Designing a Sustainable Material for 3D Printing with Spent Coffee Grounds

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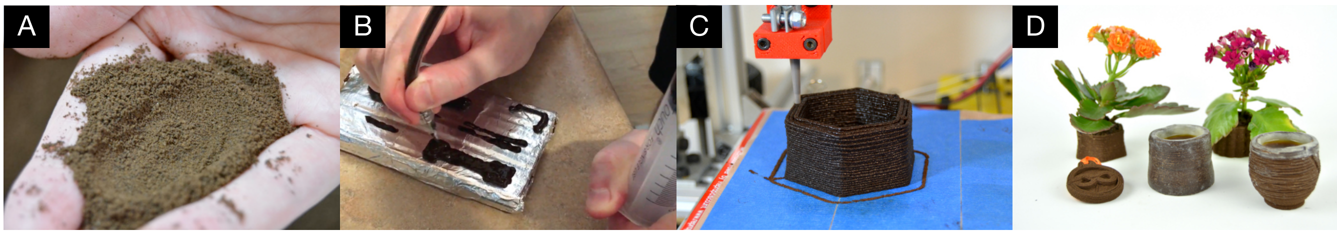

Figure 1: Design Process Overview. We investigated spent coffee grounds—a commonly wasted natural material—as a sustainable material for 3D printing (A). We experimented with different food-based binders and adjusted material composition to make the material self-supporting with hand-extrusion (B). We tuned 3D printing parameters for quality and reliability (C). We then explored how our material could enable sustainable prototyping workflows and creating objects like biodegradable espresso cups and planter pots (D).

ABSTRACT

The widespread adoption of 3D printers exacerbates existing environmental challenges as these machines increase energy consumption, waste output, and the use of plastics. Material choice for 3D printing is tightly connected to these challenges, and as such researchers and designers are exploring sustainable alternatives. Building on these efforts, this work explores using spent coffee grounds as a sustainable material for prototyping with 3D printing. This material, in addition to being compostable and recyclable, can be easily made and printed at home. We describe the material in detail, including the process of making it from readily available ingredients, its material characteristics and its printing parameters. We then explore how it can support sustainable prototyping practices as well as HCI applications. In reflecting on our design process, we discuss challenges and opportunities for the HCI community to support sustainable prototyping and personal fabrication. We conclude with a set of design considerations for others to weigh when exploring sustainable materials for 3D printing and prototyping.

CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**.

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KEYWORDS

3D printing, personal fabrication, environmental sustainability, zero-waste prototyping, bio-based materials

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1 INTRODUCTION

Environmental challenges including climate change, pollution, and waste production have reached global concern. Within the Human-Computer Interaction (HCI) community, there is a growing interest in addressing these sustainability issues that are associated with the materials and the energy we use for digital technologies [17, 28, 67, 74, 77, 98]. Researchers are examining the effects of digital technology use on energy consumption [36, 130] as well as introducing strategies to mitigate energy over-use [87, 131]. Others have investigated reducing waste output by reusing objects—such as electronics [47, 55] and textiles [135]—and designing them for decomposition [65, 66, 68, 113].

The sustainability of personal fabrication technologies, particularly 3D printing, is a pressing issue [10, 31, 57, 124]. As of 2019, over 2 million 3D printers have been integrated into the homes of consumers and small businesses [103]. This widespread adoption has been enabled by open-source movements (e.g., Fab@Home [73] and RepRap [52]) and cheap kits, costing less than $160 USD[1]. Consequently, the adoption of these machines exacerbates three

[1]Best Cheap/Budget 3D Printers: https://all3dp.com/1/best-cheap-budget-3d-printer-affordable-under-500-1000/

environmental challenges: the use of plastic materials (which have detrimental ecological effects [20, 30]); waste output (e.g., through discarded prototypes and failed prints [114]); and energy consumption, particularly from heating the build plate and nozzle during printing [1, 32]. Research has shown that material choice for 3D printing plays a significant role in countering these environmental challenges [34]. For instance, though energy consumption is the largest driver of 3D printing's environmental impacts, material choice can significantly reduce the amount of energy used if the material can be printed without heat [34]. Material choice can further reduce environmental impacts if its components are non-toxic, abundant, renewable, and compostable [31, 34].

Motivated by a need for materials with low environmental impacts in 3D printing, researchers and designers are exploring alternatives that can enable more sustainable practices. However, proposed materials often only target some environmental impacts while leaving others unaddressed. For example, thermoplastic bio-composite filaments (e.g., [21, 35, 62, 129, 136, 137]) typically aim to reduce waste production but not high energy consumption. In addition, some proposed materials—despite having lower environmental impacts—introduce new safety concerns or require laboratory equipment for production and/or use. For instance, sodium silicate (used in [33, 34]) is a known hazardous material that necessitates handling considerations [33, 90]. Similarly, thermoplastic bio-composite filaments (such as those in [136, 137]) require using a lab-grade parallel twin extrusion system [121] for production. These materials and their methods are generally less approachable, and ultimately, unlikely to be adopted by the broader community.

As designers and researchers, it is critical to not only design sustainable materials but also consider *how* individuals can utilize these materials with readily available tools and equipment [115]. Evidently, designing a material that is sustainable and approachable for 3D printing is a challenging process, requiring careful consideration of its material components to ensure printability, low environmental impacts, and ease of use [31, 50]. Technical descriptions of such materials are typically well-documented (e.g., [34, 136]), but their design processes are often not. Yet offering insight into these design processes could spur innovation in the space of sustainable personal fabrication.

In this work, we explore designing a sustainable material for 3D printing with spent coffee grounds—a commonly wasted natural material [51, 84, 102]. The presented material avoids thermal energy consumption; accounts for life cycle considerations by being recyclable and compostable; and can be easily made and used at home. We provide a detailed account of our design process (Figure 1), the material's use with a 3D printer, its material characteristics, and how it supports sustainable prototyping workflows and HCI applications.

In reflecting on our design process, we discuss insights and challenges in the development and use of sustainable materials for 3D printing and prototyping. We highlight opportunities for HCI researchers to innovate in sustainable fabrication and promote sustainable prototyping practices. Finally, we conclude with a set of design considerations for others to weigh when exploring sustainable materials for 3D printing and prototyping.

2 RELATED WORK

This work relates to four areas of research that examine environmental challenges with common 3D printing materials; the environmental impacts of 3D printing; sustainable prototyping and personal fabrication in HCI; and bio-based materials in 3D printing processes. In this section, we discuss these areas to provide context for our work.

2.1 Environmental Challenges with Common 3D Printing Materials

Fused Deposition Modeling (FDM) / Fused Filament Fabrication (FFF) 3D printers are the most commonly used 3D printers [82, 132]. These printers place material down as small beads in lines or curves to form the layers of an object. Each layer then successively builds on top of the previous one. The most commonly used materials on FDM/FFF 3D printers are the thermoplastic polymers acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) [82, 132].

ABS is not biodegradable and is produced from petroleum, which is a non-renewable resource [86]. PLA, on the other hand, is produced from plant starch and is generally viewed as being biodegradable [101]. However, its biodegradability has some caveats. PLA will decompose into carbon dioxide and water within 90 days only if it is processed in a controlled composting facility containing a specific microbiome while also consistently being heated at a temperature of 60 °C [101]. Owing to these requirements, very few facilities accept PLA for composting. Thus, the material almost exclusively ends up in landfills [110]. Within landfills, PLA can take anywhere from 100–1000 years to degrade [58].

Processing PLA through traditional recycling streams is also problematic as it often contaminates other commonly recycled plastics, such as polyethylene terephthalate (PET, e.g., soda bottles) [63]. Recently, some companies (e.g., Filabot[2]) have explored recycling printed PLA objects back into a printable filament. Objects are ground, melted, and mixed with fresh plastic pellets before being extruded into a filament. Though promising, this approach is energy-intensive, requires additional machinery, and is generally not ideal for individuals at home.

2.2 Environmental Impacts of 3D Printing

Researchers have shown that the ecological impacts of 3D printing are primarily driven by electricity use [32, 54, 72]. However, material choice can greatly influence the amount of electricity used during a 3D printing process [34]. In general, reducing the use of plastics (and especially thermoplastics) in 3D printing is ecologically beneficial. With thermoplastic 3D printing, significant energy is used to heat up the material for extrusion as well as maintain an appropriate build plate/volume temperature during printing [34]. Thus, materials that can be printed without heating (i.e., bond chemically as opposed to thermally) can greatly reduce the environmental impacts of 3D printing [31, 34]. These impacts can be further reduced if the material is non-toxic, abundant, renewable, and compostable [31]. Moreover, materials that can be produced from local waste streams (e.g., recycling) can further reduce environmental impacts associated with material transport and support

[2]Filabot Machines: https://www.filabot.com/collections/filabot-core

sustainable circular economies [105, 108]. In this work, we focus on designing a more sustainable material for 3D printing that accounts for these aforementioned aspects. Specifically, our material is printed without heat; is renewable, non-toxic, and compostable; and is primarily produced from local waste.

