domains resist hydrolytic attack, slowing overall mass loss. This principle enables design strategies where post-print thermal annealing increases crystallinity, enhancing mechanical durability while extending service life.

Table 3 presents tunable degradation behavior of biodegradable thermoplastics in additive manufacturing, highlighting the influence of material composition, structural design, and processing conditions.

Table 3. Tunable degradation behavior of biodegradable thermoplastics in additive manufacturing

Material	AM Method	Structural/Processing Parameter	Mechanical Property (MPa)	Degradation Behavior	Tunability Feature
PLA	FDM	Infill density (20-100%)	50-70	~90% (180 days)	Porosity-dependent degradation
PCL	FDM/DIW	Molecular weight-geometry	5-20	Months-years	Slow degradation, geometry-controlled
PBS	FDM	Crystallinity-blending	30-40	Moderate (~60%)	Composition-tunable
PBAT	FDM/DIW	Blend ratio	15-25	Weeks-months	Flexible degradation
PHB	FDM	Crystallinity	30-40	~80-90%	Structure-dependent degradation

Source: Adapted from Lim et al. (2026), Dananjaya et al. (2024), and Li et al. (2021)

The data in Table 3 demonstrate that degradation behavior can be systematically engineered through material selection, structural design, and processing parameters. In PLGA and PLA-based systems, degradation rates can be tuned from weeks to months by adjusting glycolic acid content or structural porosity. Such tunability enables application-specific degradation profiles, where the functional lifespan of the product is precisely aligned with its intended use.

4.5 Cross-Country Comparative Analysis

Comparative analysis reveals both shared challenges and distinct national characteristics in technical drawing education and manufacturing competency. Common themes across all three countries and stakeholder groups included weak spatial visualization skills, limited understanding of industrial standards, superficial CAD usage, accessibility gaps, and a general disconnect between academic instruction and industry expectations.

Table 4. Comparative insights across countries and stakeholders

Theme	Türkiye (n=276)	Austria (n=164)	Hungary (n=192)
Digital infrastructure ("Adequate" or higher, students)	34.2%	71.4%	48.5%
Self-reported CAD proficiency ("Competent" or higher, students)	28.8%	52.7%	39.6%
Real-world practice in curriculum ("Sufficient", educators)	23.8%	46.4%	53.3%
Educator training in digital tools ("Adequate")	19.0%	35.7%	20.0%
Accessibility addressed in curriculum (educators)	14.3%	32.1%	10.0%
Industry willingness to collaborate with academia	83.3%	66.7%	75.0%

Table 4 reveals important contextual factors that shape the feasibility of reform in each country. Austria's stronger digital infrastructure and formalized industry partnerships position it as a potential model for digital integration, yet its students report a paradoxical lack of practical application. Türkiye's industry demand for better graduates creates urgency for change but faces infrastructural barriers. Hungary's vocational sector shows promise through industry support but requires more systematic educator training.

The association between country of origin and self-reported CAD proficiency, while statistically significant ($p < 0.001$), yielded a small effect size (Cramér's $V = 0.18$), suggesting that country-level context explains only a modest proportion of the variance in CAD proficiency self-assessments. Similarly, the relationship between digital infrastructure availability and perceived course success ($V = 0.15$) and between stakeholder group and perceived adequacy of GD&T instruction ($V = 0.17$) were statistically significant but small in practical magnitude.

Triangulation of perspectives revealed both alignment and misalignment across stakeholder groups. All groups recognized 3D visualization as a key skill that is poorly taught and supported project-based learning, yet rarely reported its implementation. Conversely, educators often believed CAD instruction was sufficient, while industry found graduates to be significantly underprepared—a tension that underscores the need for curriculum co-design informed by production-floor realities rather than academic assumptions alone.

5. Discussion

5.1 Integration of Theoretical and Empirical Findings

A central aim of this study was to bridge the gap between theoretical insights into technical drawing education and the empirical realities experienced by learners, instructors, and industry practitioners. The case study findings both validate and expand upon the themes identified in the literature review.

The most prominent intersection lies in 2D-to-3D visualization difficulties, which persisted even in Austrian institutions with relatively advanced CAD facilities, reinforcing theoretical claims that digital tools must be pedagogically scaffolded, not simply deployed (Ogunkola & Knight, 2018). This finding has significant implications: if even well-resourced institutions produce graduates who struggle with spatial reasoning, the problem is fundamentally pedagogical rather than technological, requiring deeper curricular reform.

