SustainaPrint: Making the Most of Eco-Friendly Filaments

Maxine Perroni-Scharf
MIT CSAIL
Cambridge, Massachusetts, USA
max1@mit.edu

Jennifer Xiao
MIT CSAIL
Cambridge, Massachusetts, USA
xiaoj@mit.edu

Cole Paulin
MIT CSAIL
Cambridge, Massachusetts, USA
cpaulin@mit.edu

Zhi Ray Wang
MIT CSAIL
Cambridge, Massachusetts, USA
zrwang@mit.edu

Ticha Sethapakdi
MIT CSAIL
Cambridge, Massachusetts, USA
ticha@mit.edu

Muhammad Abdullah
University of Potsdam
Hasso Plattner Institute
Potsdam, Germany
muhammad.abdullah@hpi.de

Patrick Baudisch
University of Potsdam
Hasso Plattner Institute
Potsdam, Germany
baudisch@hpi.de

Stefanie Mueller
MIT CSAIL
Cambridge, Massachusetts, USA
stefanie.mueller@mit.edu

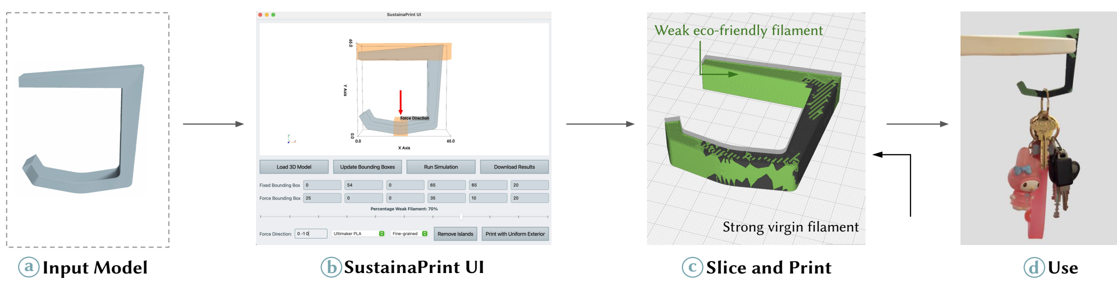

Figure 1: *SustainaPrint* workflow illustrated on a table hook. (a) The user begins with a 3D model of the object. (b) In the *SustainaPrint* UI, the user simulates the object by specifying forces and the desired balance between eco-friendly and virgin filament. (c) The model is assigned virgin filament to high-stress regions and eco-friendly filament to the remainder. (d) The final printed object supports real-world loads while minimizing the use of virgin plastic.

Abstract

We present *SustainaPrint*, a system for integrating eco-friendly filaments into 3D printing without compromising structural integrity. While biodegradable and recycled 3D printing filaments offer environmental benefits, there is a trade-off in using them as they may suffer from degraded or unpredictable mechanical properties, which can limit their use in load-bearing applications. *SustainaPrint* addresses this by strategically assigning eco-friendly and standard filaments to different regions of a multi-material print—reinforcing the areas that are most likely to break with stronger material while maximizing the use of sustainable filament elsewhere. As eco-friendly filaments often do not come with technical datasheets, we also introduce a low-cost, at-home mechanical testing toolkit that enables users to evaluate filament strength before deciding if they want to use that filament in our pipeline. We validate *SustainaPrint* through real-world fabrication and mechanical testing, demonstrating its effectiveness across a range of functional 3D printing tasks.

CCS Concepts

• **Applied computing** → **Engineering**; **Computer-aided design**.

Keywords

Materials Recycling, Fused Deposition Modeling, Polylactic Acid Filament, Eco-friendly Filaments

UIST '25, Busan, Republic of Korea

ACM ISBN 979-8-4007-2037-6/25/09
https://doi.org/10.1145/3746059.3747640

ACM Reference Format:
Maxine Perroni-Scharf, Jennifer Xiao, Cole Paulin, Zhi Ray Wang, Ticha Sethapakdi, Muhammad Abdullah, Patrick Baudisch, and Stefanie Mueller. 2025. SustainaPrint: Making the Most of Eco-Friendly Filaments. In *The 38th Annual ACM Symposium on User Interface Software and Technology (UIST '25), September 28–October 01, 2025, Busan, Republic of Korea.* ACM, New York, NY, USA, 13 pages. https://doi.org/10.1145/3746059.3747640

1 Introduction

Over the years, personal fabrication research within HCI has made significant advances, enabling the rapid creation of a wide range of objects. Recently, there has been growing interest within the community in developing circular and sustainable fabrication methods [8, 33]. Prior work has explored several strategies: using biodegradable materials that can be composted at home (e.g., *EcoThreads* [42]), minimizing material consumption with sparse print structures (e.g., *WirePrint* [29]), and integrating existing objects into new designs to avoid printing entire models from scratch (e.g., *Encore* [6] and *FusePrint* [43]). Other approaches involve repurposing waste material directly—for example, *Scrappy* [38] embeds failed prints as infill for new ones. While these solutions help reduce overall material waste, they mainly focus on reusing discarded prints and scraps, rather than supporting the use of sustainable filament options.

Eco-friendly filaments include those made from sustainable materials [31] or recycled from melted-down scrap [4]. However, users of such filaments—like PLA derived from industrial waste or bio-based additives (e.g., Polymaker PolyTerra PLA)—may lack the effective tools necessary to optimize their use in prints. Furthermore, eco-friendly filaments often suffer mechanical degradation, with reduced tensile strength and elongation compared to virgin filament [2, 4, 17]; for example, PLA's tensile strength can drop by over 20% after multiple recycling cycles [2]. These limitations hinder sustainable filament use in load-bearing designs, and makers often lack guidance on how to compensate. Moreover, current tools do not support systematic trade-off analysis for mixed-material printing involving degraded filaments.

To address this gap, we present *SustainaPrint* (Figure 1a), a system that strategically assigns eco-friendly and stronger conventional filaments within multi-material prints to maximize sustainable material use while preserving structural integrity. Designed for makers seeking systematic integration of eco-friendly filament, *SustainaPrint* optimizes material distribution across a design—going beyond infill-only use or trial-and-error settings. Structurally critical regions are printed with stronger virgin material, while the rest uses the sustainable filament. We demonstrate this approach using biodegradable filament as a case study, though it generalizes to other filament types with similar trade-offs.

Our goal is to help makers replace new plastic with eco-friendly filament while minimizing mechanical performance loss. *SustainaPrint* does so by selectively reinforcing high-stress regions using just 20% virgin PLA. Using *SustainaPrint* with PolyTerra and Tough PLA yields maximum strength boosts by an average of **22%** and up to **78%**. These gains are statistically significant ($p < .001$), supporting *SustainaPrint* as a practical path to more sustainable structural 3D printing.

We also introduce a low-cost mechanical testing toolkit that lets users assess their filament's mechanical properties at home. It provides material-specific data (e.g., tensile strength) used by *SustainaPrint*'s material assignment algorithm. Since recycled and bio-based filaments often lack standardized datasheets and vary by batch, on-demand testing helps users decide if reinforcement is needed and tailor simulations to the specific material.

Our contributions include:

(1) *SustainaPrint*, a system that strategically combines sustainable and standard filaments within a multi-material 3D print, ensuring that structurally critical areas receive stronger material while maximizing the use of eco-friendly filament elsewhere.
(2) A user interface that enables makers to specify material properties, set up simulations, and explore the trade-off between mechanical performance and sustainability in their designs.
(3) An evaluation of *SustainaPrint* across a range of real-world 3D-printed objects, showing that prints made with 80% biodegradable filament retain statistically significantly greater strength compared to those made entirely from recycled filament.
(4) A mechanical testing toolkit that allows users to measure the strength of their filament and feed those measurements into *SustainaPrint*'s pipeline, empowering users to work confidently with recycled or bio-based materials.

2 Related Work

Unlike previous multi-material printing systems aimed at aesthetics or geometry reuse, *SustainaPrint* is the first to focus on reinforcing recycled filament prints to maintain strength, bridging fabrication-aware geometry design with the use of sustainable materials. In this section, we provide an overview of sustainability in HCI research and fabrication practices and outline how our approach brings these two areas together.

2.1 Sustainable Digital Fabrication in HCI

A growing body of HCI research focuses on making personal fabrication more sustainable [8] by intervening at various stages of the fabrication lifecycle, from raw material acquisition to end-of-life disposal [24]. Researchers have developed tools across the spectrum—from recycling electronic waste into new devices [25], to zero-waste fashion [41], to helping users adopt greener transportation habits [11].