2.3 Sustainable Prototyping and Personal Fabrication in HCI

Sustainability in prototyping and personal fabrication is a growing topic of interest amongst HCI researchers and designers. A recent five-year review of the HCI community has foregrounded the environmental impacts of the most commonly used materials and machines (e.g., 3D printers) for physical prototyping [124]. The review reveals that 3D printed thermoplastic filaments account for more than 30% of the materials used in all physical prototypes [124]. Owing to their prevalence, HCI researchers have examined ways to reduce the use of thermoplastics in 3D printing. These efforts range from printing low-fidelity wireframes of objects [80] to substituting an object’s components with plastic bottles [59, 60] or reusable Lego-style blocks [81]. Others have explored reusing scrap materials as infill in 3D printed objects [126] and re-printing on top of previously printed objects during prototyping iterations [120]. While these approaches are promising, they still heavily rely on thermoplastic materials, which use significant energy (see Section 2.2). In addition, approaches that combine or encapsulate different materials inside of 3D printed plastic, can result in so-called “monstrous hybrids” [76]. These monstrous hybrids make recycling and biodegradation of an object’s components difficult or impossible. In contrast, our material is designed without the use of thermoplastics and instead uses bio-based components, which naturally biodegrade.

More broadly, research focused on sustainable personal fabrication has examined approaches to reuse waste as well as consider the different stages of a material’s life cycle when creating an object [67, 123]. HCI researchers have investigated salvaging waste from makerspaces [26] and compost [12] as a way to support making, understand disposal practices, and create opportunities for local material production. Others have explored design strategies that leverage a material’s ability to degrade and decompose as a function of its use [68, 113]. As an extension of these works, researchers have investigated using bio-based materials—which readily biodegrade—with digital fabrication processes [67], and to prototype interactive objects using mycelium [65, 66], biofoams [64], and bioplastics [56]. Our material builds upon these efforts and is also composed of bio-based components, enabling it to be biodegradable, recyclable, and compostable at home. However, our use of bio-based materials differs from past work in that it specifically focuses on design challenges within a 3D printing context.

2.4 Bio-based Materials for 3D Printing

Bio-based materials, which consist of or are derived from living matter [24], have emerged as possible alternative materials for 3D printing that support environmental sustainability [31] and promote circular economies [105, 108]. Here we discuss the use of bio-based materials in thermoplastic composite filaments, FDM/FFF paste printing processes, and binder jetting processes. We summarize and compare the different FDM/FFF bio-based materials with our material in Table 1.

2.4.1 Thermoplastic Bio-Composite Filaments. Researchers in the Materials Science and Mechanical Engineering communities have examined the use of biomass resources as filler materials in thermoplastic filaments. These fillers include bamboo fiber [129]; spent coffee grounds [21]; hemp fiber [136]; oyster shells [35]; and lignin [62, 137]. As fillers, these materials are used in low percentages (typically ≤30%) and are usually combined with a thermoplastic like PLA [15]. Combining them with thermoplastics allows them to be printed on FDM/FFF 3D printers without any hardware modifications. However, any combination of biomass resources with thermoplastic materials still requires significant energy for printing and increases the consumption of thermoplastics. Furthermore, as composites, these filaments become more difficult to recycle and biodegrade. In this work, we avoid the use of thermoplastics. Instead, we focus on using materials that are renewable, recyclable, compostable, and can be printed without the use of thermal energy.

2.4.2 Paste Extrusion of Bio-based Materials. FDM/FFF 3D printing processes can be modified with syringe-based [91, 116] or pneumatic [46] extrusion set-ups to print a variety of viscous materials. Many of these materials do not require thermal energy during printing though may require it for pre-/post-processing (e.g., firing in a kiln). Materials supported in this set-up include ceramics [116], mica [34], hydrogels (e.g., sodium alginate [91] and kappa-carrageenan [97]), and food (e.g., chocolate [88], potato starch [88], and corn flour [18]). Of these materials, ceramics and mica are not bio-based or compostable. On the other hand, food-based materials like potato starch and some hydrogels (e.g., agar, alginate) are compostable but are typically structurally weak and not ideal for functional prototyping [128].

Designers have developed other bio-based and compostable materials from a mycelium-straw mixture [61] as well as mussel shells [105, 108]. Mycelium has a strong potential as functional material (especially in HCI [65, 66]). However, its growth requires care to avoid potential adverse health effects caused by fungal spores [11]. This safety aspect makes mycelium not ideal as a printing material for use within a home setting. Mussel shells have also shown promise as a printing material, but they require significant thermal energy to convert into a printable powder [105].

Closely related to this work, the open-source community Materiom [75] offers different recipes for 3D printable bio-based materials that are made from eggshells [85], olive pomace [7], oyster shells [38, 134], and mussel shells [104, 105, 107]. Like the SCG material presented in this work, these bio-based materials are designed to encourage sustainability in 3D printing. However, all of these materials rely on thermal energy for processing. As previously discussed in Section 2.2, the use of heat in materials for 3D printing is a primary contributor to its environmental impacts [34] . In contrast, our work presents a sustainable material for 3D printing that avoids thermal energy consumption and accounts for end-of-life considerations while still being approachable to users at home. We summarize and compare different FDM/FFF bio-based materials and our SCG material in Table 1.

Table 1: Comparison of FDM/FFF 3D Printing materials introduced in prior works (e.g., Materiom [75]) and our spent coffee ground (SCG) material. Checkmarks (✓) indicate the material supports a given aspect; and bullet points (•) indicate that PLA-based materials are only compostable in industrial settings and not at home or through residential compost streams. In contrast to prior works, the SCG material can be made, printed and reused at home; it is both biodegradable and compostable; and it avoids thermal energy use for material processing and printing.

	Approachability		**End-of-Life Considerations**			**Avoid Thermal Energy Use**		
Material	*Make At Home*	*Print At Home*	*Reprintable*	*Biodegradable*	*Compostable*	*During Processing*	*During Printing for Build Plate*	*During Printing for Extrusion*
Thermoplastic Bio-Composites [21, 35, 62, 129, 136, 137]		✓		•	•	≥180°C	≥60°C	≥200°C
Ceramics [116]	✓	✓				≥950°C	✓	✓
Mica [33, 34]						✓	✓	✓
Mycellium-PLA [61]				•	•	≥180°C	60°C	≥180°C
Mycellium-Straw [61]				✓	✓	✓	✓	✓
Oyster Shell [38, 134]	✓	✓	✓	✓	✓	200°C (1 hour)	✓	✓
Mussel Shell [104–107]	✓	✓	✓	✓	✓	100°C (30 mins) 180°C (45 mins) 200°C (45 mins)	30°C	✓
Olive Pomace [7]	✓	✓		✓	✓	Oven-Dried	✓	✓
Egg Shells [85]	✓	✓		✓	✓	100°C (5 mins) 100°C (15 mins)	✓	✓
This Work (SCG Material)	✓	✓	✓	✓	✓	✓	✓	✓

2.4.3 Binder Jetting of Bio-based Materials. As an alternative to FDM/FFF processes, others have examined printing bio-based materials in binder jetting 3D printing processes. These processes fabricate objects by selectively placing a liquid binder over a bed of powdered material [139]. Researchers and designers have explored using mussel shells [105], spent coffee grounds [93], cellulose [137], and sugar [93] as binder jet material. Binders for these materials include synthetic polymers (e.g., polyvinyl alcohol [137]), alcohols (e.g., isopropyl alcohol and rice wine [93]), and sugar-water [105]. Despite their ability to use bio-based materials, binder jetting printers are much more expensive and less approachable to consumers than their FDM/FFF counterparts [96]. The cheapest binder jetting printers can cost approximately $30,000 USD[3], whereas an FDM/FFF 3D printer typically costs around $160 USD[1]. In addition, objects produced using binder jetting require significant post-processing to remove excess powder [82]. In the current work, we focus on designing a bio-based material for FDM/FFF 3D printers to promote ease of access and use at home.

[3]2022 Best Binder Jetting 3D Printer - Pros and Cons & Buying Guide - Pick 3D Printer: https://pick3dprinter.com/binder-jetting-3d-printer/

3 MATERIAL DESIGN

In reviewing prior works as seen in Table 1, proposed sustainable materials generally target only some environmental impacts (e.g., compostability) while leaving others (e.g., high energy consumption) unaddressed. In addition, there is sometimes a trade-off between lower environmental impacts and approachability for end-users. Some materials can be more ecologically beneficial when compared to typical thermoplastics, but require safety precautions or laboratory methods for production and/or use [33, 61]. Informed by previous work, we set out to close these gaps with the design of our material. In this section, we describe our design principles, our material components, and our process for creating the material.

