From Access to Awareness: A Comprehensive Review of Makerspace Material Policies and Their Role in Advancing Sustainability Education

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My research aims to understand the concepts and mechanisms of lifted jet combustion, electrohydrodynamics, aerodynamics, composite structures, and engineering education . I use advanced techniques and technologies to explore these topics. My students and

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Abstract

This paper reviews studies on the effectiveness of sustainability-related material availability policies in university makerspaces. Makerspaces play a central role in digital fabrication and experiential learning but generate significant plastic waste, particularly from 3D printing. Despite growing institutional attention to sustainability, there is limited empirical evidence on how makerspace policies influence user behavior, material consumption, and environmental outcomes. Guided by the Engineering for One Planet (EOP) framework, this review synthesizes literature from environmental science, engineering education, and policy studies.

The analysis reveals a clear gap between sustainability theory such as life cycle assessment, circular economy principles, and behavioral change models and their application in makerspace policy evaluation. Most existing studies rely on descriptive case reports or baseline waste audits, with few employing experimental designs, longitudinal data, or validated behavioral measures.

The paper calls for future research that prioritizes experimental and multi-institutional studies, standardized waste auditing, and mixed methods approaches that link environmental metrics with user behavior. It argues that combining educational interventions with enforceable material policies can improve sustainability outcomes and position makerspaces as effective sites for cultivating circularity and sustainability competencies in engineering education.

Introduction

University makerspaces are recent additions to U.S. campuses that offer considerable potential to expose students to diverse production activities, disciplines, and people thereby supporting their development as professional engineers [1]. Makerspaces can transform formal education by providing extracurricular opportunities for students to engage in hands-on projects and develop a broad range of skills that are currently underemphasized [2].

Dale Dougherty, a foundation figure in the Maker Movement defines the “Maker Mindset” as a “can-do” attitude characterized by persistence, curiosity, creativity, risk-taking, and an openness to failure, traits essential for learning through making [3]. Educational researchers and practitioners fostered the maker mindset through project-based learning, critical pedagogy, and interest-driven curricula, leading schools to create makerspaces that encourage autonomy, creativity, and problem-solving. The maker mindset continues to evolve in response to rapid technological advancements and the growing emphasis on flexible adaptive learning within educational systems. As emerging tools such as digital fabrication, artificial intelligence, and networked collaboration reshape how individuals create and learn, the maker mindset has become increasingly recognized as a crucial framework in both formal education and industry. It fosters a culture of hands-on experimentation, iterative problem-solving, and resilience, encouraging learners to approach challenges with curiosity and persistence. Furthermore, its emphasis on creative confidence empowers individuals to translate abstract ideas into tangible outcomes, bridging the gap between conceptual understanding and practical application. By integrating these principles into learning environments, the maker mindset not only enhances technical and creative competencies but also cultivates the adaptability and innovation essential for success in the evolving landscape of work and education.

As makerspaces proliferate across university campuses, they have emerged as strategic environments for developing student competencies in industrial design and manufacturing [4], [5]. Beyond skill acquisition, these spaces function as innovation hubs and experimental testbeds through which universities can research, prototype, and evaluate emerging approaches to design and production. By integrating both traditional and emerging technologies within publicly accessible, communal settings, makerspaces foster creativity and experiential learning while democratizing fabrication through shared tools, technical expertise, and collaborative knowledge networks [2], [6]. Typical makerspace technologies include 3D printing, laser cutting, CNC milling, waterjet cutting, vinyl cutting, 3D scanning, PCB prototyping, and electronics lab facilities [7]. These processes employ a diverse array of feedstocks and tools, including biological materials and processed organic and inorganic substrates such as plastics, rubber, metals, glass, wood, ceramics, and paper that may be pulverized, sintered, or melted [8].