Specifically in 3D printing, a recent survey of makerspaces [40] highlights persistent issues with plastic waste and the lack of tools to address them. Prior research addresses this challenge through two main strategies: optimizing the *materials* used—such as recycling materials or developing biodegradable filaments—and optimizing the *geometry* of prints to reduce material consumption.

Several systems target material savings through geometry modifications. *WirePrint* [29] prints sparse wireframe previews to save filament, while Jones et al. [21] optimize infill patterns to reduce plastic use without compromising strength. *Encore* [6] attaches new prints to existing objects to avoid redundant printing. *Scrappy* [38] repurposes failed prints as internal infill, and *FusePrint* [43] incorporates recycled fragments directly into new prints. Similarly, *TrussFab* [22] connects 3D-printed nodes with used plastic bottles to build large load-bearing structures. *Patching* [35] reduces waste by repairing failed prints post hoc, avoiding full reprints; *RevoMaker* [12] minimizes support material by printing on a rotating axis; *Unmaking* [33] examines end-of-life behaviors, introducing techniques that let prints deform or break down intentionally over time.

On the materials side, researchers have explored novel eco-friendly filaments such as spent coffee-based filament [31], biodegradable e-textiles like *EcoThreads* [42], and mycelium-based composites [15]. However, many eco-friendly filaments suffer from reduced strength or brittleness. Commercial products like Polymaker PolyTerra and Terrafilium PLA, while compostable, may lack the mechanical properties needed for structural applications, and there is limited research on how to adapt fabrication workflows to accommodate their limitations.

To address this gap, *SustainaPrint* operates at the intersection of geometry and material properties. We ask: given access to eco-friendly filament, how can we use geometry to maximize its use without compromising structural performance? By combining mechanical simulation with multi-material 3D printing, our approach allows users to reinforce structurally critical regions of a print with virgin filament while using sustainable filament elsewhere.

2.2 Sustainable Filaments and Their Challenges

In parallel to HCI efforts, materials researchers have studied the properties and limitations of recycled and composite 3D printing filaments. Overall, studies show that making filaments "greener" often comes with mechanical trade-offs. For example, recycled PLA—produced by melting and re-extruding waste prints—typically exhibits lower tensile and impact strength than virgin PLA [6]. Hasan et al. [17] review these effects, noting consistent drops in polymer molecular weight and strength across recycling cycles. Beltrán et al. [2] found that PLA's tensile strength decreased by 21.6% (from 51 MPa to 40 MPa) after six recycling cycles, along with reduced stiffness and impact resistance. Bio-based additives or high recycled content can also introduce brittleness or inconsistent print quality [21].

Researchers have explored ways to mitigate these issues at the material level. For example, Beltrán et al. [2] explored chemical additives such as chain extenders and peroxides to restore strength to degraded PLA. Other work investigates reinforcing bioplastics with fibers or nanoparticles [13]. While promising, such material-level solutions are often inaccessible to everyday makers and fail to fully eliminate degradation.

These limitations motivate our approach: rather than requiring specialized materials or chemical knowledge, we provide a fabrication-aware software workflow that compensates for material weaknesses through intelligent design and multi-material printing, and that can be readily accessed by non-specialized users.

2.3 Fabrication-Aware Design Tools

Another line of prior work improves sustainability by adapting the geometry of fabricated objects or optimizing the printing process. Some approaches reduce material use by printing sparse previews [29], optimizing infill structures [21], or integrating recycled scrap into new designs (*Scrappy* [38], *TrussFab* [22]). Other efforts focus on zero-waste design principles, such as the *PacCAM* system for material-efficient furniture design [32]. While *PacCAM* minimizes waste in laser-cut furniture design, *SustainaPrint* tackles a different stage of the lifecycle by optimizing 3D print material usage for strength vs. sustainability.

Beyond sustainability, HCI and graphics researchers have developed fabrication-aware tools that integrate simulation into the design process. Bermano et al. [3] survey such tools, which often rely on finite element analysis (FEA) or geometric segmentation to improve structural integrity. Recent systems like *Style2Fab* [10] use stress simulations to guide both aesthetic and functional remixing of models.

We extend prior work by using simulation not only for strength, but to balance structural integrity with sustainability—enabling users to combine virgin and recycled filament in one print while navigating tradeoffs between performance and eco-material use. Unlike tools focused on aesthetics or geometry reuse, *SustainaPrint* directly compensates for degraded materials, avoiding the need for new formulations or trial-and-error tuning. While *Style2Fab* segments for functional aesthetics, *SustainaPrint* segments based on simulated stress, assigning strong filament to high-stress regions and eco-friendly material elsewhere. This integrates material- and geometry-aware strategies into a fabrication-aware system for greener, stronger 3D prints.

3 Workflow

Users may first assess filament quality using our mechanical testing toolkit (Section 8). If the material exhibits significant degradation, they can proceed with *SustainaPrint* to optimize the distribution of virgin and eco-friendly filament.

The *SustainaPrint* workflow (summarized in Figure 1) follows these steps:

(1) The user uploads a file of the model they wish to print.
(2) Through the UI, they specify fixed regions and applied forces, based on the intended use case.
(3) A simulation (typically 1–2 minutes) estimates internal stress and highlights areas most likely to fail if printed in weak material.
(4) The user selects a target percentage of eco-friendly material via a slider. *SustainaPrint* segments the model accordingly and generates two STL files: one for high-stress regions (to be printed in strong filament), and one for low-stress regions (to be printed in eco-friendly filament).
(5) The user downloads, slices, and prints the resulting STLs using a dual-material workflow.

We use SfePy, a widely adopted open-source FEA library [7], to perform linear elastic simulations using material properties representative of the weaker filament. The simulation outputs a volumetric stress field, assigning each tetrahedral element a von Mises stress value. Even when users provide only coarse force directions, high-stress regions tend to cluster in intuitive locations (e.g., hooks and legs), as shown later in Section 7. This stress map forms the basis for segmentation.

The runtime scales with mesh size, and is approximately one minute for the meshes produced by fTetWild's default settings, as shown in Figure 4.

4 *SustainaPrint* Method

SustainaPrint comprises two core steps: (1) simulating internal stress to identify vulnerable regions, and (2) segmenting the model

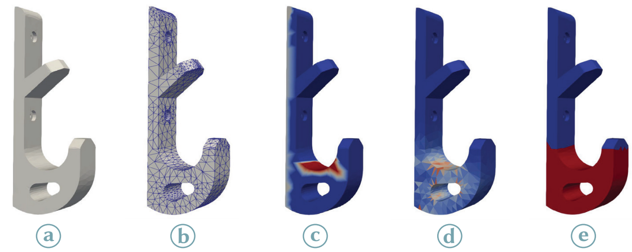

Figure 2: *SustainaPrint* simulation pipeline: (a) The original STL model; (b) tetrahedral mesh; (c) user-defined boundary conditions (white: fixed, red: load); (d) von Mises stress result from simulations; (e) segmentation into strong (red) and weak (blue) filament regions.

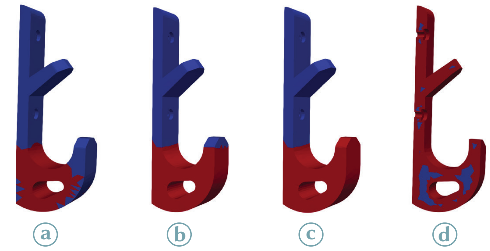

Figure 3: *SustainaPrint* segmentation pipeline: (a) Hook segmented by stress threshold. (b) Same model segmented by layer-based threshold. (c) Layer-based segmentation with island removal, reducing small print pieces. (d) Cross-section showing segmentation with uniform exterior.

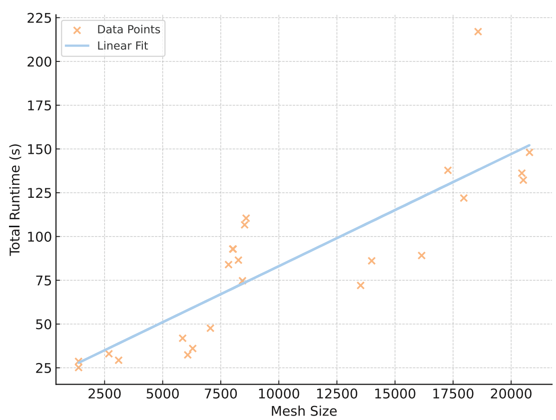

Figure 4: *SustainaPrint* simulation and segmentation runtime (in seconds) versus mesh size (number of tetrahedra). Each orange cross represents a model from our test set, and the blue line is a linear regression fit.