3.1 Design Considerations

The design of our material was guided by three interrelated considerations: principles of Sustainable Interaction Design [17], material-focused strategies to reduce the environmental impacts of 3D printing [31, 32, 34, 105, 108], and Stegall's design for sustainability philosophy [115].

Sustainable Interaction Design (SID) establishes five principles that the design of an object, whether with physical or digital materials,

Table 2: Proportions and purpose of the different components that are used to prepare our SCG material for 3D printing.

Name	Purpose	Mass Proportion (g)	Source
Spent Coffee Grounds (SCG)	Primary Structural Material	50	Local Coffee Shop
Carboxymethyl Cellulose (CMC)	Binder & Thickening Agent	8	Modernist Pantry [69]
Xanthan Gum (XG)	Stabilizer & Thickening Agent	1.2	Modernist Pantry [70]
Water	Carrier & Mixing Fluid	100	Local Tap

should consider from a sustainability perspective [17]. In designing our material, we focused on the two main SID principles: linking invention and disposal, and promoting renewal and reuse. The principle of linking invention and disposal dictates that the creation of an object must include a detailed account of how the object and materials resulting from its use will be discarded. Promoting renewal and reuse requires the design of an object to consider possibilities for the renewal and reuse of existing objects or systems [17].

In the design of our material, we linked invention and disposal by prioritizing components that are renewable, biodegradable, and compostable. These considerations minimize waste output and support a circular material life cycle. To promote renewal and reuse, we sought to recycle a commonly wasted natural material as our primary material component. Objects made with our material can also be recycled back into printing material during prototyping iterations and be composted at home to create a soil fertilizer.

As previously discussed in Section 2, prior work has demonstrated that avoiding thermal energy use can greatly reduce the environmental impacts of 3D printing [31, 34]. Moreover, materials that are non-toxic, abundant, renewable, and compostable can further reduce these impacts [31]. In support of low environmental impact, we designed our material to be printed without thermal energy. Moreover, in alignment with principles of SID, all of our material components are non-toxic, abundant, renewable, and compostable. These strategies emphasize creating a sustainable 3D printing material from a material's energy usage and life cycle perspective. However, widespread sustainability is a *process* that requires considerations beyond the material itself. To design for sustainability, Stegall [115] argues it is enough to not just consider sustainable products but rather "to envision products, processes, and services that encourage widespread sustainable behavior". In the context of 3D printing and prototyping, Stegall's argument alludes that there must be further considerations on *how* users can utilize sustainable materials with readily available equipment. To this end, we prioritized how users could potentially make and use our sustainable material within a home setting. We focused on using materials that were non-toxic and food-safe, and capable of being processed with in-home tools (e.g., a strainer in a kitchen). In terms of use, we also sought out materials that were capable of being recycled and composted within a home setting. By emphasizing these considerations, we aimed to promote the approachability of our material while simultaneously supporting sustainability goals.

3.2 Material Components

Guided by our design considerations (Section 3.1), our material consists of four components: spent coffee grounds, carboxymethyl cellulose, xantham gum, and water as seen in Table 2. First, we describe each of these components and their purpose. Then we detail the design process that we used to select these components for our material.

3.2.1 Spent Coffee Grounds. Coffee is one of the most consumed beverages in the world. At least 9.6 billion kg of coffee have been consumed every year since 2016 [84]. During brewing, typically only 18-22% of coffee mass is extracted as solubles into a beverage [16, 71, 112]. The remaining amount (78-82%) is referred to as spent coffee grounds (SCG). SCG are the primary by-product of coffee production in both consumer settings (e.g., at home, coffee shops) and industrial processes (e.g., instant coffee production) [3]. The majority of SCG are disposed of in landfills [51, 102], making them an ideal candidate for being recycled as a printing material. Additionally, SCG are a natural material primarily composed of cellulose, hemi-cellulose, and lignin [8]—components that make up the cell walls of plants and trees [99]. Thus, they are renewable and biodegradable. SCG can also be composted and used as a soil fertilizer [19, 23, 100]. In collaboration with a local coffee shop, we recycle SCG as the main component of our printing material.

3.2.2 Carboxymethyl Cellulose. Carboxymethyl cellulose (CMC) is a biodegradable water-soluble polymer derived from cellulose [9]. It is commonly used as a binding, thickening, and stabilizing agent in food (e.g., ice cream, cheese) and cosmetic products (e.g., lotions, toothpaste) [13, 39, 45]. CMC is compostable and has been shown to beneficially increase water retention in soil [79]. In our material, CMC primarily serves as a binding agent for SCG. CMC also increases the viscosity of the material for printing. Our CMC is purchased from Modernist Pantry [69], an online food ingredients supplier.

3.2.3 Xanthan Gum. Xanthan gum (XG) is a natural polysaccharide produced via the fermentation of carbohydrates (e.g., glucose) by the bacteria *Xanthomonas campestris* [37, 53]. XG is completely biodegradable within two days [53]. It is water-soluble and is often used as a stabilizer and thickener in food products (e.g., salad dressing) and cosmetics (e.g., toothpaste) [53]. In our material, XG prevents SCG from separating out of the mixture and also increases the mixture's viscosity and its degree of shear thinning. Without XG's inclusion, we found that our material would not readily flow during printing. Our XG is purchased from Modernist Pantry [70].

3.2.4 Water. The primary purpose of water in our material is to combine the SCG, CMC, and XG components for printing. As hydrocolloids, both CMC and XG dissolve in water and form gel networks around the granules of the SCG. After printing, the water evaporates and the gel network dries, bonding the SCG together. Once dry, our material is composed of 84.46% SCG, 13.51% CMC, and 2.03% XG.

3.3 Process of Choosing Material Components

Printing without thermal energy immediately narrowed our possible directions for creating a sustainable material. Specifically, it meant that we had to rely on a room-temperature paste-based extrusion process. Materials used in paste-based processes typically have at least 3 components: a primary structural material; a binder that joins pieces of the structural material together; and a fluid for mixing the two previous components together. In some cases, the binder and fluid may be one and the same. Other components can also be added to tune material properties (e.g., viscosity).

For our printing material, we focused on using water as a carrier fluid as it is a highly approachable and versatile material. For the structural material and binder, the most direct way to achieve our design goals was to focus on using bio-based materials. Because these materials are derived from living matter, they are generally non-toxic, abundant, renewable, and compostable. Inspired by previous work that examined reusing oyster shells [134] and mussel shells [105], we were particularly interested in reusing waste biomaterial from commonly disposed of items.

In our initial explorations, we found that many commonly disposed of bio-based materials, such as paper (e.g., egg-cartons, newspaper), are already highly recycled for other purposes [29, 125]. Using one of these as our printing material would potentially dilute existing reuse/recycling streams and may not have as large of a positive environmental impact. Instead, we opted to focus on a material that does not have an established stream to maximize environmental benefits. Food waste, in particular, is one of the largest contributors to landfills and one of the least reused and recycled materials [29]. After a discussion with a local coffee shop's staff, we discovered that SCG are almost exclusively disposed of in landfills [51, 102]. This discussion led us to explore SCG as our primary structural material.

Mixing SCG with water resulted in a slurry that could be extruded through a syringe but the grounds would not adhere together. We searched for commonly used and easy-to-acquire food-based binders as these would be most likely to be bio-based and support our design goals. Our initial list consisted of wheat flour, rice flour, kappa carrageenan, XG, CMC, and agar powder. However, we immediately excluded kappa carrageenan as it required heat to become a gel. For the remaining binders, we experimented with mixing different proportions of binder into solutions consisting of 10 g of spent coffee grounds and 20 g of water. We gradually increased the proportion of a particular binder until a mixture's viscosity was reminiscent of peanut butter. Using a 10 mL syringe[4], we hand-extruded line samples of each mixture (Figure 1B) and allowed them to dry. Once dried, we tried to pull apart and compress the samples until they broke. Some binders, such as XG and wheat flour, resulted in samples that would crumble upon manipulation, making them unsuitable for use in a 3D printing material. On the other hand, samples containing CMC were much stronger compared to the aforementioned binders. This led us to use CMC as our binder.

[4]10 mL Syringe: https://www.amazon.com/dp/B013WWFJX0/

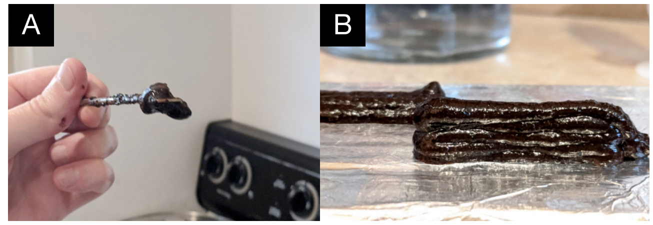

Figure 2: Determining suitable thixotropy. We found when the SCG material holds its shape on a stirring rod and does not drip (A), it is self-supporting and exhibits thixotropic behavior suitable for hand-extrusion and 3D printing (B).