An aspect of the maker mindset that has not been fully explored is the sustainable mindset which incorporates sustainability related practices through policies and behaviors that benefit both users and the environment. Sustainability-related design and material policies in makerspaces remain underexplored, reflecting early-stage circular economy practices with inconsistent implementation. This review examines the effectiveness of sustainability-oriented material availability policies in university makerspaces, focusing on three operational models: pay-per-use systems, in which users are charged based on actual resource consumption (e.g., cost per gram of filament, machine time, or number of fabrication attempts); quantity restrictions, which impose explicit limits on the amount of material or number of fabrication attempts permitted per user or project within a defined time period; and bring-your-own-materials (BYOM) approaches, which encourage makers to supply their own fabrication materials. Despite their growing implementation, empirical research assessing how these specific policy mechanisms shape user behavior, material consumption patterns, and environmental impacts remains limited.

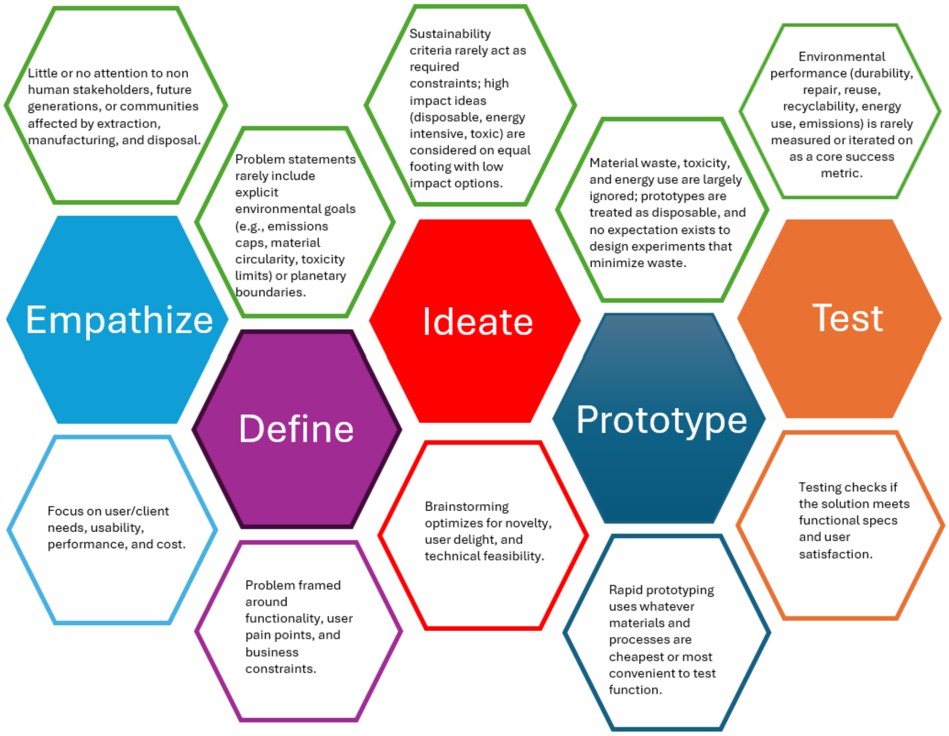

Figure 1: Design thinking framework illustrating standard engineering design steps and highlighting gaps where sustainability considerations are often absent [Courtesy NYU Tandon Makerspace].

Discussion

The rise of the maker movement has prompted discussions regarding the environmental impacts of makerspaces and their role in supporting the circular economy [4]. Greater accessibility to maker technologies has contributed to a measurable increase in material waste, driven largely by the proliferation of amateur and small-scale makers. This expanded production activity is often accompanied by inefficient material use, including failed prints, prototyping iterations, support structures, and end-of-life disposal of short-lived products. Collectively, these practices have intensified the volume of waste generated from additive manufacturing, raising concerns about the environmental implications. This includes rising quantities of thermoplastic waste PLA, ABS, and PETG from desktop FDM 3D printers. 3D printing, despite its low material and operating costs, contributes substantially to plastic waste generation due to misprints and the limited ability to disassemble printed components for partial replacement [6]. In the UK, an estimated 39 metric tonnes of such waste is generated annually, with the bulk of them not being properly disposed of, globally, 260 to 460 metric tonnes of plastic waste is estimated to be generated between 2016 and 2030 [9], [10]. Yan et al in their study of sustainability making practices found that waste in makerspace contexts typically falls into two primary categories: raw material waste produced during machining or handcrafting, and artifact waste comprising intermediate prototypes and stored projects that, while still functional, have ceased to serve an active purpose [11].