Table 1: Material interface performance with and without interlocking interface structures.

Condition	Compression at Break (mm)	% Improvement
Eco-friendly (baseline)	12.79	0%
Without Interlocking Structures	10.05	−21.4%
With Interlocking Structures (ours)	14.21	+11.1%

into strong and weak material regions. In this section, we outline the method behind each of these steps.

4.1 Mechanical Simulation for Weak Region Identification

The simulations pipeline is shown in Figure 2. To identify stress-prone regions, we perform finite element analysis (FEA) on a tetrahedral mesh of the model. Objects were meshed using fTetWild [18]. The user provides boundary conditions via the UI: the fixed support zone, force application region, and an approximate force direction and magnitude.

4.2 Segmenting the Model into Strong and Weak Regions

Using the stress distribution, we assign regions to strong or weak material, as shown in Figures 3a and 3b, using one of two segmentation modes:

Per-tetrahedron segmentation. Each mesh element is labeled based on its stress percentile (by default the top 10% of elements are labeled as strong). While this method maximizes the use of eco-friendly material, it can produce fragmented regions that are harder to print (Figure 3a).

Layer-aligned segmentation. To simplify printing, we also offer a height-based mode. We find the highest z-plane intersecting with a high-stress region and assign all material above (or below) it to the strong filament. This yields a planar boundary, avoiding material switching within a single layer and improving print reliability (Figure 3b).

Both modes are available in the UI to let users balance structural precision with ease of fabrication.

4.3 Heuristics for Printability and Aesthetics

We apply two optional heuristics to improve print quality and usability:

Island Removal. Small, isolated regions of strong material can be reassigned to the weak material if they fall below a user-defined volume threshold, reducing unnecessary material changes. This is shown in Figure 3.

Uniform Outer Shell. Users can choose to print the outermost n layers of tetrahedrons in a single filament for visual consistency. For instance, applying virgin filament to the outer shell can mask texture or color mismatches in eco-friendly infill infill. The finer the mesh, the thinner this layer can be. This can also instead be enabled directly during slicing by using one filament for the shell and another for the core.

Together, these heuristics improve surface finish and reduce print complexity, especially on consumer-grade dual-extrusion printers.

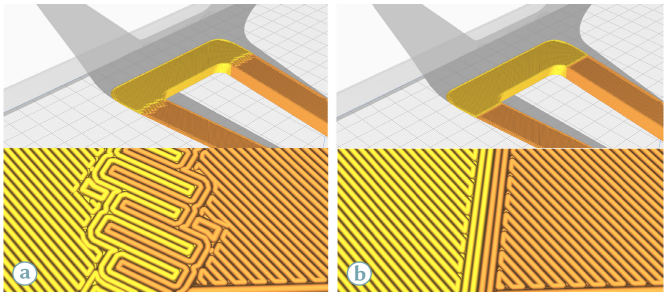

Figure 5: (a) Headphone stand sliced with interlocking material structures at the interface, which increases contact surface area between materials. (b) Headphone stand sliced with interlocking interface structures, showing a simple planar transition between materials.

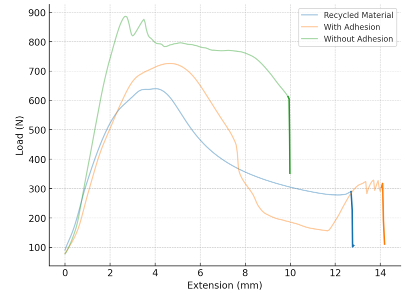

Figure 6: Extension vs. force curve from three test prints: one fully eco-friendly, one multi-material without interlocking interface structures, and one multi-material with interlocking interface structures. Interlocking improves performance beyond baseline.

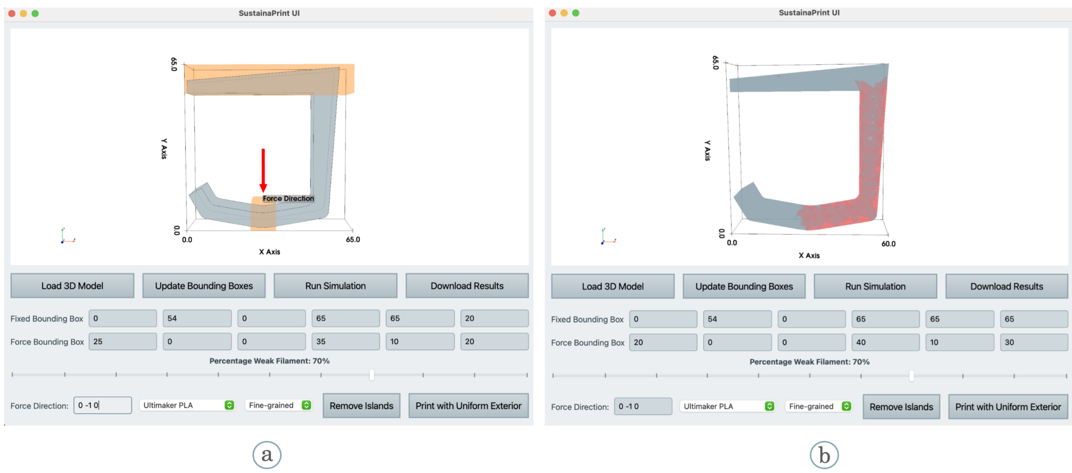

Figure 7: (a) *SustainaPrint* UI, where users load a 3D model and specify its use case via bounding boxes and force direction. (b) After segmentation, users adjust the percentage of weak filament, select a segmentation mode, and download STL files for slicing and printing.

4.4 Interlocking Interface Structures

Interfaces between different filaments are common failure points, especially when the materials have different print temperatures or extrusion characteristics. Previously, *Multi-ttach* [23] has identified and addressed this problem by leveraging variations in print parameters near the interface between different materials in multi-material prints to improve bonding.

We follow a similar protocol to *Multi-ttach* in *SustainaPrint*, where we use Ultimaker Cura's interlocking structures feature, shown in Figure 5, which automatically generates zig-zag (comb-like) patterns at material interfaces. This creates mechanical interlocking interface structures, which increase the contact area between the print materials and help to resist separation.

Because this feature is handled entirely at the slicing stage, users can easily enable it after segmentation without modifying the model geometry. In our formative tests, interlocking interface structures consistently reduced delamination and improved strength at the material boundary. We printed and tested a multi-material headphone stand with and without interlocking structures (Figure 6 and Table 1). Only when interlocking was enabled did *SustainaPrint*'s segmented model outperform a print made entirely from eco-friendly filament.

5 User Interface

SustainaPrint is accompanied by a user interface, shown in Figure 7, that guides makers through the process of setting up their print for dual-material optimization. The interface allows users to:

(1) Input Model and Materials: Users begin by loading their 3D model and specifying which two filaments they will use, either by inputting material properties or choosing from a preset filament. The UI provides default mechanical property values for these preset materials, which users can customize based on their own filament.
(2) Specify Model Usage Conditions: Through a simple 3D bounding box visualization, users can mark regions on the model that correspond to support and force application points. They can also enter their estimated force direction for when the

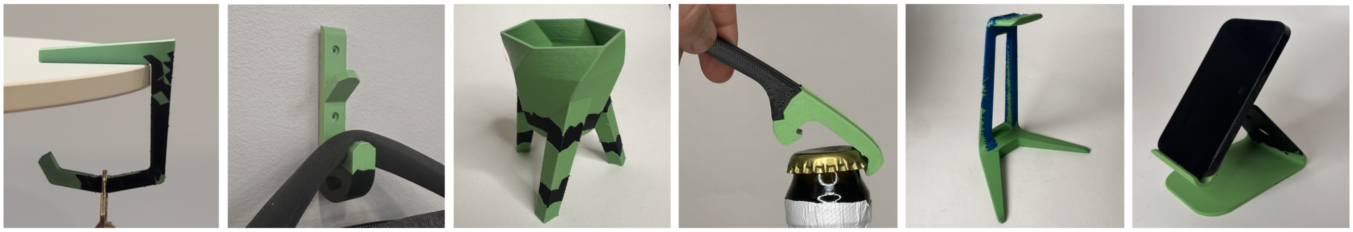

Figure 8: Applications. *SustainaPrint* can be applied to a wide range of everyday items, including reinforced hooks, plant pots, bottle openers, headphone stands, and phone stands.

model is used, which is utilized to define the boundary conditions for simulation (Section 4.1).