When applying pressure to a mixture of SCG, CMC, and water inside a larger syringe (60 mL), we noticed the SCG were prone to separating out of the mixture. This separation caused clogging and inconsistent extrusion. To address this challenge, we explored adding a small amount of XG to the mixture as it prevents similar separation from occurring in cosmetics (e.g., toothpaste) and increases thixotropy [78]—a material's ability to readily flow when force is applied and then gradually returns to a more thick, stable state. We further tuned the amount of XG to reach a suitable thixotropy that would support stacking "layers" of the material for 3D printing (Figure 2B).

4 3D PRINTING APPROACH

This section describes our preparation procedure for our spent coffee ground-based material (SCG material), our 3D printer set-up, printing parameters, and our decision process for aspects such as nozzle diameter and print speed.

4.1 Material Preparation

We partnered with a local coffee shop[5] to receive their SCG that were previously used to make espresso-based drinks (e.g., lattes, cappuccinos). The obtained grounds were finely ground to approximately 200 μm in diameter (visually similar in size to table salt) and initially wet. We opted to dry the SCG in direct sunlight for two days to avoid energy consumption associated with oven-drying. Once fully dried, we sifted the grounds using a basic kitchen strainer[6] to remove any large clumps.

After measuring their proper proportions, all of the dry powders (i.e., SCG, XG, CMC) were combined together in a single jar. The powders were then shaken together for approximately 1 min to ensure a uniform mixture. This combination was then slowly mixed into another jar containing a proportional amount of water by mass. Once the mixture was homogeneous, the SCG material was loaded into 60 mL syringes[7]. Following the exact proportions in Table 2 produces approximately 90 mL of the SCG material. Notably, this entire procedure can be accomplished in a standard kitchen at home with food-safe ingredients.

[5]Arriviste Coffee Bar: https://arriviste.coffee
[6]OXO 8-inch Strainer: https://www.amazon.com/dp/B00133DRIK/
[7]60 mL Syringe: https://www.amazon.com/dp/B01M1R392V/

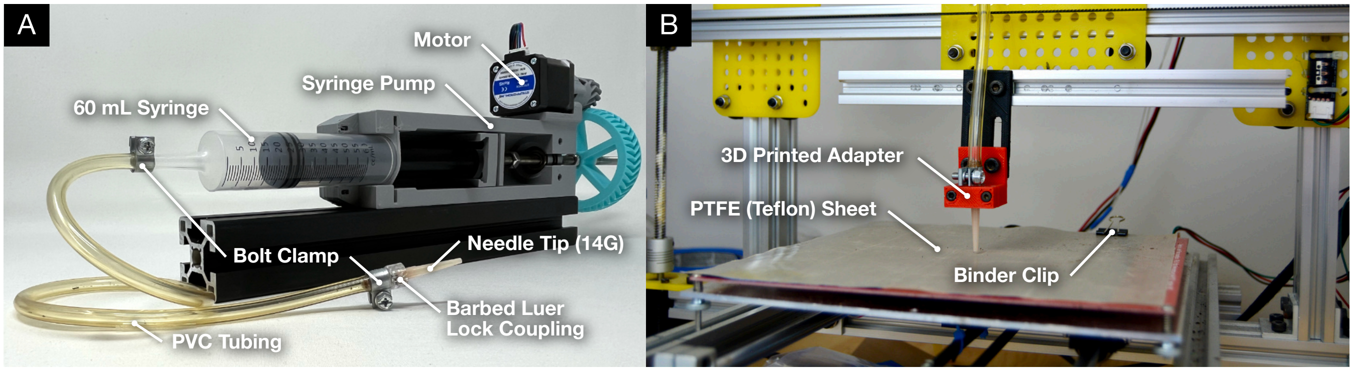

Figure 3: The extrusion set-up and components (A) used to print our SCG material on a modified FDM/FFF 3D printer (B).

4.2 3D Printer Set-Up

We modified a consumer-grade FDM/FFF 3D printer similar in design to a Prusa I3[8] to support printing the SCG material as seen in Figure 3. The SCG material is extruded from a syringe using an open-source large-volume pump [91]. The slip-end of the syringe is inserted into one end of PVC plastic tubing (5/32" inner diameter)[9]. The other end of the tubing is connected to a barbed luer lock coupling[10]. Both the syringe tip and the coupling are secured to the hose using bolt clamps[11]. Finally, the luer lock coupling is fitted with a 14 gauge (1.6 mm inner diameter) dispensing needle tip[12]. We experimented using needle tips that have smaller inner diameters (e.g., 16 and 20 gauge) but found these were more prone to clogging. The luer lock coupling and needle are mounted onto the x-axis of the printer using a 3D printed adapter (Figure 3B). We have open-sourced the designs of the adapter[13]. Finally, a PTFE sheet[14] is affixed to the surface of the printer's build plate using binder clips[15]. This allows printed objects to be relocated for drying so that the printer can be repeatedly used without delay.

4.3 Printing Parameters

Within our slicing software[16], the nozzle diameter is set to 1.6 mm to match the diameter of the dispensing needle. The layer height is generally set to 1.0 mm. The SCG material is printed at a speed (i.e., feed rate) of 300 mm min^{-1}. We slice 3D models with a solid infill (100%) and print with retraction disabled to maintain a consistent flow of the SCG material during printing.

4.3.1 Process of Choosing Printing Parameters. We used a trial-and-error approach to determine these different parameters. We set the feed rate by testing different extrusion speeds. Thermoplastics like PLA can typically be extruded around 3600 mm/min, while syringe-based pastes must be extruded more slowly to prevent the syringe pump's motor from skipping steps (i.e., jamming). Beginning with 1000 mm/min, we extruded 5 mm worth of the SCG material while listening for any "clicking" sounds from the syringe pump's motor (Figure 3A), which would indicate it was skipping steps. If the motor skipped steps, we decreased the feed rate by 100 mm/min and repeated the process until the motor could continuously extrude the SCG material without any issues. Our layer height was determined by extruding lines of 50 mm at varying layer heights ranging from 0.4 mm to 1.4 mm). We then examined each line for consistent extrusion. Though we can successfully print using layer heights as small as 0.8 mm, we opted to use 1.0 mm, reducing some feature resolution for faster printing times. In the next section, we characterize the properties of our SCG material to better understand how it can support sustainable prototyping.

5 MATERIAL CHARACTERIZATION

We were interested in understanding different aspects of our material and how they could support sustainable prototyping. This section provides a basic characterization of our SCG material consisting of its shrinkage during drying, tensile strength, dissolution in water, and compostability. For shrinkage, we demonstrate a strategy to mitigate errors in dimensional accuracy when the material dries. For strength, we compare SCG material to PLA. In our water dissolution test, we discuss the rate of dissolution and explore how to prevent dissolution using beeswax. Finally, we provide the results of a composting study that demonstrates that the SCG material can be composted at home.

5.1 Shrinkage Characterization and Mitigation

In our preliminary printing tests, we discovered that the SCG material was prone to shrinking as an object dried. This behavior is due to the evaporation of water from XG and CMC. We characterized this shrinkage behavior to determine a mitigation strategy. We printed five rectangular specimens (30 mm x 30 mm x 5.6 mm) with 100% infill. The specimens were left to air-dry for three days. We then recorded and averaged the length, width and height of each sample as seen in Figure 4A. The error in length, width, and height

[8]Prusa I3: https://reprap.org/wiki/Prusa_i3
[9]Tygon PVC Soft Plastic Tubing (5/32"" ID, 9/32" OD): https://www.mcmaster.com/6516t16
[10]Plastic Quick-Turn Tube Coupling (5/32" ID Barbed Tube): https://www.mcmaster.com/51525k274
[11]Bolt Clamps for Soft Hose (9/32" to 21/64" ID): https://www.mcmaster.com/53175K81/
[12]Dispensing Tip with Luer Lock Connection (14 Gauge Gauge): https://www.mcmaster.com/6699A1/
[13]https://github.com/utilityresearchlab/scg-3d-printing
[14]PTFE (Teflon) Sheet: https://www.amazon.com/dp/B009AYTYAO/
[15]Binder Clips: https://www.amazon.com/dp/B07DXSBT5J
[16]PrusaSlicer: https://www.prusa3d.com/page/prusaslicer_424/

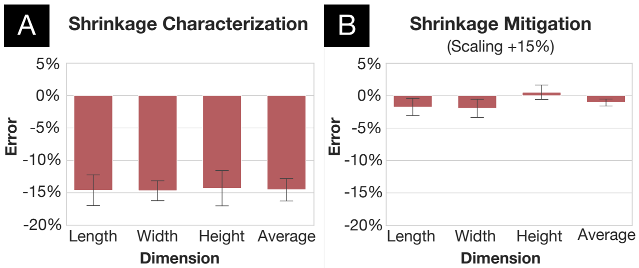

Figure 4: Shrinkage characterization and mitigation for our SCG material. The average error in dimensional accuracy for five printed specimens (30 mm x 30 mm x 5.6 mm) once dried is -14.53% (SD=1.94) (A). After uniformly scaling the geometry of specimens by 15.0% before printing, the average error in dimensional accuracy caused by shrinkage for five printed specimens reduced to -1.05% (SD=0.60).

are -14.61% (SD=2.64); -14.69% (SD=1.71); and -14.29% (SD=3.05), respectively. The average of these dimensions is -14.53% (SD=1.94).