Table 1: Waste typically found in makerspaces

Category of Waste	Description	Examples Specific to Makerspaces	Source
General Solid Waste	Non-hazardous materials with no recycling or reuse pathway; typical byproducts of fabrication tasks.	Failed cuts from laser/woodworking, off cuts of materials, packaging, general trash.	
Recyclable Materials	Discarded items with recoverable value that can be processed by recycling systems if sorted correctly.	Paper, cardboard, certain plastics, metals shavings intended for recycling.	
Material Scrap	Unwanted but potentially reusable remnants from fabrication that makerspaces may redistribute to members.	Wood scraps, polymer off-cuts (PLA/ABS), surplus material pieces, metal shavings from CNC milling or lathes.	
Electronic Waste (E-Waste)	Discarded electronic components or devices containing complex materials and potentially toxic substances.	Broken PCBs, wires, batteries, obsolete devices discarded by makers.	[12], [13], [14]
Chemical and Hazardous Waste	Substances that pose health or environmental hazards and require specialized handling.	Solder waste (alloys, wicks), solvents, adhesives, resin waste from 3D printing.	
Sharps and Dangerous Debris	Items that present physical risk (cuts/punctures) and require distinct waste protocols.	Broken cutting tools, glass shards, sharp metal off cuts.	
Airborne/Nuisance Byproducts	Fine particulates or fumes from tooling processes requiring capture rather than bin disposal.	Ultrafine particles from 3D printing, sawdust, laser cutter smoke.	
Valuable Intermediate/Abandoned Projects	Projects or parts that are unfinished or no longer used but could be repurposed. Often managed separately rather than thrown away.	Discarded prototypes, unfinished assemblies.	[15]

The growing strain on global resources, coupled with climate change, stricter environmental regulations, and a rising interest in sustainable consumption, has driven a transition toward circularity across various disciplines [16], [17]. Addressing the needs of future generations is an urgent priority. Everyday choices in makerspaces; including materials selection, fabrication methods, and product lifetime considerations can meaningfully reduce greenhouse gas (GHG) emissions and, consequently, atmospheric CO_2 concentrations. Therefore, makers have a direct responsibility to mitigate GHG emissions through deliberate project design and practice [7]. This aligns with international agendas such as the United Nations Sustainable Development Goals (SDGs) and criteria emphasizing sustainability competencies [18]. The incorporation of the SDGs into maker education seeks to prepare future makers by cultivating the competencies, domain knowledge, and problem-solving mindsets required to design and implement solutions that adhere to sustainable development principles [19], [20]. Embedding layered thinking and green-design competencies within engineering curricula equips makers with environmental awareness, technical expertise, and the interdisciplinary problem-solving skills required to develop innovative design solutions that address increasingly complex sustainability challenges. [21], [22], [23].

Promoting the adoption of sustainable materials and practices among designers necessitates an environment conducive to exploration and hands-on experimentation [24]. While certain makerspaces exhibit emerging experimentation with sustainability-oriented practices, sustainable product development is not yet an intrinsic component of makerspace operations. Unsustainable material use is partly driven by behavioral factors shaped by social norms, perceived convenience, and incentive structures. The ease and speed of CAM processes such as laser cutting and additive manufacturing for example can discourage deliberate planning, resulting in iterative part production and excessive material consumption [25]. Notably, policies governing material provision in university makerspaces commonly fail to incorporate sustainability criteria, thereby limiting opportunities to advance circular economy principles and environmentally responsible use of resources [7].