(3) Choose Segmentation Strategy: The interface presents the two segmentation modes (precise vs. layer-aligned segmentation) with a brief explanation and a preview of how each would partition the current model (using a color overlay). Advanced settings for island removal and shell thickness can also be toggled here.
(4) Review and Iterate: After completing the simulation and segmentation steps, the user can review the results through the interface, which highlights the regions of the model assigned to each material. If some aspect of the outcome is not as desired—for instance, if an excessive portion of the model is designated as virgin material—the user can adjust the "percentage weak filament" slider or switch segmentation modes to better balance sustainability and structural performance.
(5) Export Print Files: Once satisfied, the user exports the multi-material print files (separate STL files for each material). They can then proceed to print the object on a dual-extruder 3D printer.

Throughout this process, the interface provides visual feedback and guidance to keep the workflow intuitive. For example, when users select a force direction, the UI displays an arrow on the model. to help those unfamiliar with FEA concepts, the UI provides default force presets and visual guidance, so even a novice can specify approximate load conditions. We designed the interface to abstract away the underlying complexity of the simulation, making sustainable fabrication more accessible to non-expert makers.

We use the Python library PyVista [34] for implementing the 3D viewer.

6 Applications

In this section, we present a variety of real-world applications of *SustainaPrint*, illustrated in Figure 8. These examples demonstrate how our system can be used to reinforce structurally critical regions while maximizing the use of eco-friendly filament.

We also evaluate the mechanical performance of household objects in Section 7, demonstrating that they are significantly stronger than versions printed entirely in eco-friendly filament, while still maintaining a composition of 80% sustainable material.

Hooks and Hangers. Hooks are a common and practical object to 3D print, but they must endure concentrated loads at the mounting point and at the hanging edge. With *SustainaPrint*, users can specify the fixed mounting location (e.g., wall or table edge) and simulate the directional load that occurs when items are hung. This enables structurally sound designs that use strong filament only where necessary. We printed and tested both a wall-mounted and a table-mounted hook, each designed to support heavy items like coats and bags while minimizing virgin plastic usage.

Standing Plant Pot. Planters and other legged objects are vulnerable to failure at the base, especially under the weight of soil or water. *SustainaPrint* allows users to simulate these loading conditions and reinforce the base and leg junctions accordingly. The walls of the pot, which are under relatively low stress, can be printed with eco-friendly filament, striking a balance between durability and sustainability.

Bottle Opener. Bottle openers experience significant torque, particularly at the prying edge and fulcrum. We simulate this scenario in *SustainaPrint* by fixing one end of the model and applying a perpendicular force to the other, mimicking real-world usage. The system assigns strong material to the region under maximum bending stress, ensuring the opener remains functional without fully relying on virgin filament.

Phone Stand / Headphone Stand. Stands must remain upright while supporting downward loads. Using *SustainaPrint*, we simulate compression at the vertical supports and identify high-stress regions, such as the cantilevered hook of a headphone stand or the cradle of a phone holder. Strong filament is applied to these areas, while the remaining structure is printed in eco-friendly material. This ensures both balance and longevity.

7 Evaluation

We evaluate *SustainaPrint* on five functional objects and five primitive geometries, comparing three types of material conditions: 100% eco-friendly, *SustainaPrint* mix (20% virgin / 80% eco-friendly), and 100% virgin filament. Each object was printed and tested to failure under relevant loads, and we recorded metrics including maximum load, stiffness, elongation, and toughness. Our tests focus on static load failure; evaluating long-term fatigue or energy consumption remains an important direction for future work.

Table 2: Print parameters used for mechanical evaluation.

Parameter	Value	Parameter	Value
Printer	Ultimaker S5	Infill Density	100%
Materials	PolyTerra, Ultimaker PLA	Infill Pattern	Zig Zag
Diameter	2.85 mm	Shell Thickness	0.8 mm
Resolution	0.15 mm	Support	Tree

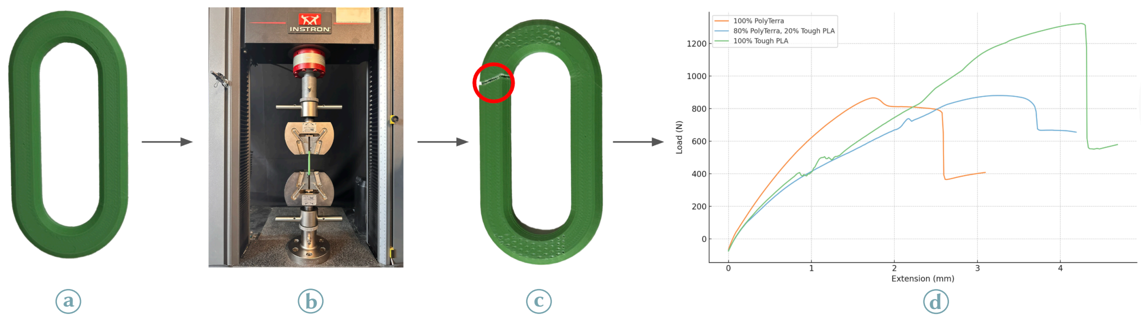

Figure 9: Mechanical Testing Setup. (a) 3D-printed chain. (b) Mounted in an Instron machine and pulled to failure. (c) Broken chain. (d) Stress–strain curves are recorded for comparison. Incorporating 20% tough PLA into a PolyTerra print increases strength and extension before break by over 30%.

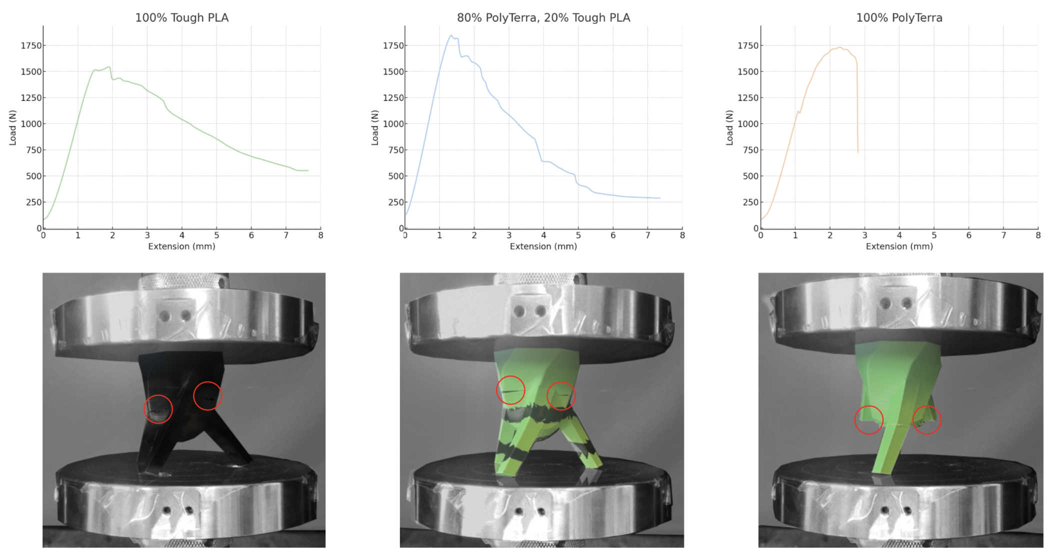

Figure 10: Failure mode comparison across material configurations for the tripod pot. Right: 100% eco-friendly PolyTerra results in catastrophic breakage at 2.8 mm of compression. Middle: *SustainaPrint* reinforces high-stress leg joints, resulting in gradual failure elsewhere. Left: Virgin PLA shows a similar stress profile, with slightly delayed fracture onset.

SustainaPrint targets scenarios where mechanical strength is important and where users have access to both a strong, non-sustainable filament and a weaker, eco-friendly alternative. For our evaluation we used Polymaker PolyTerra PLA as the eco-friendly filament due to its wide availability and accompanying datasheet, and Ultimaker Tough PLA, as a conservative, high-performance virgin material baseline. We also perform additional tests on the primitive structures with standard Ultimaker PLA to show how *SustainaPrint* performs with different material combinations. All models were printed on an Ultimaker S5 dual-extrusion printer with the print settings shown in Table 2.