As a shrinkage mitigation strategy, we examined applying a uniform scale factor (15%) to object geometry prior to slicing for printing. We scaled the rectangular geometry that was used for the characterization and printed five specimens (34.5 mm x 34.5 mm x 6.4 mm) with 100% infill. The specimens were left to completely dry for three days. We then measured the dimensions of the specimens and computed the percent error based on their expected values (30 mm x 30 mm x 5.6 mm) as seen in Figure 4B. The error in length, width, and height are -1.74% (SD=1.49); -1.95% (SD=1.57); and 0.54% (SD=1.24), respectively. The average error across all of these dimensions was reduced to -1.05% (SD=0.60). These results indicate a uniform scaling can greatly increase the dimensional accuracy of solid objects when printed with our SCG material. We use this strategy to mitigate shrinkage throughout this work.

5.2 Tensile Strength Characterization

We performed a tensile strength test according to ASTM standard D638-14 [25] using an MTS Exceed E43.504 Universal Testing Machine with a 5 mm/min crosshead speed (Figure 5). We used a 5 kN load cell for the PLA condition, and a 250 N load cell for the SCG material condition. For each condition, we printed five Type-I specimens [25] with 100% infill. We printed the PLA specimens using Prusament PLA filament [95] on a Prusa I3 MK3S+ [94]. We let the SCG material specimens completely dry for 48 hours. The results of the test are shown in Table 3. In the PLA condition (Figure 5A), the average tensile strength was 44.4 MPa (SD: 1.45). In the SCG material condition (Figure 5B), the average tensile strength was 0.62 MPa (SD: 0.42). Overall, the SCG material is considerably weaker than PLA, having approximately 1.4% of PLA's tensile strength. The SCG material is closer in magnitude to the tensile strength of non-reinforced concrete (i.e., 1 MPa to 5 MPa [6]). As we demonstrate in Section 6, this strength is suitable for basic prototyping.

5.3 Water Dissolvability and Prevention

In our initial investigations, we found that briefly exposing a dry SCG material object to water by pouring or submergence would moisten the surface of the object, but the object as a whole would maintain a solid shape and quickly air-dry once the water source was removed. This is largely because SCG is not water-soluble and makes up the majority of the material. To dissolve, water must penetrate the surface going between the SCG to dissolve the CMC and XG within the object. To better understand how susceptible our SCG material is to being dissolved, we performed a water dissolution test. We printed five rectangular specimens (25 mm x 25 mm x 5 mm) with 100% infill. The specimens were then left to completely dry for two days. Figure 6A shows our experimental set-up. To perform the test, we first recorded the mass (g) of each specimen. We then placed a beaker containing water (150 mm) and a magnetic stirrer (380 mm in length) onto a stirrer plate. The stirrer plate was then placed directly below a metal fixture. We then suspended a specimen from the top of the fixture using monofilament fishing line. The specimen was then placed inside the beaker approximately 20 mm from the bottom such that it was completely submerged in the water. We then set the stirrer rate to 600 RPM and ran the test for 30 min. After the time elapsed, we removed the specimen from the water and let it completely dry for two days. We then recorded the specimen's mass. Figure 6C and D show the results of the water dissolution test. Across the five specimens, the average loss in mass is 0.786 g (SD: 0.0329) and the average rate of dissolution is 0.0260 g/min (SD: 0.00119). At this rate, each of the specimens would completely dissolve in approximately 1.5 h when fully submerged in highly agitated water.

As a strategy to water-proof SCG material objects, we printed a sixth specimen (Figure 6C6) and coated it in beeswax[17], which is a natural and compostable material. After performing the dissolution test, we found no change in mass with this specimen. Thus, we suggest using this strategy with SCG material objects that are intended to continuously interact with water (e.g., to hold liquid).

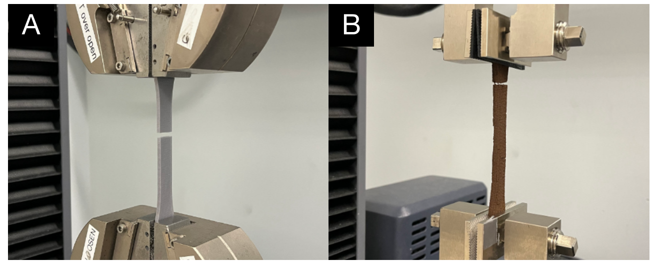

Figure 5: Experimental apparatus for the ASTM standard D638-14 tensile strength test comparing PLA (A) to SCG material (B).

Table 3: Tensile strength results for PLA and SCG Material.

Material	Average Tensile Strength (MPa, N=5)	Std. Deviation (MPa)
PLA	44.4	1.45
SCG Material	0.62	0.42

[17] Organic Beeswax Pellets: https://www.amazon.com/dp/B01LYMZK4V/

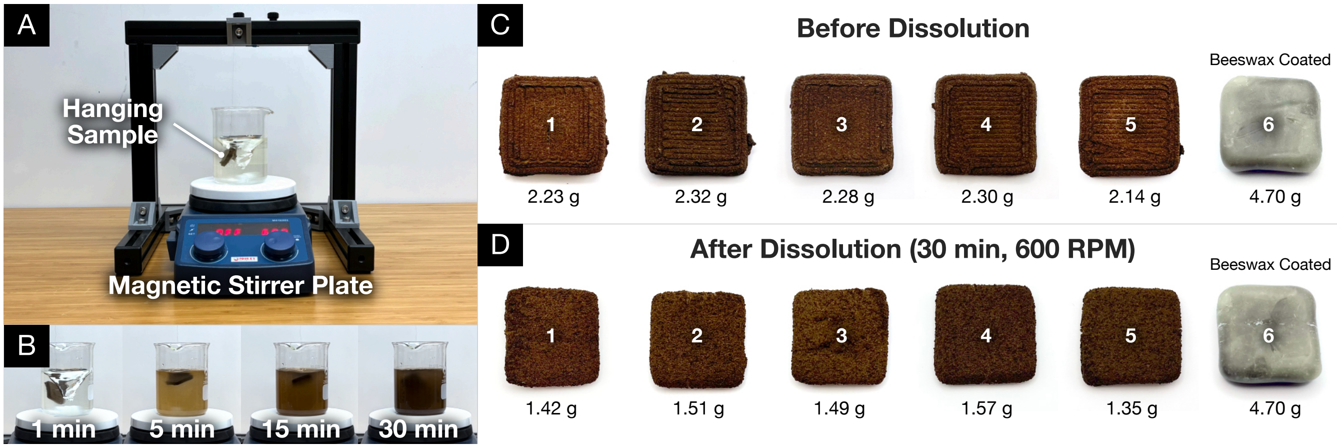

Figure 6: Water dissolution test set-up and results for six SCG material specimens. (A) An SCG material sample is suspended with monofilament fishing line inside a beaker containing 150 mL of water. (B) The water is agitated at 600 RPM using magnetic stirrer plate for 30 minutes to progressively dissolve the material. The visual quality and mass (g) of six specimens (five consisting of only SCG material and a sixth is coated in beeswax) before (C) and after (D) the test are shown.

5.4 Composting Study

Composting is the controlled decomposition of organic matter [22, 27, 122]. This decomposition is achieved by providing a rich environment for microorganisms to thrive. Both the growth of microorganisms and increased soil temperature relative to ambient temperature serve as indicators of the biodegradation of materials [22, 27, 122]. We examined the ability of our SCG material to decompose through an indoor home composting study. We opted for home composting (as opposed to industrial composting) to demonstrate that our material can be readily composted at home unlike thermoplastics commonly used in 3D printing.

We used a simple aerobic home composting approach [118, 119] as seen in Figure 7. This approach can process approximately 500 g of organic waste material (e.g., food scraps) per day that would otherwise be disposed of in landfills. We mixed coco coir[18] and horticultural ash[19] (biochar) in a 2:1 ratio into a cardboard box (29 cm x 29 cm x 43 cm) until the box was approximately two-thirds full. When inserting the material, we dug a hole in the center of the box, placed the material, and covered it up. The box lid was then closed, covered with a thin towel, and placed on top of wooden blocks to increase aeration. We also turned (i.e., mixed) the contents of the box every other day with a garden trowel[20] to increase aeration. The box was stored with an indoor temperature between 20 °C to 30 °C and away from excessive moisture (i.e., rain).