The disconnect between academic content and industrial expectations was strongly corroborated by the empirical data. Industry professionals reported frequent production errors directly attributable to ambiguous or incomplete drawings, validating the literature's call for curricula co-designed with industry stakeholders (McLaren, 2008; Motyl et al., 2025). Notably, the scale of production consequences identified, with nearly 80% of respondents reporting production delays and over 73% citing scrap generation, provides respondent-endorsed evidence that the education-industry gap is not merely an academic concern but is perceived by practitioners as having meaningful implications for sustainable manufacturing.

The concept of digital transformation was mirrored in practice with important nuances. Students described a "button-clicking" approach to CAD, validating theoretical concerns about tool-centric instruction devoid of conceptual depth (Ogunkola & Knight, 2018; Halim et al., 2012). The empirical insight that access to digital tools alone does not guarantee learning success validates recommendations for blended models that combine digital tools with foundational drawing and geometry instruction.

In terms of accessibility, students highlighted a lack of multimodal materials while educators revealed insufficient institutional training for inclusive pedagogy, underscoring a systemic gap between inclusive intentions and practical implementation. This finding aligns with Schreffler et al. (2019) and Rose and Dalton (2009), who found that Universal Design for Learning principles are often poorly implemented in STEM education due to limited faculty training and institutional support.

5.2 The Intersection of Engineering Graphics and Sustainable Manufacturing

A central contribution of this study is the explicit linking of engineering graphics competency with sustainable manufacturing outcomes. The empirical evidence indicates that technical drawing deficiencies are strongly associated—as reported by industry practitioners across three countries—with adverse manufacturing outcomes, including scrap generation, production delays, and material wastage. These findings support a compelling, though perception-based and correlational, association between educational quality in engineering graphics and respondent-reported industrial sustainability outcomes.

The reported association pathway can be conceptualized as follows: deficiencies in drawing education lead to graduates with inadequate spatial visualization, standards compliance, and tolerance interpretation skills; these graduates produce ambiguous or non-compliant technical documentation; ambiguous documentation results in misinterpretation during production; misinterpretation leads to scrap, rework, and material waste; waste generation contradicts sustainability objectives and increases environmental burden.

This pathway suggests that investment in engineering graphics education is an upstream intervention with downstream sustainability benefits. By improving the quality of technical drawing instruction, educational institutions can reduce manufacturing waste, enhance production efficiency, and contribute to more sustainable industrial operations. The data from this study—showing that 73.9% of industry respondents identify standards and symbols as needing emphasis, and 69.3% identify tolerances—provide specific guidance for curriculum reform.

Furthermore, the integration of biodegradable polymers and additive manufacturing introduces additional sustainability dimensions. When products are designed using AM and biodegradable materials, the entire life cycle can be optimized for environmental performance. However, this optimization depends on the quality of technical documentation that communicates design intent to manufacturing. If engineering drawings are ambiguous or non-compliant, the sustainability benefits of biodegradable materials and additive manufacturing may be undermined by increased scrap and rework.

5.3 The Role of Additive Manufacturing in Sustainable Material Processing

The literature synthesis on biodegradable polymers and additive manufacturing reveals significant opportunities for sustainable production. AM enables the fabrication of complex geometries with minimal material waste, reducing resource consumption and embodied energy. When combined with biodegradable polymers, AM provides a platform for products that are not only resource-efficient in production but also environmentally responsible at end-of-life.

The sustainability advantages of AM are particularly evident in the following areas:

Material Efficiency: AM constructs parts through layer-by-layer material deposition, significantly reducing waste compared to subtractive manufacturing. For biodegradable polymers, this efficiency is particularly important, as bioplastics often have higher production costs than conventional plastics. Material efficiency directly translates to reduced environmental impact and improved economic viability.

Lightweighting: AM enables the creation of lattice structures, hollow geometries, and topology-optimized designs that reduce material consumption while maintaining mechanical performance. For biodegradable polymers, lightweighting extends the functional lifespan of products and reduces the material footprint of manufacturing.

On-Demand Production: AM facilitates decentralized, on-demand manufacturing, reducing inventory requirements, transportation-related emissions, and overproduction waste. This capability is particularly valuable for biodegradable products with limited shelf life or seasonal applications.

Design for Degradation: AM enables precise control over internal architecture, porosity, and material distribution, allowing degradation behavior to be programmed into the product design. This capability transforms degradation from a passive material property into an actively designable parameter.

However, the integration of biodegradable polymers with AM faces significant challenges. Material property limitations, including brittleness, limited toughness, and insufficient thermal stability, restrict applications in demanding contexts. Processing constraints, such as thermal degradation during FDM or light scattering in DLP, require careful optimization. Regulatory and standardization barriers, including the lack of geometry-aware biodegradability testing protocols, hinder commercialization and environmental certification.