Each specimen was tested under uniaxial compression and evaluated using five mechanical metrics:

Maximum force: the peak load reached during testing.

Elongation at yield: the point where the load-extension curve deviates from its initial linear trend, determined manually.

Elongation at break: reported only for full fractures and determined manually. This value was marked “–” if the sample remains intact (e.g., if the sample never fractures but just elastically deforms until it cannot be compressed anymore).

Stiffness: the slope of a linear fit to the initial 1 mm of extension.

Toughness: the area under the load-extension curve up to breaking point; reported only if there is a full fracture, marked “–” if the sample remains intact.

We analyze both absolute performance and relative gains compared to the eco-only and virgin-only baselines. For each model, we compute the percentage improvement of *SustainaPrint* over eco-only, as well as how close it comes to matching the performance of fully virgin PLA. A Wilcoxon signed-rank test across all models confirms that the maximum force improvement of *SustainaPrint* with Tough PLA over eco-only is statistically significant with a p-value of .00098.

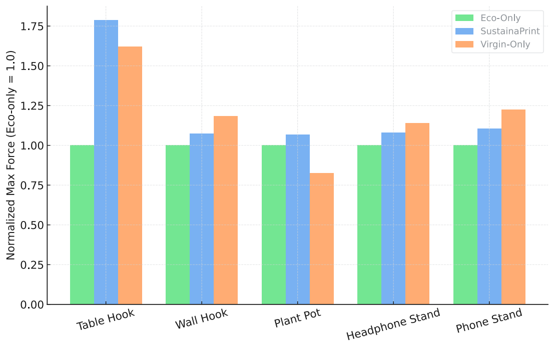

Figure 11: Maximum force sustained by functional objects.

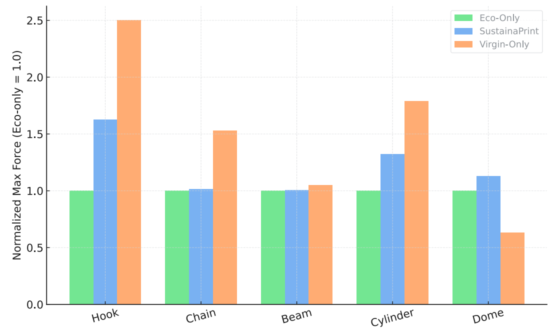

Figure 12: Maximum force sustained by primitive objects.

Table 3: Mechanical testing results for the functional models, each tested under three material configurations: eco-only (PolyTerra), our *SustainaPrint* assignment, and virgin Tough PLA. We report maximum force, elongation at yield, elongation at break, stiffness, and toughness.

Model	Condition	Max Force (N)	Elongation at Yield (mm)	Elongation at Break (mm)	Stiffness (N/mm)	Toughness (N·mm)
Table Hook	Eco-only	304.1	1.4	2.4	335.4	428.9
	SustainaPrint	543.1	1.4	1.7	328.0	426.9
	Virgin-only	493.0	1.4	2.2	549.0	736.9
Wall Hook	Eco-only	512.0	1.5	2.1	474.4	658.1
	SustainaPrint	550.4	1.8	1.9	426.6	585.7
	Virgin-only	605.8	1.7	3.8	516.5	1,655.1
Plant Pot (Tripod Base)	Eco-only	1,735.1	2.0	2.8	945.1	3,234.2
	SustainaPrint	1,850.5	1.5	–	842.8	–
	Virgin-only	1,431.4	1.4	–	948.6	–
Headphone Stand	Eco-only	634.1	4.1	12.28	174.1	1,651.1
	SustainaPrint	683.9	5.9	13.78	209.7	2,907.2
	Virgin-only	723.0	7.4	13.15	153.9	3,399.1
Phone Stand	Eco-only	160.3	9.3	10.0	10.2	700.7
	SustainaPrint	177.1	9.3	10.0	11.9	765.2
	Virgin-only	196.4	10.2	10.6	10.3	1,071.0

7.1 Testing Functional Geometries

We first test *SustainaPrint* on five real-world functional objects from Thingiverse [36], a table hook [37], a wall hook [30], a plant pot with a tripod base [9], a headphone stand [27] and a phone stand [14]. We used an idealized test setup with metal plates for compression and clamps for tension, where the choice of tension or compression for each object was made to best match the object's function. The table hook and wall hook were clamped and pulled apart, whereas the plant-pot, headphone stand and phone stand were compressed. The models were scaled to fit into the Inston testing rig. Each object was printed with 100% PolyTerra, an 80%/20% mixture of PolyTerra and Tough PLA (*SustainaPrint*) and 100% Tough PLA.

Table 3 presents mechanical performance across material configurations for the five functional objects. In terms of maximum force, *SustainaPrint* improved load capacity by up to **78.5%** (table hook), with an average improvement of **22.2%** over eco-friendly PolyTerra filament, as shown in Figure 11.

Elongation at Yield: *SustainaPrint* also improved flexibility, with an average yield extension of **4.0 mm** compared to **3.7 mm** for eco-only and **4.4 mm** for virgin Tough PLA. In three out of five models, it closely tracked or exceeded virgin Tough PLA's performance.

Stiffness: Results varied by geometry, ranging from *SustainaPrint* yielding a **+20.5%** increase (headphone stand) to a **−10.8%** drop (plant pot), with an overall average change of **−2.0%** relative to 100% PolyTerra. These shifts reflect material–geometry interactions and tradeoffs between flexibility and rigidity.

Toughness: Toughness increased by an average of **18.5%** across models, peaking at **76.1%** in the headphone stand. While virgin

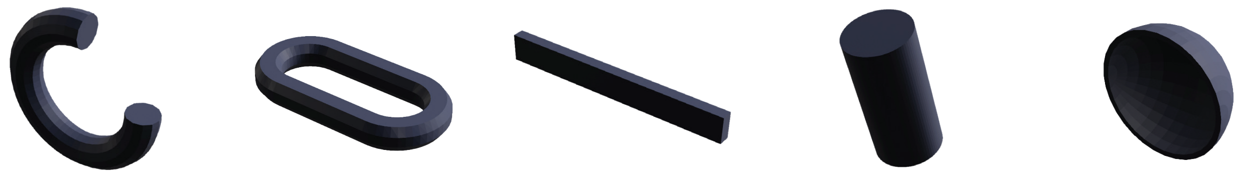

Figure 13: The five primitive geometries used in our evaluation: hook, chain, beam, cylinder, and dome. Each represents a distinct load condition relevant to structural 3D prints.

Tough PLA still leads on average, *SustainaPrint* recovered a substantial portion of durability with a lower environmental footprint.

Case Study: Tripod Plant Pot

For the plant pot (Figure 10), 100% PolyTerra failed catastrophically at just 2.8 mm compression. *SustainaPrint*, by contrast, reinforced the stress-concentrated legs and redistributed strain, producing a smoother failure curve and delaying buckling. Its performance closely matched that of virgin Tough PLA, showing how material-aware design can maintain performance while reducing reliance on virgin plastic.

7.2 Testing Primitive Geometries

We selected five primitive geometries (Figure 13) representing a range of load cases, including tensile, bending, and compressive failure modes.

Standardized models: The beam and cylinder follow ASTM standards—D790 for 3-point bending and D695 for compression, respectively [19, 20].

Custom models: The hook, chain, and dome represent realistic digital fabrication use cases such as cantilevered hooks and shell structures.

Load conditions include:

1. **Hook:** Cantilevered tension + bending.
2. **Chain:** Pure tension.
3. **Beam:** 3-point bending.
4. **Cylinder:** Axial compression.
5. **Dome:** Buckling from apex compression.

All tests were performed on an Instron 3369 universal testing machine, as shown in Figure 9. Table 5 presents mechanical performance across material configurations. In terms of maximum force, *SustainaPrint* with Tough PLA consistently improved over eco-only in all five primitives, as shown in Figure 12, with an average increase of **22.0%**. In the dome, *SustainaPrint* improved over eco-only filament by **12.7%**, and also surpassed Tough PLA in both strength and toughness, an outlier behavior in the dataset. The Tough PLA sample in this case likely experienced premature failure due to excessive stiffness, which can make structures more brittle under buckling loads.

To demonstrate *SustainaPrint*'s compatibility with different material pairings, we also reproduced the same experiments using standard PLA, also shown in Table 5. We find that *SustainaPrint*, across all testing geometries, *SustainaPrint* with standard PLA increases the maximum force endured by an average of **44.1%** compared to PolyTerra alone.