We set up a Raspberry Pi Zero[21] with an ambient temperature-humidity sensor[22] and a waterproof temperature sensor[23] to capture data from our compost box during the study. The ambient temperature-humidity sensor was mounted onto the lid inside of the compost box to provide baseline ambient temperature and humidity readings (Figure 7B). We used the humidity readings to ensure that our compost materials had optimal moisture content (40-60%) for promoting microbial growth [27]. The waterproof temperature sensor was placed into soil at the depth of the most recently inserted material (as seen in Figure 7C) to capture any increase in temperature resulting from microorganisms breaking the material down. The sensor readings for soil temperature, ambient temperature, and humidity were recorded at an interval of one minute throughout the duration of the study.

Across a three-week period, we performed five material insertions with a average SCG material mass of 62.98 g (SD=20.50) per insertion. The resulting average change in temperature after material insertion is shown in Figure 8A. Soil temperature consistently rose after each material insertion. In some cases, it rose approximately 10 °C higher than ambient temperature. The overall trend of increased temperature continued for more than 80 hours after a given material insertion. We also recovered a few small pieces of SCG material (approximately 10 mm to 15 mm in length). In contrast to our SCG material before composting, the pieces were brittle and showed significant mold growth as seen in Figure 8B. Both the growth of microorganisms and increased soil temperature relative to ambient temperature throughout our compost study indicate that our SCG material can be composted at home.

6 MATERIAL EXPLORATION

This section describes our exploration of SCG material informed by our characterization of its properties in Section 5. First, we explore how SCG material supports three sustainable prototyping workflows (summarized in Figure 9). For each workflow, we demonstrate an example object made with the material. Second, we show how SCG material can be used to support two common applications in HCI. These explorations are meant to demonstrate the SCG material's breadth of applicability. Each produced artifact is a

[18] Burpee Natural & Organic GardenCoir: https://www.amazon.com/dp/B078GQPRX4/
[19] Wakefield Biochar Soil Conditioner: https://www.amazon.com/dp/B077SWSPC4/
[20] Garden Trowel: https://www.amazon.com/dp/B01N297HU0/
[21] Raspberry Pi Zero: https://www.adafruit.com/product/3708
[22] DHT22 Temperature-Humidity Sensor: https://www.adafruit.com/product/385
[23] High Temp Waterproof DS18B20 Digital Temperature Sensor: https://www.adafruit.com/product/642

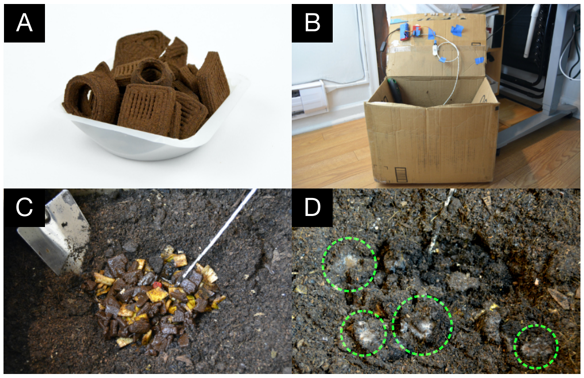

Figure 7: Composting of SCG Material. Objects made with our SCG material (A) can be inserted into a compost box at home (B) with other food scraps (C). Within a few days, microorganisms like mold grow and begin breaking the material down into compost (D).

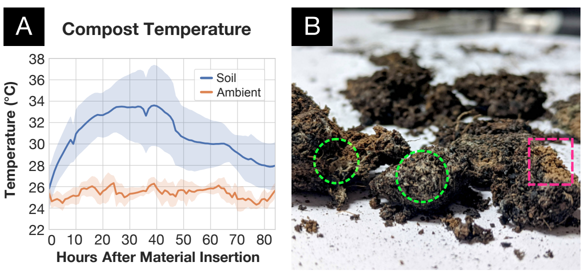

Figure 8: Compost Study Results. The average soil (blue) and average ambient (orange) temperatures for five SCG material insertions (A). The standard deviation of each temperature is depicted as the shaded region around each solid line. Soil temperature consistently rose above ambient temperature, indicating the material's decomposition by microorganisms. Pieces of SCG material recovered after 3 weeks of composting (B), distinguishable by the color of the coffee grounds (pink rectangular outline). Mold growth (green circles) indicates material decomposition.

proof-of-concept illustrating how the SCG material can be used for sustainable prototyping.

6.1 Sustainable Prototyping Workflows and Examples

6.1.1 Material Recycling for No-Waste Prototyping. Prototyping with 3D printing creates physical waste in the form of stale designs and failed prints. This can amount to over 30% of the plastic material used in a workshop [114]. In contrast, objects made from SCG material can be recycled back into printing material using a basic coffee grinder[24] during prototyping sessions (Figure 10).

[24]Krups Adjustable Burr Grinder (GX500050): https://www.krupsusa.com/BREAKFAST-APPLIANCES/COFFEE-GRINDERS/Adjustable-Burr-Grinder-GX500050/p/8000035582

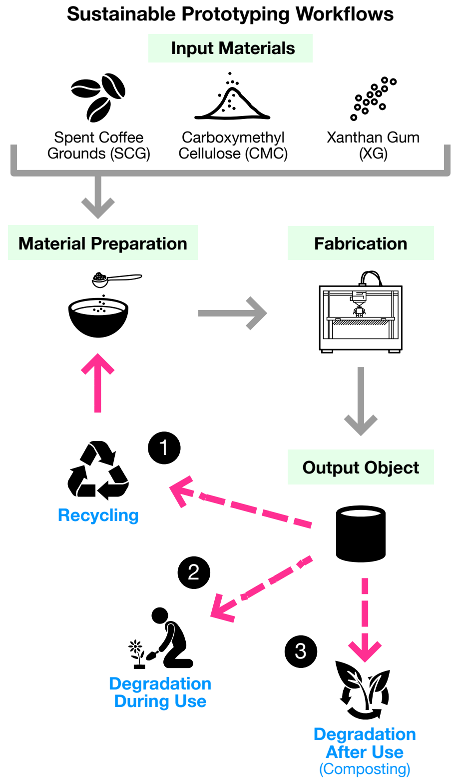

Figure 9: Overview of three sustainable prototyping workflows supported by our material. Printed objects can (1) be easily recycled at home to form new printing material; (2) readily biodegrade during their use when placed into soil; and (3) be composted at home.

As an example of this workflow, we prototyped an ornament necklace that went through 3 iterations of material reuse. In the first iteration, we explored the shape and logo of the ornament, producing a hexagonal object with two initials of one of the authors in the center. In the second iteration, we reused the material from the first prototype and other objects (Figure 10A) to re-make the ornament with a circular shape, an infinity symbol in the center, and a hoop region for tying a necklace. However, due to a gap in extrusion caused by an air bubble in our syringe (Figure 10E), the hoop of the second prototype was not printed fully closed. We recycled this object back into printing material to create the final prototype shown in Figure 11.

6.1.2 Degradation During Use. Objects made with bio-based materials can encapsulate their degradation as a design opportunity [26, 68, 113]. We explored how degradation can be part of an object's intended use. The components of our SCG material are all naturally biodegradable and have been shown to have positive effects in soil including increasing water retention [5, 14, 79] and promoting plant growth [19, 23, 40, 79, 100]. With these considerations in mind, our SCG material enables creating objects that are designed to beneficially decompose in soil over time. We created two custom-shaped

Figure 10: Material Recycling Workflow. Objects printed with our SCG material such as prototypes and failed prints (A) can be ground up using a basic coffee grinder at home (B). The resulting granules (C), once weighed, can then be mixed with a proportional amount of water (D) to produce our SCG material again for printing (E). This recycling approach is useful in minimizing waste when a printing error unexpectedly occurs such as a gap in extrusion (green circle).

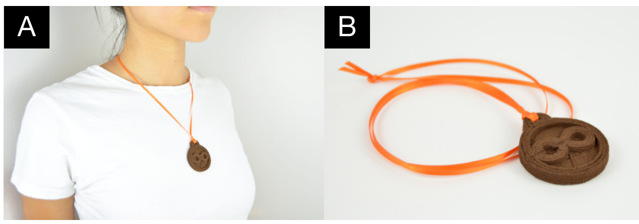

Figure 11: An ornament necklace (59 mm **x** 50 mm **x** 8 mm**) that was prototyped and re-printed three times with our SCG material (A). The ornament has a printed hoop for attaching a necklace and features the infinity symbol at its center (B).**

Figure 12: Planter pots printed with our SCG material and their flowering plants (A). The first pot (52 mm **x** 60 mm **x** 36 mm**) has a hexagonal-shape (B). The second pot (**48 mm **x** 49 mm **x** 40 mm**) is cylindrical with a ribbed pattern (C).**

planter pots to demonstrate this workflow (Figure 12). These pots serve as an initial home for small plants. Once the plants have sufficiently matured, they can be buried with their pots into soil to continue supporting their growth. In our case, we watered plants in these pots every other day for two weeks. Throughout the two weeks, the pots did not mold and maintained their overall form, only exhibiting slight cracking at their base.