Makerspace material sustainability: frameworks and scope

The United Nations has emphasized the need for higher education institutions to embed the SDGs into their curricula in order to enhance sustainability literacy in students [26]. These goals underpin the development of frameworks intended to promote material circularity and environmental sustainability in makerspaces**.** Adopting a sustainability mindset involves pursuing strategies that regenerate natural resources and strengthen communities while minimizing dependence on institutional environmental and economic impacts [27]. Engineering and manufacturing organizations increasingly recognize the importance of product sustainability and life cycle assessment (LCA) - which assesses the total environmental and economic effects including material, energy consumption and carbon emissions across the life span of a product from raw material extraction to end of life disposal [28]. Considerations such as design, material selection, manufacturing techniques, packaging, energy efficiency, emissions, and waste management are central to design decisions and to meeting regulatory requirements [27]. Adding the sustainability mindset to the design process in makerspaces requires a "thinking before making" approach which considers other broader aspects of a made object's lifecycle such as production energy and cost of disposal. The Engineering for One Planet (EOP) framework guides the development of sustainable makerspace policies. This framework can most easily be implemented in a space which functions as both the design and manufacturing hub, by bringing tools, software and mindset needed to complete the entire creative process in one location. A growing consensus in engineering education underscores the necessity of embedding sustainability into curricula and practice, prompted by declining non-renewable resources, more rigorous environmental and safety regulations, and heightened public interest in sustainable products and systems [28]. Solanki et al piloted and reported preliminary data on the outcome of two Materials courses structured to embed six sustainability categories of the Engineering for One Planet (EOP) framework. Their results showed a positive increase in student's behaviors towards sustainability, this included understanding of life cycle assessments, economic benefits of sustainability, incorporation of sustainable design and novel green technologies for innovative products [29]. Jayasinghe et al similarly implemented the EOP framework into engineering design courses (SUSE 300 and SUSE 400). These courses were designed to challenge engineering students to solve problems from a holistic standpoint, by engaging students to collaboratively solve real world problems using creative and sustainable design thinking, all of which aligned with EOP principles[30]. Further efforts are being designed to encourage faculty to adopt sustainable engineering principles in course curriculums, programs aimed at building faculty competency and advocacy for EOP incorporation have been described as essential to institutional adoption. Wadzuk and Minerva developed an ongoing study at Villanova University to advance faculty capacity to develop course-level learning tools while offering a framework for institutionalizing sustainability principles within engineering education, demonstrating that while individual courses build students' sustainability knowledge and design skills, full curricular adoption of EOP is necessary to cultivate systems-thinking approaches to engineering design [31].

Aligned with the United Nations Sustainable Development Goals, EOP emphasizes the balanced consideration of economic, social, and environmental costs and benefits. Its principal objective is to inform curricular reform so that all engineers acquire the knowledge, skills, and dispositions necessary for sustainable design. By specifying a clear, organized set of educational outcomes, the framework enables the systematic integration of sustainability topics across engineering curricula [32]. These principles are operated through key elements such as systems thinking and strategies to minimize resource use, combined with deliberate appraisal and balancing of economic, social, and environmental benefits and costs. This integrative perspective is often summarized as "people, planet, profit" and referred to as the triple bottom line [32]. Makerspace material policies intersect with EOP competencies by shaping the practical learning environment and resource use, influencing students' sustainability practices[7]. The EOP framework defines nine learning outcomes; systems thinking, environmental literacy, responsible business and economy, social responsibility, environmental impact assessment, materials selection, design, critical thinking, and communication and teamwork, that collectively articulate the sustainability-oriented competencies expected of graduates [33]. Together, these outcomes shape students' engagement with sustainability policy by emphasizing life-cycle interdependencies among materials, waste, energy, and social systems; fostering literacy in resource use and environmental limits; and requiring the evaluation of material choices, business practices, and social equity impacts to support lower-impact, more responsible engineering decisions.