While most trends were consistent, mechanical performance ultimately depends on both material and geometry. For example, differences in shape can introduce torque or buckling effects, and 3D printed materials exhibit directional stiffness due to anisotropic toolpaths. To ensure a fair comparison, we held all slicing and print parameters constant across conditions, varying only the material type.

7.3 Trade-offs

Using dual-material 3D printers introduces additional overhead in material usage, print time, and energy consumption. Table 4 compares average waste and time values for*SustainaPrint* prints—produced on a dual-material Ultimaker S5—against single-material prints under otherwise identical settings. The evaluation objects were printed without a purge tower, but below we report metrics for prints made both without and also with an optional purge tower.

Energy consumption is also a key factor that scales with time and depends on printer model, print conditions, and hardware configuration. Dual-head printers consume more energy than single-head ones. For example, the reported power draws of single-headed Ender 3 printers and and Prusa i3Mk3s are 125 W [26] and 100 W [16] respectively, whereas our measured power draw of the Ultimaker S5 is 170–200 W during printing.

Table 4: Percentage changes in waste, print time, and virgin material savings for *SustainaPrint* prints (with and without optional purge towers), relative to single-material prints.

Metric	No Purge (SustainaPrint)	With Purge (SustainaPrint)
Total Waste Increase	0%	37%
Print Time Increase	11%	45%
Virgin Material Saved	80%	80%

7.4 Alternative Approaches

Alternative methods like increasing infill density or perimeter count can enhance mechanical strength [28], but they are complementary—not substitutes—for *SustainaPrint*. We performed an ablation

Table 5: Mechanical testing results for primitive models under five material configurations: Eco-only (PolyTerra), SustainaPrint (Tough PLA), Virgin Tough PLA, SustainaPrint (PLA), and Virgin PLA.

Model	Condition	Max Force (N)	Elongation at Yield (mm)	Elongation at Break (mm)	Stiffness (N/mm)	Toughness (N·mm)
Hook	Eco-only	102.2	2.5	11.0	95.3	672.0
	SustainaPrint (Tough PLA)	166.0	7.5	20.0	105.6	2,221.3
	Virgin Tough PLA	255.5	5.5	6.5	110.3	1,191.5
	SustainaPrint (PLA)	243.1	1.5	16.0	185.5	2,366.1
	Virgin PLA	354.0	2.0	3.1	259.7	763.1
Chain	Eco-only	866.3	1.7	2.5	688.4	1,504.3
	SustainaPrint (Tough PLA)	880.5	3.1	3.7	487.4	2,150.1
	Virgin Tough PLA	1,323.3	3.7	4.2	486.2	3,208.6
	SustainaPrint (PLA)	994.7	1.4	5.6	524.7	2,088.5
	Virgin PLA	867.4	3.0	5.7	635.5	4,274.8
Beam	Eco-only	248.5	2.0	2.4	47.7	455.3
	SustainaPrint (Tough PLA)	250.3	2.0	2.8	35.8	528.2
	Virgin Tough PLA	261.3	2.0	–	61.7	–
	SustainaPrint (PLA)	167.4	5.2	3.5	38.6	614.8
	Virgin PLA	223.0	4.3	3.0	38.2	584.9
Cylinder	Eco-only	4,300.8	1.0	–	2,860.3	–
	SustainaPrint (Tough PLA)	5,696.1	1.2	–	1,855.0	–
	Virgin Tough PLA	7,686.2	1.6	–	3,909.4	–
	SustainaPrint (PLA)	7,114.2	0.7	–	6,193.5	–
	Virgin PLA	8,451.8	1.0	–	4,312.2	–
Dome	Eco-only	2,472.8	3.1	8.0	616.5	14,458.0
	SustainaPrint (Tough PLA)	2,787.0	3.9	8.9	521.3	16,346.2
	Virgin Tough PLA	1,563.9	3.9	–	585.8	–
	SustainaPrint (PLA)	3,335.3	3.0	6.6	804.0	9,843.4
	Virgin PLA	3,159.6	2.2	8.2	561.8	15,625.0

study on the ASTM-D790 model across six configurations: PolyTerra, *SustainaPrint* (80% PolyTerra + 20% PLA), and pure PLA, each at 15% and 30% infill (Table 6). Results show that *SustainaPrint* alone improves strength more than doubling infill (e.g., 125.2N vs. 107.9N for PolyTerra), and that both approaches can be combined for additive gains.

Table 6: Table comparing the maximum load (N) by material and infill density, measured using the ASTM-D790 model.

Material	Maximum Load 15% Infill (N)	30% Infill (N)
PolyTerra	101.5	107.9
SustainaPrint	125.2	131.3
Virgin PLA	177.7	189.1

8 Mechanical Testing Toolkit

Integrating eco-friendly filament into 3D prints as described in Section 4 may require the user to first assess the mechanical properties of the filament in question. Unlike virgin filament, which comes with detailed datasheets, eco-friendly or recycled variants vary across batches due to differences in source material and processing—yet accessible tools for at-home testing are not readily available.

To address this, we introduce a low-cost testing toolkit that lets users characterize their filament at home. It helps assess degradation and guides the decision to print entirely with eco-friendly filament or use *SustainaPrint*.

The toolkit includes an all-in-one, 3D-printable device for basic mechanical evaluations, such as uniaxial load testing. Paired with standard off-the-shelf components, it provides meaningful performance data for comparing with virgin materials and enables more informed, sustainable printing decisions.

8.1 Tool Design

The 3D-printable tool (Figure 14a) has two main parts: a tensile section with handles joined by a thin breakable bridge, and a flexural section with bridges of varying thicknesses that break under downward force. The sections are connected by a thin filament layer for single-piece printing and can be used as-is or snapped apart for convenience.

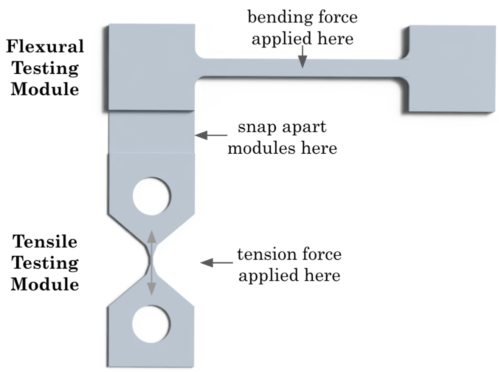

Figure 14: (a) All-in-one mechanical testing tool, with bridges for 3-point testing and tensile testing combined.

Figure 15: (a) Equipment needed for mechanical testing with our toolkit. (b) At-home setup for performing tensile strength mechanical tests using our toolkit.

8.2 Preparation

For each filament, we used an Ultimaker S5 to print the all-in-one testing toolkit. To reduce surface stress concentrations, we lightly sanded all specimen faces and manually detached the tensile test section by separating the thin tab between it and the bridge section. We then gathered the testing setup (Figure 15a), including dumbbell weights, a pull-up bar, sturdy bag, towels, tent rope, a crane scale, and the testing tool.

8.3 Tensile Testing

To perform tensile testing, we attach a digital crane scale to a pull-up bar. As shown in Figure 15b, we use a 2 mm rope with bowline knots to secure the specimen to the scale, placing cushioning below for safety. We start testing by manually pulling the bottom end of the specimen while monitoring force on the scale. We increase force until the specimen fails, recording the maximum force (F_{max}) and failure location. Tensile strength, σ_t, is calculated as

$$\sigma_t = \frac{F_{max}}{A_0},$$

where σ_t is in MPa, F_{max} in N, and A_0 is the initial cross-sectional area in mm^2.

8.4 Flexural Testing

For flexural testing of bridge panels (3 mm thickness; 100 mm length; 8 mm width), we arrange two parallel surfaces with a gap under 100 mm. We use mounting tape to secure both ends of the bridge panel onto the flat surfaces. To further ensure no slippage of the bridge ends during testing, we stack identical empty cardboard boxes with one 15-lb dumbbell on top of each box. We apply a digital crane scale to the bridge, flipping the scale upside down so that its hook hangs from the midpoint of the bridge. We start testing by manually pulling the scale downward while monitoring the force on the scale. We record deflection and material behavior until deflection threshold or failure, documenting damage and deformation. Flexural strength, σ, is computed as

$$\sigma = \frac{3PL}{2wh^2},$$

where σ is in MPa, P is the applied load (N), L is length (cm), w is width (cm), and h is thickness (cm).