6.1.3 Degradation After Use. Our SCG material enables objects to be readily biodegradable and compostable after their intended use, avoiding disposal in landfills entirely (as seen in Figure 7). To demonstrate this workflow, we created two custom-shaped single-use espresso cups (Figure 13). Inspired by Cradle-to-Cradle design [76],

Figure 13: Compostable espresso cups made from SCG material (A). The left cup is 57.8 mm **x** 57.8 mm **x** 55 mm **and the right cup is** 57.8 mm **x** 57.8 mm **x** 49 mm**. The cups hold liquid once beeswax is applied either on the inside of the cup (B, left) or around the cup entirely (B, right).**

the grounds of previously created espresso drinks serve as vessels for subsequent drinks. We coated the inside of these cups with beeswax to waterproof the cups during their use (as discussed in Section 5.3). Prior work [117, 133] has shown that a natural wax coating can slow biodegradation of an object (e.g., in soil). However, beeswax wax itself will biodegrade within 2 weeks [117]. Thus, beeswax does not compromise the overall biodegradability or compostability of SCG material objects (e.g., the espresso cups). Once a cup serves its purpose, it can be disposed of in a compost bin.

6.2 Exploring Applications in HCI

Alongside prototyping workflows, we explored how our SCG material could support sustainable prototyping in two common HCI applications: capacitive sensing [43] and shape-changing interfaces [92].

6.2.1 Biodegradable Capacitive Touch Sensors. Our SCG material is not conductive on its own. However, when combined with a biodegradable conductor (e.g., activated charcoal powder from coconut shells), the resulting mixture can be used to create capacitive sensors. We examined two ways to make capacitive sensors with our SCG material. Our first approach consisted of post-processing printed objects with a surface coating. After an object dried, we dipped a portion of the object into water and then applied charcoal powder[25] to the wet region. We used this approach to convert a hollow cube into a capacitive touch sensor (Figure 14A). As a second approach, we mixed charcoal power directly into our SCG

[25] Activated Charcoal Powder: https://www.amazon.com/dp/B077C7CCTK/

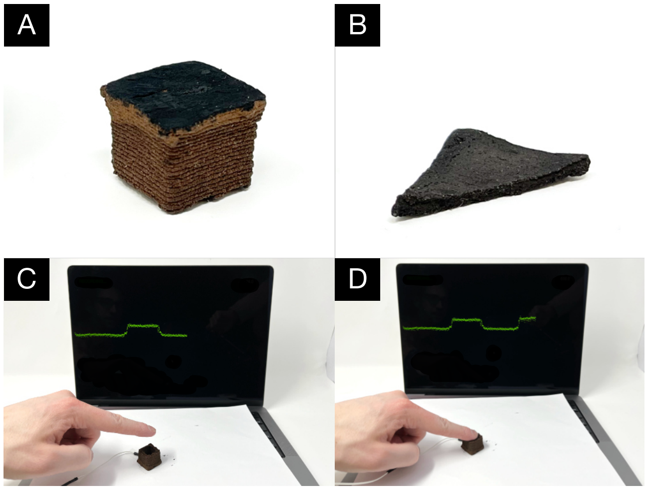

Figure 14: Two capacitive sensors made from the SCG material and activated charcoal powder: a hollow cube (A), and a cast triangle (B). The conductivity in the material provides touch-sensing capabilities as a finger touches the surface of an object (B,C).

Figure 15: Two objects printed with our SCG material that changed their shape as they dried: a flat square morphed into a saddle shape, and a rectangular rod bent upwards as a result of shrinkage during drying.

during our material preparation phase (Figure 14B). We used the same ratio of the materials as listed in Table 2 and added 2 g of activated charcoal charcoal. This mixture can then be printed or cast into different shapes to create capacitive sensors.

We tested our capacitive touch sensors by connecting a wire to the charcoal-coated region of their surface. The other end of the wire was connected to a 3 MΩ resistor and an Arduino Uno microcontroller[26]. Using the Capacitive Sensor Library[27], we were able to sense basic interactions like proximity and a touch gesture (Figure 14C-D). These sensors could be used for prototyping interactive artifacts that can readily biodegrade after their use.

6.2.2 Shape-Changing Interfaces. The HCI community has been increasingly interested in materials that can change their shape to convey information and support interactivity [4, 44, 92, 97, 127]. Throughout our material exploration, we observed that objects printed with SCG material could morph out-of-plane into different shapes as a result of shrinkage while drying (see more information in Section 5.1) (Figure 15). For example, when we printed a single-layer square, it morphed into a saddle. Similarly, a rectangular rod bent upwards while drying. Both of these objects suggest that further control over the shrinkage behavior of our SCG material could be used to create biodegradable shape-changing interfaces.

7 DISCUSSION

In this work, we sought to address gaps in sustainability and access considerations with previously proposed sustainable materials for 3D printing. In particular, we designed a material that avoided using thermal energy for processing and printing; and ensured that our material could be made, printed, recycled, and composted at home. At the same time, we codified our approach and experimentation activities to provide insights into a process that is difficult and typically not documented.

In this section, we reflect on our material, design process, and explorations to offer insights, challenges, and opportunities when pursuing sustainable materials and personal fabrication within HCI.

7.1 Reflection on Design Considerations

The design of our material was driven by two principles of Sustainable Interaction Design—linking invention and disposal and promoting renewal and reuse [17]. Alongside these principles, we also aimed to support more holistic and sustainable behavior within the context of 3D printing by following Stegall's design philosophy for sustainability [115]. Though these considerations ultimately provided useful guidance in creating a sustainable 3D printing material suitable for prototyping, our focus on these principles introduced challenges and constraints with our material's general use.

7.1.1 Revisiting SID. In our design process, we sought to link invention and disposal and promote renewal and reuse through the use of bio-based materials. Bio-based materials were ideal candidates for supporting these sustainability goals because these materials are inherently renewable, biodegradable, and compostable. However, at the same time, these materials can exhibit less controllable behavior in a 3D printing context when compared to engineered thermoplastics.

Engineered thermoplastics—like 3D printing filaments—are materials designed to have highly controllable behavior and properties [48]. Consequently, an end-user working with thermoplastics in 3D printing has more control over details (e.g., surface design) and can more readily anticipate how their object will appear once fabricated. In contrast, we found that we were not able to achieve the same level of quality with our SCG material. We often observed slight defects in the surface details of objects that we printed with SCG material. For example, the espresso cups had variations in layering (apparent in Figure 13A). While these imperfections had no impact on the overall function of the objects, they do indicate a decreased level of material control. Along similar lines, material shrinkage during the drying process (which we discuss more in Section 7.2.1) can potentially affect the outcome of an object. These occurrences can induce frustration for individuals hoping to use such a material over less sustainable alternatives.

We chose to focus on the two main principles of SID as its other principles are in support of promoting renewal and reuse over

[26] Arduino Uno: https://store.arduino.cc/products/arduino-uno-rev3
[27] Capacitive Sensor Library: https://github.com/PaulStoffregen/CapacitiveSensor

Table 4: Various applications in HCI rely on the material properties of different thermoplastic 3D printing filaments, many of which have no sustainable alternatives currently available as indicated by a dash symbol (–) above. This presents an opportunity for HCI researchers and designers to develop and explore new sustainable materials to support these applications.

Applications in HCI	Material Properties [2, 92, 111]	Thermoplastic Filament Examples [2, 111]	Examples of Sustainable Alternatives
Low-Fidelity Prototyping [80, 81]	Rigid	PLA, ABS, PETG	SCG Material, Oyster Shell [38, 134], Egg Shell [85]
Compliant Mechanisms [41, 49]	Flexible	TPU/TPE, Nylon	–
Time-Dependent Mechanisms [83]	Soluble	PVA	–
Touch Sensors [109]	Conductive	Conductive PLA	SCG Material + Charcoal
Haptic Input Devices [138]	Magnetic	Iron-PLA	–
Shape-Changing Interfaces [4, 127]	Shape-Change	PLA	SCG Material

invention and disposal [17]. However, we also considered how our design process might have changed if we incorporated another principle from SID: promoting quality and equality. This principle is described as a second-order design requirement of SID and can be considered a natural extension of our work. The principle of promoting quality and equality focuses on how to better motivate the longevity of the use of materials—as seen in the case of preserving family heirlooms [17]. However, this notion of the longevity of use falls into direct conflict with bio-based materials as these materials are inherently meant to biodegrade over time. We reflect that often SID principles can be in conflict with each other when we try to apply these principles at face value to all design contexts.

With every object, including ones that are 3D printed, it is critical to consider the object's intended use. For example, if we examine plastic containers often used for fruits like berries, their intended purpose is to be a vessel for transportation before the fruits are consumed. Yet, these plastic containers will long outlive the fruits themselves from a life cycle perspective. In such cases, a sustainable material like our SCG material could be more appropriate as a temporary container. Conversely, when the use of an object calls for longevity, it would make the most sense to create it from (ideally sustainable) materials that could last for generations. For instance, if we intended to preserve our ornament necklace as an heirloom, we should consider using a strong material like aluminum—which can be endlessly recycled [42]—rather than our SCG material. With a clear understanding of an object's use, we can better design it to support sustainability.

7.1.2 Revisiting Stegall's Design for Sustainability. According to Stegall [115], designing for sustainability requires a holistic approach that considers both a design product in addition to processes and services that can encourage widespread sustainability. Within the context of 3D printing and prototyping, we focused on how an individual could produce, use, recycle, and compost their material at home in a safe and sustainable manner. As such, in our design process, we prioritized the use of material components that are bio-based, non-toxic, and kitchen-friendly. We also relied only on common kitchen tools (i.e., a strainer, jars, and a coffee grinder) to process, mix, and recycle our material.

In reflecting on our material, there are other aspects that one can consider in regard to how approachable a material is. For example, the amount of time it takes a material to dry or solidify after printing can affect how easy the material is to use. Similarly, a material that shrinks in undefined ways as it dries can be a source of frustration. Both of these were challenges that we faced with our SCG material. However, we were able to mitigate shrinkage to a large extent by scaling objects prior to printing. Importantly, a source of frustration tied to sustainable materials could influence an end-user to opt for a less sustainable alternative. Future work is necessary to explore designing sustainable materials such that they can be on par with typical thermoplastics as well as to study the human factors related to using sustainable materials. This work should include studying individuals using sustainable materials to uncover challenges with their use and where flexibility might exist to design around people's expectations of these materials. In addition, because sustainable materials for 3D printing and prototyping are an emerging area of research and not as well-explored as traditional ones, there are likely to be unexpected obstacles that arise with their use. As such, documenting these challenges, as we have in this work, is crucial to support others in exploring this area and pushing toward the development of more approachable materials.

7.2 Trade-offs, Opportunities, and Insights with Sustainable Materials

In this work, we also sought to understand how a sustainable material might be integrated into prototyping workflows. Currently, the HCI community relies heavily on 3D printing for prototyping. A review of prototyping in the CHI community found that thermoplastic filaments (e.g., PLA, ABS, etc.) account for more than 30% of materials used in all prototypes [124]. Sustainable alternatives like our SCG material can support workflows like designing for degradation and material reuse. However, these materials can introduce challenges and come with functional trade-offs.

7.2.1 Comparing SCG Material to Thermoplastics. When prototyping with thermoplastic filaments, objects solidify rapidly as the plastic cools to room temperature. There is hardly any material shrinkage. Objects can be printed with overhanging parts (typically with a slope $\leq 45°$ relative to a previous layer of material). In addition, these objects tend to be very strong [111]. In contrast, objects made with SCG material take much longer to dry (e.g., a day); need to be printed on a relocatable substrate (e.g., a PTFE sheet) to avoid occupying the build plate; and tend to shrink as they dry. Large overhanging parts are difficult to print as previously printed layers are less supportive while not fully dry. Furthermore, objects made with SCG material are much more brittle and weak than their thermoplastic alternatives. With this in mind, the SCG material is not suitable for very strong loads (as evidenced by our strength characterization).

Table 5: Considerations when designing a sustainable material for 3D printing and prototyping.

Stage	Considerations	Purpose
Material Design	- Prioritize the use of bio-based/organic material components as they are generally non-toxic, renewable, biodegradable, and compostable	- This accounts for life-cycle considerations and link the material's invention and disposal
	- Prioritize the use of waste material components that are readily available	- To promote renewal and reuse by extending the life of existing materials that are also approachable
	- Prioritize material components that do not have an established reuse/recycling stream	- To maximize environmental benefits and avoid diluting existing reuse/recycling streams
	- Avoid material components that rely on thermal energy for processing or printing	- To minimize the largest negative environmental impacts associated with 3D printing
	- Consider commonly used food-based materials (e.g., xanthan gum, agar, flour) as binders	- These are typically bio-based and support approachability of the material (e.g., can be made and used at home)
	- Consider using water as a carrier fluid	- Support approachability
Material Printability	- Use Peanut Butter Test for Viscosity: Start with a large amount of structural material and gradually increase carrier fluid/binder to reach consistency of peanut butter	- Helps determine when the material mixture has a high enough viscosity (thickness) for 3D printing
	- Use Stirring Rod Test for Thixotrophy: If a material mixture holds its shape on a stirring rod, it is likely to be self-supporting and thixotrophic	- Helps determine when a material exhibits thixotrophic behavior suitable for layer stacking in 3D printing
	- If the structural material separates from the carrier fluid/binder during hand extrusion, add a small amount of a stabilizer (like xanthan gum) to the mixture	- Stabilizers prevent mixture separation and increase thixotrophic behavior
	- Extrude lines of the material mixture through a syringe by hand and allow them to dry; if the dried material crumbles upon handling, choose a different binder	- Ensures the material mixture binds properly and is not structurally weak
3D Printing Parameters	- Choose a nozzle with a diameter that produces consistent extrusion; a small diameter gives higher object fidelity but longer print times	- Ensures printability and emphasizes the trade-off between resolution and speed
	- Choose a layer height that gives consistent extrusion and the needed resolution for objects; larger layer heights result in shorter print times, but lower object fidelity	- Ensures printability and emphasizes the trade-off between resolution and speed
	- Choose the fastest feed rate that results in consistent extrusion without jamming the pump motor	- Ensures printability and minimizes print time

The amount of available material for printing is another point for comparison. With our current printer set-up, 60 mL of SCG material (1 syringe full) is enough to print either 2 flower pots, 4 infinity necklaces, or 1.5 espresso cups. This volume is approximately the equivalent of 25 m in length of a 1.75 mm diameter thermoplastic filament. Given that a 1 kg roll of thermoplastic filament has around 346 m in length of material [89], 1 syringe can only provide about 7% of the material found on a typical filament spool. As a result, our set-up is not ideal for mid-to-large scale objects much greater than the size of our example objects. Modifying the printer to use a valve-based pneumatic extrusion system would enable printing from a much larger container than a syringe, but would also add complexity to our printer modifications. Given these considerations, our SCG material works best for low-fidelity prototyping or when there is a need to create objects that are specifically designed to biodegrade.

7.2.2 Opportunities for New Sustainable Materials in HCI. Paste-based sustainable alternatives for 3D printing generally have similar limitations to our SCG material. These materials tend to have lower printing resolution; be more brittle; and be less strong compared to typical thermoplastic filaments [7, 85, 104, 106, 107]. Moreover, there is currently a lack of sustainable materials that can replace the variety of functional capabilities that different thermoplastic filaments offer for applications in HCI and prototyping as seen in Table 4. Current alternatives largely focus on replacing rigid materials like PLA. Beyond the explorations in this work, researchers have yet to uncover sustainable materials for 3D printing that are conductive, flexible, or magnetic. To move towards greater sustainability, we need to explore materials with functional properties beyond rigidity. At the same time, these materials might open new design opportunities. For example, we highlighted how our material could support sensing and exhibited shape-changing behavior in Section 6.2. Further exploring conductivity and shape-changing behavior with our material could enable creating impermanent devices that change their shape or sensing functionality as an indicator of their biodegradation. Such devices could support applications in HCI that extend to wildlife sensing and agricultural monitoring (e.g., in [117]) With HCI researchers continuing to develop and explore new smart and morphing materials [92], we believe there is a huge opportunity to design a new generation of materials that are functional, sustainable, support prototyping, and enable the creation of interactive devices.

7.2.3 Insights into Designing Sustainable Materials. Technical descriptions of sustainable materials are typically well-documented (e.g., in [34, 136]), but their design processes are often not. For example, online repositories like Materiom [75] enable individuals to explore and share material recipes. However, information about how and why different material components and printing parameters are chosen is generally not provided. The process of designing a material for 3D printing involves a lot of experimentation to find a suitable binder, tune material viscosity/thixotropy, and optimize various printing parameters. We approached each of these endeavors methodically and developed strategies to help simplify the process for others. We codified these considerations in Table 5. For example, one can use the "peanut butter test" to determine suitable viscosity for material printability. Through this work, we aim to lower barriers to innovation and inspire other HCI researchers and designers to create their own sustainable and approachable materials.

8 CONCLUSION

In this work, we introduced a material for 3D printing made from spent coffee grounds that closes sustainability and approachability gaps in existing sustainable material offerings. We described our design process and experimentation activities with the goal of aiding others in developing their own sustainable materials. We studied our material's properties to understand its utility for prototyping and its ability to be composted at home. We explored how our material could support sustainable prototyping workflows as well as applications in HCI. In reflecting on design process, we presented insights, challenges, and opportunities in pursuing sustainable prototyping and personal fabrication within HCI. Moving forward, HCI researchers and designers are uniquely positioned to create and explore interactive possibilities with such materials and more broadly enable sustainable material practices in prototyping and personal fabrication.

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