Integrating foundational decision-making theory into efforts to promote sustainable product development within makerspaces produces a theoretical framework of pro-environmental decision-making tailored to these settings. By working with makerspace operators to cultivate pro-environmental makerspaces, the maker's perceived social role shifts toward membership in a community that embraces environmental considerations as part of its routine practice [34]. When community members experience this process collectively, they reinforce one another's commitment to sustainable product creation, thereby consolidating the collective view that sustainable product development is an essential component of maker identity [34]. Members of the maker community comprise diverse constituencies with distinct objectives: students who use makerspaces as part of their coursework, hobbyists, do-it-yourself practitioners, self-employed individuals, and start-ups pursuing commercial aims. For many makers, the making process, characterized by exploration and iterative prototyping, carries significance comparable to the resulting artefact [6]

Measurement Instruments

Different methods to assess the performance of sustainability policies have been implemented. Yan et al, used interviews involving 17 participants to investigate the interplay between sustainable practices and makers, supplemented by notes from on-site observations. Their methodology centered on conducting in-depth discussions to gain insights into makers' experiences [35]. Several studies have employed surveys to examine the experiences and perspectives of makers and makerspace users. Lee designed a Circular Makerspace Evaluation Toolkit (CMET), a set of evaluation frameworks and tools for varied scenarios. The toolkit emphasizes raising people's awareness of carbon neutrality, cultivating the right mindset, and changing behavior of makerspace users [34]. Manfredi et al. conducted a pre and post test survey on 67 and 60 undergraduate students respectively to understand whether two codesigned interventions; trash and recycling bin, could improve sustainability literacy [36]. Life-cycle assessments are another tool that provides a comprehensive evaluation of a product's environmental and economic burdens by measuring material and energy inputs, carbon emissions, and other impacts across all stages of the product's life cycle, from resource extraction to end-of-life disposal [28].

Empirical Studies on Makerspace Sustainability

Honkala et al focused on ways to increase material circularity in university makerspaces in a 2023 study. Results from their surveys showed multiple recommendations related to recycling and reuse for sustainable materials use, material selection, and cooperation with local stakeholders to enhance information and material sharing [4]. Implementing reuse and recycling practices can lead to significant cost reductions for makers and fabrication spaces. The availability of free or low-cost recycled materials in many spaces further encourages their adoption. Economic incentives remain a primary driver of recycling behaviors among makers and emerging enterprises [4].

Unegg et al. studied the greenhouse gas footprint of various materials and two methods of fabrication in a makerspace; the methods were laser cutting and 3D printing. Their findings show that laser cutting is the most sustainable option for wooden boxes. For plastic boxes, 3D printing with PLA is preferable, producing only 752 g CO_2 eq, much lower than acrylic glass. Using recycled ABS further cuts emissions by 289 g CO_2 eq, though it requires controlled conditions. The Ultimaker printer, while slower than the Renkforce 1000 used in the experiment, was more energy efficient, making PLA printing on the Ultimaker the optimal choice for plastic production. The results show that material choice and technology used to build prototypes have an impact on the GHG footprint, and environmental impact, even when production is energy-efficient [7]. Lee (2021) studied the carbon neutrality in makerspaces at MIT identifying five key insights: MIT makerspace managers differ in their understanding of sustainability and were largely unaware of the MIT Office of Sustainability's certification and support services. There was no standardized material procurement process, students usually supply materials, while managers assist based on experience or instructor input. Most makerspaces faced limited material storage and operated independently in terms of resources, layout, and culture. Their primary focus was on providing accessible tools, machines, and training for the MIT community [34].

Another study of recycling practices at Syracuse University by Lee et al found problems with managing common waste and recycling due to inconsistency in bin colors, labels and locations, and lack of standard instruction provided to the users of the building. This contributed to the understanding that messaging and recycling knowledge and awareness are major contributors to reduced sustainability practices in such environments [37]. A Yan et al study identified three primary barriers to integrating sustainable making practices into routine activities: insufficient processes and equipment for managing waste materials, elevated costs of sustainable alternatives, and limited technical expertise [35]. These studies show that sustainability has been less considered in makerspaces operational procedures from a comprehensive perspective with more focus being given to exploration and creativity in design.

Policy Evaluation and Implementation

Limited research exists on policy enforcement levels and variability across institutions. Some makerspaces demonstrate advanced circular economy integration, while others lack formal standards of material use. The lack of sustainable practices in some makerspaces can be attributed to economic and operational concerns that means procedures that encourage circularity are often abandoned [38]. Existing literature offers limited but emerging evidence on sustainability-oriented material policies in university makerspaces, documenting early adoption of circular economy practices such as the removal of environmentally harmful materials, the establishment of material reuse stations, and product life-extension initiatives (e.g., Repair Cafés) that prioritize repair over replacement [39]. In modern sustainable design and fabrication, the conventional 3R model has been extended to the 6R and subsequently 9R frameworks, incorporating additional stages such as recovery, redesign, remanufacturing, resilience, reassessment, and restructuring. This progression reflects an ongoing shift toward a fully circular lifecycle approach [28]. Implementing structured reusing or waste minimization programs/stations if not already implemented is one of the most significant ways of helping reduce waste of materials and resources. Beyond lowering waste outputs in makerspaces, it also promotes creative problem-solving by motivating individuals to maximize the utility of the materials available [39].

Policy enforcement varies and often relies on community involvement and planning for future sustainability enhancements. Kohtala's work indicates that incorporating stakeholders with relevant technical or environmental expertise heightens the emphasis placed on sustainability within Fab Lab practices[40]. One such study was conducted by Prendeville et al. studying the role of makerspace managers and founders in developing circular makerspaces. Their findings indicate that establishing a makerspace grounded in principles of circularity requires managers and founders to articulate a clear vision for circular operations from the outset and to employ practical mechanisms that integrate circular practices into everyday workflows [38]. Another study of Toronto based universities recommended potential ways to improve makerspace sustainability by educating students and staff in makerspaces through workshops or learning sessions on various circular economy practices [39]. The study of carbon neutrality in makerspaces conducted by Lee found that the shift from a typical makerspace to a circular makerspace necessitates consideration of both core operational factors (e.g., material life cycles, energy use, infrastructure, and operations) and broader long-term strategies, including educational aims, business models, policies, and cultural practices [34].

Conclusion & Future Work

There was little evidence in peer reviewed literature of experimental studies assessing the behavioral or environmental impact of pay-per-use, quantity limits, or BYOM policies. The potential for advancing sustainability practices within makerspaces remains substantial but has yet to be fully leveraged. This review identified that sustainability practices are guided by policy enactments which in turn build up the sustainability mindset, however most material sustainability based policies are limited to the 3Rs. Evidence suggests that more experimental and comparative research designs, particularly those spanning multiple institutions, are needed to capture the diverse behaviors and material flows within these environments. To advance sustainability in makerspaces, there is a need to move beyond isolated case studies and adopt strategies that can systematically evaluate how material policies influence both practices, learning and makerspace operation.

- No experimental studies have assessed the behavioral or environmental impact of pay-per-use, quantity limits, or BYOM policies.
- Policies such as pay-per-use systems and Bring Your Own Material (BYOM) should be tested not only for operational feasibility but also for how they shape user behavior when paired with environmental metrics.
- No experimental studies have assessed the behavioral or environmental impact of pay-per-use, quantity limits, or BYOM policies.
- Pedagogical efforts promoting sustainable design and upcycling show promise but are rarely integrated with operational policy changes.
- Equity implications of cost-based policies are underexplored, raising concerns about access and participation.
- Informal reuse and sharing practices are common, but their connection to formal policy interventions is undocumented.

For future research, priority should be given to rigorous experimental designs, multi-institutional comparisons, and mixed methods approaches in line with EOP frameworks. Additionally, the development of makerspace-specific sustainability models, standardized waste auditing protocols, and policy frameworks that align educational interventions with operational controls is recommended to maximize impact. A study focused on how different material policy environments such as pay-per-use and quantity limits influence user behavior and is currently being conducted by the authors to understand the influence they have on sustainability and attitudes towards circularity. This multi-institutional study aims to assess whether these policies encourage a "Think Before Do" mindset within students. Makerspaces are uniquely positioned to become transformative environments, places where future engineers learn not only how to make, but how to make responsibly. With intentional policy design and evidence-driven implementation, makerspaces can cultivate stronger sustainability mindsets, deepen understanding of environmental impact, and embed circularity competencies at the core of hands-on learning.

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