8.5 Experimental Results

We performed validation of our toolkit by comparing results obtained with the tool against ground-truth labeled PLA filaments. Our test cases include PLA filaments from PolyMax, PolyTerra, PolyLite, and Ultimaker because they provide comprehensive technical data sheets and represent a broad range of sustainability profiles. Their widespread use among 3D printing enthusiasts further validates their practical relevance.

The tensile strength values obtained using our tool consistently fell within one standard deviation of the corresponding values in commercial datasheets, as shown in Table 7. While not a substitute for industrial-grade testing, our toolkit offers filament-specific strength estimates that are accurate enough to support practical, comparative decisions in typical maker workflows—particularly when users need to assess the relative performance of filaments they have on hand, such as in the *SustainaPrint* workflow.

Table 7: Comparison of experimental (Exp.), as evaluated by the mechanical testing toolkit, and ground-truth (GT), taken from material datasheets, tensile and flexural strength for four commercial PLA filaments.

PLA	Tensile Strength (MPa)			Flexural Strength (MPa)		
	Exp.	GT	GT Std Dev.	Exp.	GT	GT Std Dev.
PolyMax	32.8	32.4	1.2	61.5	62.0	0.9
PolyTerra	12.0	12.2	0.7	40.0	40.4	1.1
PolyLite	40.1	40.5	0.5	87.7	86.9	1.2
Ultimaker	31.6	33.1	2.8	97.7	96.8	NA

8.6 Evaluation on Recycled PLA

We also evaluate our toolkit using mechanically degraded PLA filament that has undergone multiple recycling cycles, in order to assess its effectiveness in identifying mechanical performance tradeoffs across the tested spectrum.

Most recycled filament available online does not include technical datasheets. So, to obtain truth values for recycled PLA filament, we sourced virgin and recycled PLA and datasheets from an industry partner.

The PLA recycling process involves shredding failed prints, melting the material using a twin-screw compounding line for uniform melt consistency, and re-extruding it into filament with a single-screw extrusion machine. This process was repeated between one and six times depending on the batch, with mechanical property data collected for each iteration, including tensile strength, tensile modulus, elongation at yield point, and Charpy impact strength. These values are shown in Figure 16, where we see tensile strength and modulus strictly degrading over recycling cycles.

Mechanical testing for ground-truth values was performed using a 4 J Charpy hammer and a 5 kN universal testing machine. The tests measured tensile strength, tensile modulus, elongation at yield point, and impact resistance for each recycling cycle.

The tensile strength of virgin PLA (51 MPa) decreases to 40 MPa after six recycling cycles, a 21.6% reduction. Similar decreases are observed in tensile modulus and impact strength.

Using our toolkit, we measured tensile strengths within one standard deviation of ground truth for each (Figure 17).

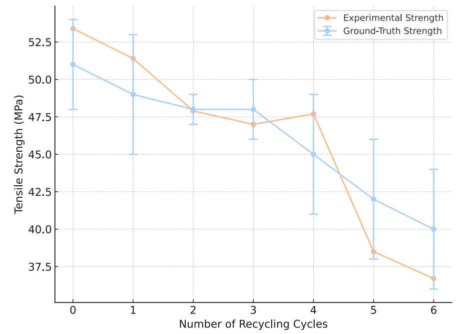

Figure 17: Experimental results for recycled PLA, as measured with our mechanical testing toolkit, remain within one standard deviation of the ground truth for each recycled sample.

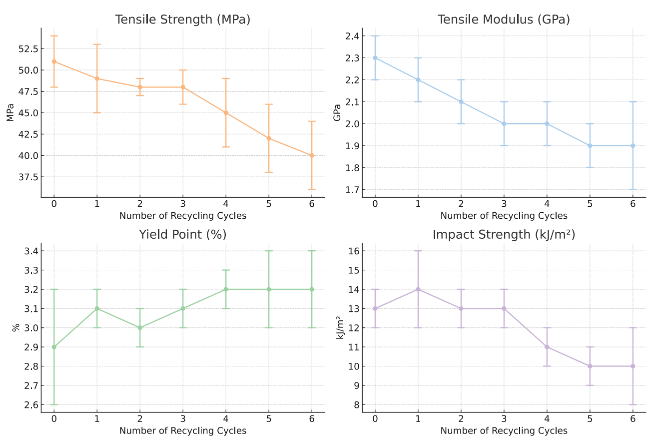

Figure 16: Tensile strength, tensile modulus, yield point, and impact strength across the number of PLA recycling cycles.

9 Limitations and Future Work

SustainaPrint assumes access to a dual-extrusion printer and requires users to specify boundary conditions such as force directions. While these align with common practices in hobbyist and educational contexts, future work could explore broader printer compatibility (e.g., manual swaps or pause-based transitions for single extruders) and automatic inference of usage conditions. Tighter integration with slicing software could also streamline generation of interlocking structures and interface optimization.

The system does not address end-of-life considerations. With studies estimating that up to 32% of hobbyist prints are discarded without reuse or recycling, this remains a key sustainability gap. Rather than focusing on post-use recycling, *SustainaPrint* targets the upstream issue—reusing waste during fabrication. By minimizing virgin plastic use while preserving strength, it reduces the impact of discarded prints.

Mixed-material outputs can complicate recycling. Recent work by Wen et al. [39] proposes a complementary approach using computational design and targeted dissolution to separate materials. Such techniques could improve recyclability in future iterations of *SustainaPrint*.

Finally, as discussed in the evaluation, *SustainaPrint* introduces trade-offs related to waste and energy. However, in standard setups without purge towers, it adds no additional waste and reduces virgin plastic use by up to 80%, offering a practical balance between sustainability and performance.

10 Conclusion

We present *SustainaPrint*, a method that helps bridge the gap between sustainable materials and personal fabrication by using intelligent software to compensate for material weaknesses. Through stress simulation and material-aware segmentation, the system enables makers to use eco-friendly filaments in structural prints. Across both test primitives and real-world objects, we show that using just 20% virgin material can recover much of the strength lost in fully sustainable configurations, enabling more sustainable prints with minimal performance trade-offs.

By reusing weaker eco-friendly materials and combining a simulation-backed design tool, mechanical testing kit, and accessible interface, *SustainaPrint* lowers the barrier to functional sustainable printing. We hope this work inspires future systems that integrate material science, simulation, and HCI to advance eco-conscious making.

While currently compatible with standard commercial filaments, the same techniques could be extended to experimental materials such as coffee grounds [31] or clay composites [1, 5]. Broadening the material scope could further democratize sustainable fabrication and encourage innovation in design with waste and environmental impact in mind.

Acknowledgments

We thank Faraz Faruqi and Leonardo Hernández Cano for their valuable feedback and support, and also gratefully acknowledge the support of the HPI-MIT Designing for Sustainability Program, the MIT MAD MAD (Morningside Academy for Design) Fellowship, and the MIT MathWorks Fellowship.

References

[1] Fiona Bell, Erin McClure, Camila Friedman-Gerlicz, Ruby Ta, and Leah Buechley. 2024. Shape-changing clay-dough: Taking a material-oriented approach to 3D printing ceramic forms. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems*. ACM.

[2] Freddys R Beltrán, Celia Infante, Ma Ulagares de la Orden, and Joaquín Martínez Urreaga. 2019. Mechanical recycling of poly(lactic acid): Evaluation of a chain extender and a peroxide as additives for upgrading the recycled plastic. *Journal of Cleaner Production* 219 (2019), 46–56.

[3] Amit H Bermano, Thomas Funkhouser, and Szymon Rusinkiewicz. 2017. State of the art in methods and representations for fabrication-aware design. In *Computer Graphics Forum*, Vol. 36. Wiley Online Library, 509–535.

[4] S Budin, NC Maideen, MH Koay, D Ibrahim, and H Yusoff. 2019. A comparison study on mechanical properties of virgin and recycled polylactic acid (PLA). In *Journal of Physics: Conference Series*, Vol. 1349. IOP Publishing, 012002.

[5] Leah Buechley, Jaime Gould, and Fiona Bell. 2024. CeraMetal: A new approach to low-cost metal 3D printing with bronze clay. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems*. ACM.

[6] Xiang 'Anthony' Chen, Stelian Coros, Jennifer Mankoff, and Scott E Hudson. 2015. Encore: 3D printed augmentation of everyday objects with printed-over, affixed and interlocked attachments. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software and Technology*. ACM.