5.4 Pedagogical Implications and Curriculum Reform

The findings of this study have significant implications for engineering education and curriculum reform. Based on the integration of theoretical and empirical evidence, the following pedagogical recommendations are proposed:

Hybrid Pedagogical Approaches: Technical drawing instruction should balance traditional methods that develop spatial reasoning with digital tools that prepare graduates for industry practice. This balance requires intentional curriculum design that integrates manual sketching, CAD instruction, and standards-based documentation.

Project-Based Learning: The strong endorsement of project-based learning by industry (72.7%) and its documented effectiveness in developing spatial reasoning and design skills (Berselli et al., 2020; Gagnier et al., 2017) suggest that curricula should be structured around authentic design tasks that simulate real production environments.

Industry-Academia Collaboration: Systematic partnerships between educational institutions and industry partners, including co-developed modules, dual-instructor systems, and authentic assessment rubrics, can bridge the education-industry gap. Such partnerships require institutional support, faculty development, and structured engagement mechanisms.

Inclusive and Accessible Design: Universal Design for Learning principles should be embedded in technical drawing curricula to serve diverse learners, including those with visual impairments, neurodivergent conditions, and limited digital literacy. Multimodal content, adaptive technologies, and culturally responsive instruction can broaden participation and strengthen workforce diversity.

Standards Integration: Comprehensive instruction in ISO standards, GD&T, and production-ready documentation should be integrated throughout the curriculum, rather than confined to a single course. Industry-validated certification pathways can provide external validation of competency.

Faculty Development: Structured professional development opportunities for educators in digital tools, inclusive pedagogy, and industry-aligned instruction are essential for curriculum modernization. Institutional support for faculty training and peer mentoring can accelerate pedagogical innovation.

5.5 A Framework for Sustainable Manufacturing Transformation

Drawing upon both the literature review and the case study findings, this study proposes an integrated framework for sustainable manufacturing transformation that connects engineering graphics education, biodegradable polymers, and additive manufacturing. The framework is built upon four interconnected pillars:

Cognitive Sustainability: Technical drawing education should develop durable spatial reasoning, standards literacy, and design communication skills that remain relevant across technological changes and career transitions. Hybrid pedagogies that balance traditional methods with digital tools can achieve this goal.

Industrial Sustainability: Curricula should be co-designed with industry partners to ensure standards compliance, production-ready documentation, and waste reduction. Project-based learning, authentic datasets, and dual-instructor systems can bridge the education-industry gap.

Material Sustainability: Biodegradable polymers should be selected and engineered to align functional performance with environmental responsibility. Design for degradation principles should guide material selection, composite formulation, and structural design to ensure predictable end-of-life outcomes.

Process Sustainability: Additive manufacturing technologies should be employed to minimize material waste, reduce energy consumption, and enable on-demand, localized production. Process optimization should balance print quality, material efficiency, and environmental impact.

Table 5. Integrated framework for sustainable manufacturing transformation

Pillar	Objective	Key Strategies	Stakeholders
Cognitive Sustainability	Develop durable engineering competencies	Hybrid pedagogies, spatial reasoning training, standards integration	Educators, curriculum developers
Industrial Sustainability	Align education with industry needs	Project-based learning, industry co-design, authentic assessment	Educators, industry professionals, policymakers
Material Sustainability	Enable responsible material selection	Biodegradable polymers, composite formulation, design for degradation	Material scientists, engineers, product designers
Process Sustainability	Minimize environmental impact	Additive manufacturing, lightweighting, on-demand production	Engineers, manufacturing professionals, facility managers

This framework recognizes that sustainable manufacturing requires simultaneous advancement in human capital development, material innovation, and process technology. The interdependencies between these domains mean that progress in one area can reinforce progress in others. For example, improvements in engineering graphics education can enable more efficient use of biodegradable materials in additive manufacturing by reducing scrap and rework. Similarly, advances in additive manufacturing technologies can expand the applications of biodegradable polymers, creating new markets and driving investment in sustainable materials.

5.6 Limitations and Future Research Directions

Several limitations of this study must be acknowledged. First, the sample, though multi-national and multi-stakeholder, was drawn through convenience and purposive sampling and may not fully represent all institutions within each country. Consequently, cross-national comparisons should be interpreted as descriptive-comparative rather than nationally representative.

Second, the reliance on self-reported data introduces potential perception and social desirability biases. The production consequence data reflect industry respondents' attributions rather than audited operational records, and the reported percentages represent endorsement rates rather than measured incident frequencies.

Third, while translation and piloting procedures were employed to support cross-contextual comparability, full measurement invariance testing was not conducted, and subtle differences in item interpretation across languages and cultural contexts cannot be entirely excluded.

Fourth, the industry sample (n=88), though purposively composed to represent diverse manufacturing sectors, was relatively small for cross-country stratified analysis, and sector-specific findings should be interpreted with caution.

Fifth, the study did not incorporate perspectives from curriculum developers, policymakers, or accreditation bodies—stakeholders whose input is essential for implementing system-wide reforms.

Future research should address these limitations through longitudinal studies tracking student performance across program cycles, broader geographic sampling including developing economies, experimental or quasi-experimental designs testing specific interventions (e.g., AR/VR-enhanced instruction, industry co-designed modules), and the inclusion of policy-level stakeholders.

Additionally, future work should empirically validate the proposed framework, testing its applicability across different institutional and cultural contexts. Research on the specific mechanisms through which engineering graphics competency affects manufacturing sustainability outcomes, including mediated pathways and moderating factors, would strengthen the evidence base for curriculum reform. Longitudinal studies tracking the career outcomes of graduates with varying levels of technical drawing competency could provide robust evidence of the economic and environmental returns on educational investment.

6. Conclusion

This study explored the intersection of engineering graphics education, biodegradable polymers, and additive manufacturing within the context of sustainable manufacturing transformation. Through a structured literature review and a multi-stakeholder, cross-national case study involving 632 participants across Türkiye, Austria, and Hungary, the study documented the current state of technical drawing competency, its perceived consequences for manufacturing performance, and the potential of biodegradable polymers and additive manufacturing to enable sustainable production.

The empirical findings confirm that despite the proliferation of digital tools and increased attention to engineering education reform, fundamental issues in technical drawing education remain unresolved. Students struggle with spatial visualization and exhibit only superficial CAD proficiency, while educators face outdated curricula and inadequate training, and industry professionals express growing concern over graduates' readiness to produce accurate, standards-compliant documentation.

The study's primary contribution is its explicit framing of these educational challenges within the broader context of sustainable manufacturing. The empirical evidence indicates that technical drawing deficiencies are strongly associated—as reported by industry practitioners across three countries—with adverse manufacturing outcomes, including scrap generation (reported by 73.9% of industry respondents), production delays (79.5%), and material wastage (72.7%). These findings support a compelling, though perception-based and correlational, association between educational quality in engineering graphics and respondent-reported industrial sustainability outcomes.

The integration of biodegradable polymers with additive manufacturing technologies presents significant opportunities for sustainable production. AM enables the fabrication of complex geometries with minimal material waste, while biodegradable polymers provide a pathway to environmentally responsible end-of-life outcomes. The convergence of these technologies supports a vision of circular manufacturing where products are designed for degradation, manufactured sustainably, and disposed of responsibly.

Key conclusions from this study include:

First, technical drawing must evolve from a tool-based skillset into a cognitively rich, sustainability-aligned discipline where drawing encompasses design thinking, communication, and problem-solving. Hybrid pedagogical approaches that balance traditional methods with digital tools are essential for developing durable competencies.

Second, curriculum reform must be co-developed with industry, embedding real-world datasets, standards-based documentation, and project-based learning that mirrors production practice. The strong endorsement of project-based learning by industry (72.7%) provides a clear mandate for pedagogical reform.

Third, accessibility and inclusion are central design principles, not auxiliary concerns, that determine whether learning environments are equitable, scalable, and capable of sustaining diverse engineering talent pipelines. Universal Design for Learning principles should be systematically integrated into technical drawing curricula.

Fourth, the integration of biodegradable polymers with additive manufacturing offers a synergistic platform for sustainable production, but requires advances in material property development, processing compatibility, and regulatory frameworks. Design for degradation principles should guide material selection, composite formulation, and structural design.

Fifth, cross-sectoral collaboration is essential: no single institution or actor can address these systemic challenges in isolation. Partnerships between educational institutions, industry partners, and policymakers are necessary to implement system-wide reforms.

This study proposes an integrated framework for sustainable manufacturing transformation built upon four interconnected pillars: cognitive sustainability (developing durable engineering competencies), industrial sustainability (aligning education with industry needs), material sustainability (enabling responsible material selection), and process sustainability (minimizing environmental impact). This framework recognizes that sustainable manufacturing requires simultaneous advancement in human capital development, material innovation, and process technology.

Looking forward, the convergence of engineering graphics education reform, biodegradable polymer development, and additive manufacturing advancement is poised to play a central role in shaping a sustainable manufacturing ecosystem. Future research should build upon these insights through longitudinal studies, broader geographic coverage, experimental validation of pedagogical interventions, and inclusion of policy-level stakeholders. By doing so, technical drawing education can reclaim its role not as a static requirement but as a dynamic platform for cultivating the engineers, designers, and innovators needed to sustain both professional excellence and environmental responsibility in 21st-century manufacturing.

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