[7] Robert Cimrman. 2014. SfePy-write your own FE application. *arXiv preprint arXiv:1404.6391* (2014).

[8] Carl DiSalvo, Phoebe Sengers, and Hrönn Brynjarsdóttir. 2010. Mapping the landscape of sustainable HCI. In *Proceedings of the 2010 CHI Conference on Human Factors in Computing Systems*. ACM.

[9] Garrett Durland. 2017. Tripod Planter. https://www.thingiverse.com/thing:2315534. Accessed: 2025-07-13.

[10] Faraz Faruqi, Ahmed Katary, Tarik Hasic, Amira Abdel-Rahman, Nayeemur Rahman, Leandra Tejedor, Mackenzie Leake, Megan Hofmann, and Stefanie Mueller. 2023. Style2Fab: Functionality-aware segmentation for fabricating personalized 3D models with generative AI. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology*. ACM.

[11] Jon Froehlich, Tawanna Dillahunt, Predrag Klasnja, Jennifer Mankoff, Sunny Consolvo, Beverly Harrison, and James A Landay. 2009. UbiGreen: Investigating a mobile tool for tracking and supporting green transportation habits. In *Proceedings of the 2009 CHI Conference on Human Factors in Computing Systems*. ACM.

[12] Wei Gao, Yunbo Zhang, Diogo C Nazzetta, Karthik Ramani, and Raymond J Cipra. 2015. RevoMaker: Enabling multi-directional and functionally-embedded 3D printing using a rotational cuboidal platform. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software and Technology*. ACM.

[13] Eleni Gkartzou, Elias P Koumoulos, and Costas A Charitidis. 2017. Production and 3D printing processing of bio-based thermoplastic filament. *Manufacturing Review* 4 (2017), 1.

[14] GoAftens. 2016. Phone Stand. https://www.thingiverse.com/thing:2120591. Accessed: 2025-07-13.

[15] Phillip Gough, Praneeth Bimsara Perera, Michael A Kertesz, and Anusha Withana. 2023. Design, Mould, Grow!: A fabrication pipeline for growing 3D designs using myco-materials. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. ACM.

[16] Sascha Hartig, Sven Duda, and Lennart Hildebrandt. 2020. Urgent need hybrid production-what COVID-19 can teach us about dislocated production through 3d-printing and the maker scene. *3D Printing in Medicine* 6, 1 (2020), 37.

[17] Mohammad Raquibul Hasan, Ian J Davies, Alokesh Pramanik, Michele John, and Wahidul K Biswas. 2024. Potential of recycled PLA in 3D printing: A review. *Sustainable Manufacturing and Service Economics* (2024), 100020.

[18] Yixin Hu, Teseo Schneider, Bolun Wang, Denis Zorin, and Daniele Panozzo. 2020. Fast tetrahedral meshing in the wild. *ACM Transactions on Graphics (ToG)* 39, 4, Article 117 (2020).

[19] ASTM International. 2017. Standard test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials.

[20] ASTM International. 2023. Standard test method for compressive properties of rigid plastics.

[21] Andrew Jones, Thomas Cameron, Benjamin Eichholz, Martin Eichers, Taylor Kray, and Jeremy Straub. 2019. Reducing space sensing and other mission cost with 3D printing infill optimization. In *Sensors and Systems for Space Applications XII*, Vol. 11017. SPIE, 69–74.

[22] Robert Kovacs, Anna Seufert, Ludwig Wall, Hsiang-Ting Chen, Florian Meinel, Willi Müller, Sijing You, Maximilian Brehm, Jonathan Striebel, Yannis Kommana, et al. 2017. TrussFab: Fabricating sturdy large-scale structures on desktop 3D printers. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM.

[23] Nahyun Kwon, Himani Deshpande, Md Kamrul Hasan, Aryabhat Darnal, and Jeeeun Kim. 2021. Multi-ttach: Techniques to enhance multi-material attachments in low-cost FDM 3D printing. In *Proceedings of the 6th Annual ACM Symposium on Computational Fabrication*. ACM.

[24] Eldy S Lazaro Vasquez, Hao-Chuan Wang, and Katia Vega. 2020. Introducing the sustainable prototyping life cycle for digital fabrication to designers. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference*. 1301–1312.

[25] Jasmine Lu, Beza Desta, K. D. Wu, Romain Nith, Joyce E. Passananti, and Pedro Lopes. 2023. ecoEDA: Recycling e-waste during electronics design. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology*. ACM.

[26] Usama Mahmood. 2024. *How Much Electricity Does a 3D Printer Use?* https://acom.pk/blogs/news/how-much-electricity-does-3d-printer-use Published by ACOM Distributors. Accessed July 11, 2025.

[27] MakerBot. 2017. Headphone Stand. https://www.thingiverse.com/thing:2050885. Accessed: 2025-07-13.

[28] Mohammad Azeeb Mazlan, Mohamad Azizi Anas, Nor Aiman Nor Izmin, and Abdul Halim Abdullah. 2023. Effects of infill density, wall perimeter and layer height in fabricating 3D printing products. *Materials* 16, 2 (2023), 695.

[29] Stefanie Mueller, Sangha Im, Serafima Gurevich, Alexander Teibrich, Lisa Pfisterer, François Guimbretière, and Patrick Baudisch. 2014. WirePrint: 3D printed previews for fast prototyping. In *Proceedings of the 27th Annual ACM Symposium on User interface Software and Technology*. ACM.

[30] Serge Payen. 2016. Wall Hook. https://www.thingiverse.com/thing:1367661. Accessed: 2025-07-13.

[31] Michael L Rivera, S Sandra Bae, and Scott E Hudson. 2023. Designing a sustainable material for 3D printing with spent coffee grounds. In *Proceedings of the 2023 ACM Designing Interactive Systems Conference*. ACM.

[32] Daniel Saakes, Thomas Cambazard, Jun Mitani, and Takeo Igarashi. 2013. PacCAM: Material capture and interactive 2D packing for efficient material usage on CNC cutting machines. In *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology*. ACM.

[33] Katherine W Song and Eric Paulos. 2021. Unmaking: Enabling and celebrating the creative material of failure, destruction, decay, and deformation. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. ACM.

[34] C. Bane Sullivan and Alexander Kaszynski. 2019. PyVista: 3D plotting and mesh analysis through a streamlined interface for the Visualization Toolkit (VTK). *Journal of Open Source Software* 4, 37 (May 2019), 1450.

[35] Alexander Teibrich, Stefanie Mueller, François Guimbretière, Robert Kovacs, Stefan Neubert, and Patrick Baudisch. 2015. Patching physical objects. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software and Technology*. ACM.

[36] Thingiverse. 2008. Thingiverse: Design-sharing platform for 3D printable objects. https://www.thingiverse.com/ Launched October 18, 2008. Owned by Ultimaker (formerly MakerBot Industries). Accessed July 11, 2025.

[37] Mattia Dalla Via. 2017. Shelf Hook. https://www.thingiverse.com/thing:2571346. Accessed: 2025-07-13.

[38] Ludwig Wilhelm Wall, Alec Jacobson, Daniel Vogel, and Oliver Schneider. 2021. Scrappy: Using scrap material as infill to make fabrication more sustainable. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. ACM.

[39] Xin Wen, S. Sandra Bae, and Michael L. Rivera. 2025. Enabling recycling of multi-material 3D printed objects through computational design and disassembly by dissolution. In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems*. ACM.

[40] Zeyu Yan, Mrunal Sanjay Dhaygude, and Huaishu Peng. 2025. Make Making Sustainable: Exploring Sustainability Practices, Challenges, and Opportunities in Making Activities. In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems*. 1–14.

[41] Ruowang Zhang, Stefanie Mueller, Gilbert Louis Bernstein, Adriana Schulz, and Mackenzie Leake. 2024. WasteBanned: Supporting zero waste fashion design through linked edits. In *Proceedings of the 37th Annual ACM Symposium on User Interface Software and Technology*. ACM.

[42] Jingwen Zhu, Lily Winagle, and Hsin-Liu Kao. 2024. EcoThreads: Prototyping biodegradable e-textiles through thread-based fabrication. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems*. ACM.

[43] Kening Zhu, Alexandru Dancu, and Shengdong Zhao. 2017. FusePrint: A DIY 2.5D printing technique for good-fit fabrication with daily objects. In *Extended Abstracts of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM.