Abstract

As the HCI community continues to develop new materials for tangible interfaces, the way in which knowledge is disseminated has also expanded to more effectively communicate complex, embodied material experiences. Accordingly, we explore two goals in this pictorial: (1) to develop new sustainable biomaterials for 3D printing, thus extending the current library of materials for digital fabrication, and (2) to further the way the pictorial format is used to disseminate material knowledge by exploring alternative types of publications, specifically cookbooks. This cookbook discusses how to develop biomaterials for paste extrusion 3D printing by first introducing printability, usability, and sustainability as qualities that biomaterial recipes should strive to achieve. We then present ingredients, tools, and processes for working with biomaterials, followed by three exemplary biomaterial recipes made from sawdust, orange peels, and tree leaves. The cookbook closes with recommendations for adapting new biomaterials in the future.

Author Keywords

Biomaterials; Biodesign; Bio-HCI; Cookbook; Clay 3D Printing; Digital Fabrication; Materiality; Sustainability

CSS Concepts

- Human-centered computing ~ Interaction design;
- Social and professional topics ~ Sustainability.

How to Assemble this Pictorial

1. print one-sided copy of cookbook
2. cut the cover in half and fold the internal pages inward along dotted line
3. stack internal pages on top of each other in order and place the front and back covers on top and bottom
4. staple at designated spots to bind cookbook
5. adhere blank pages together (e.g., back of front cover to back of p1, back of p2 to back of p3, etc.) then read!

more extensive instructions can be found in our supplementary materials

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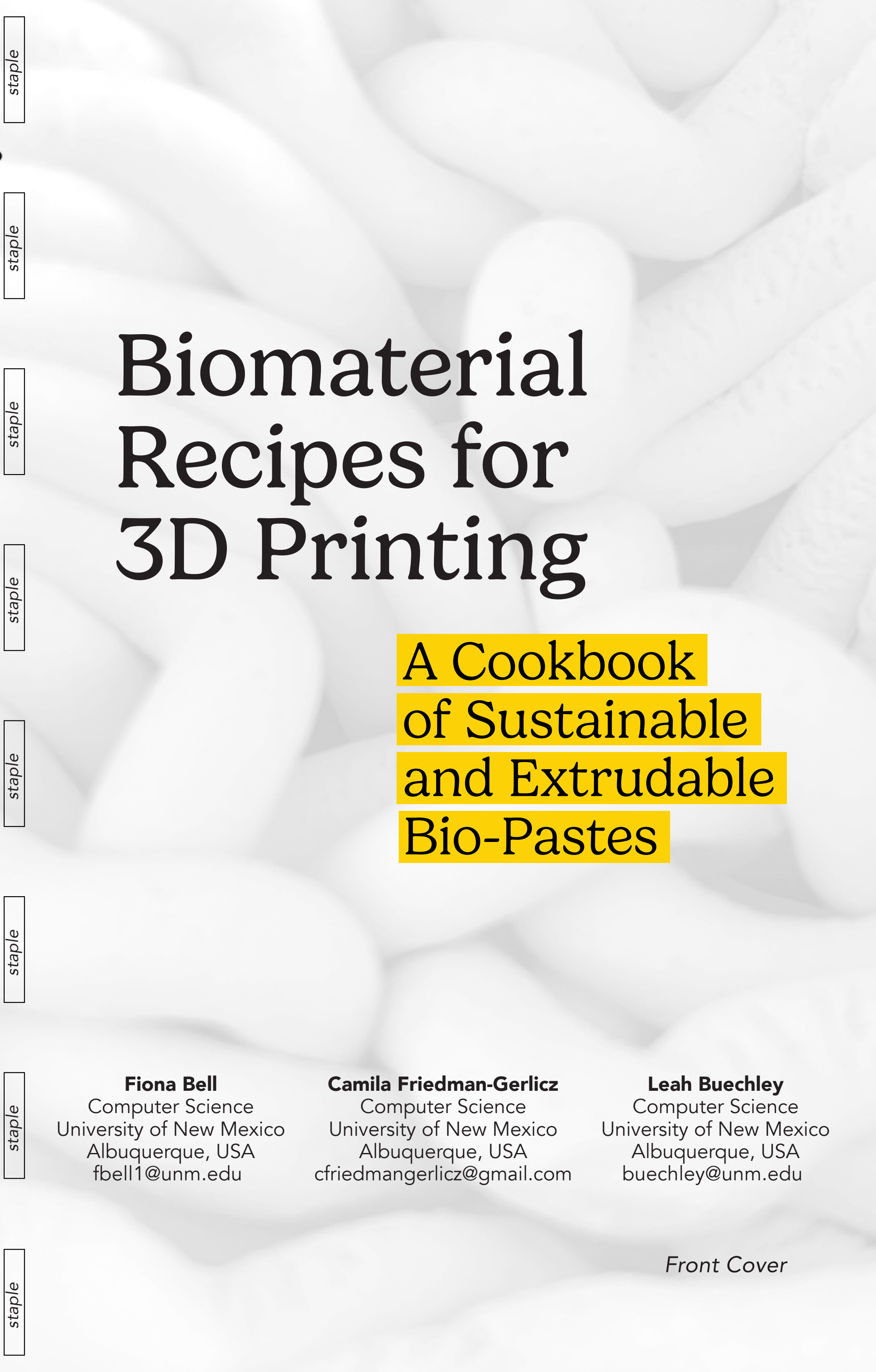
Back Cover



Biomaterial Recipes for 3D Printing

A Cookbook of Sustainable and Extrudable Bio-Pastes

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Front Cover

Contents

fold inward

Introduction

We are a team of human-computer interaction (HCI) researchers based in the arid desert of New Mexico, who have been developing biomaterials for the past 5 years and developing materials specifically for 3D printing for the past 2 years. Drawing on these experiences, we present this cookbook to build a deeper understanding within the HCI community of how to approach the development of sustainable biomaterials for 3D printing. This work by no means presents the "only" or "best" way to develop biomaterials, but intends to share our learnings from the past few years to support other practitioners in designing new materials that extend the options for sustainable 3D printing and tangible interfaces.

Why a Cookbook?

Cooking and science have entangled histories, with cooking being known as a form of practical chemistry [54]. Recipes and scientific protocols hold a high resemblance to one another, both including a list of required ingredients and tools, as well as a step-by-step procedure. Recipes/protocols act as a way for cooks/scientists to both disseminate their work as well as reproduce the work of others. Beyond reproducibility, however, the recipe/protocol can also act as a starting point which can then be flexibly adjusted and adapted to suit specific needs and requirements.

Cooking, ceramics, and biology communities have long used recipes as a format to communicate Do-It-Yourself (DIY) procedures for everything from baking soufflés [16] and formulating glazes [18, 33] to editing DNA [23, 47] and making bioplastics [24, 48, 53]. Inspired by the recipe as a tradition for sharing knowledge of physical practices, we utilize the cookbook format to present a collection of our own biomaterial recipes.

Just like a traditional cookbook, this pictorial is intended to encourage readers to engage in making our recipes and adapting new recipes of their own. Through these recipes, we hope to communicate embodied material knowledge that can be lost through other forms of written dissemination. In doing so, we align ourselves with other HCI researchers engaged in academic publishing that utilizes the pictorial format "as a platform for sharing activities and modes of representation that can scaffold craft knowledge" [22] by employing more instructional, interactive, and creative methods for imparting material knowledge [19, 20, 26, 36, 62, 84].

We intend for this cookbook to be printed out and assembled so that it can live beyond traditional academic settings in makerspaces, kitchens, and creative labs—acting as a practical 'how-to' guide for making biomaterials for paste extrusion 3D printing.

Sustainable Biomaterials in HCI

With rising demands for physical goods such as consumer electronics, fashion, and homeware, it is now more imperative than ever to consider sustainable modes of making, using, and disposing. Within the field of HCI, design researchers have begun developing methods and materials for the circular design and disposal of goods [12, 50]. Methods of unmaking [71] such as upcyling, repairing, and disassembling have introduced new design workflows that encourage the continued use of existing material goods like electronics [42, 44, 52], textiles [49, 83], and 3D prints [73, 79]. Beyond these methods, new biodegradable materials have been developed to promote ecological regeneration [17, 41].

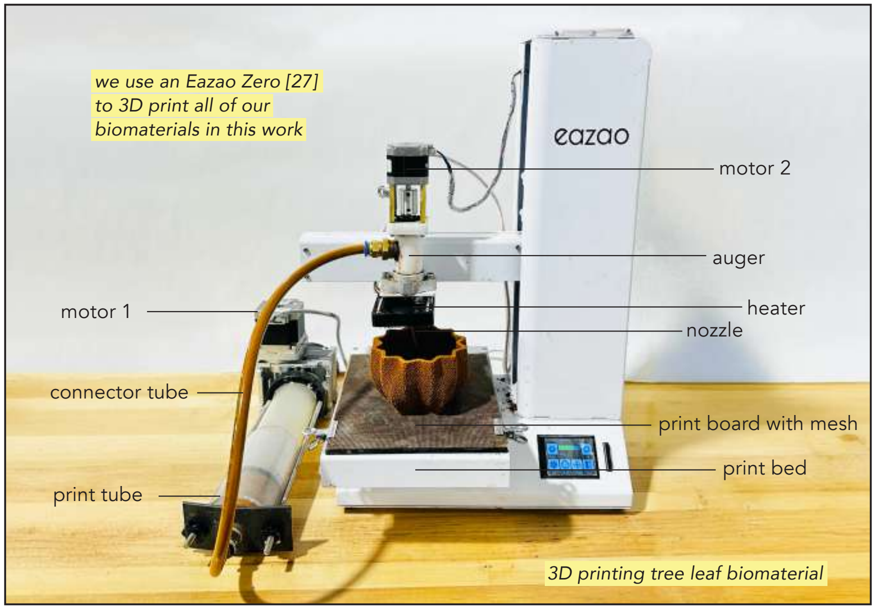
Biodegradable materials are most commonly referred to as biomaterials—materials derived from biological sources that biodegrade naturally when disposed of in the environment [11]. Popular biomaterials include mycelium [32, 34, 77, 81], algae [4, 45, 74, 86], microbial cellulose [7, 8, 58-60], plants [15, 38, 71], and food waste [10, 68], which have been used as sustainable alternatives to plastics, fabrics, foams, concretes, and clays. In this cookbook, we present a collection of clay-like biomaterials designed specifically for paste extrusion 3D printing.

Due to the increasing popularity of 3D printing as a method for fabricating beautiful objects with forms, textures, and computational meaning that cannot be achieved by hand, we present sustainable biomaterial alternatives to traditional materials for 3D printing, namely plastics. Polylactic acid (PLA) and Acrylonitrile Butadiene Styrene (ABS) are the most commonly used printing materials. While PLA is bio-based it does not naturally biodegrade in the environment, instead requiring commercial composting systems [46]. Meanwhile, ABS is derived from petroleum and cannot biodegrade when disposed of [61]. Moreover, PLA and ABS are notoriously difficult to recycle [37]. In contrast, our biomaterials are derived from renewable bio-waste streams, readily biodegrade when disposed of in the environment, and are easily recyclable. As such, these biomaterials enable a more sustainable avenue for 3D printing.

Previous biomaterials developed for 3D printing have been made from spent coffee grounds [68], corn and wheat flour [14], pecan shell flour [28], mussel shells [69], and bamboo fibers inoculated with mycelium [70]. We add three new biomaterial recipes—based on sawdust, orange peels, and tree leaves—to this growing library, as well as a broader set of considerations and methods regarding DIY biomaterial development to promote more widespread use of sustainable materials for 3D printing.

3D printed sawdust biomaterial

Paste Extrusion 3D Printing



3D printing tree leaf biomaterial

We design all of our biomaterials for paste extrusion 3D printing. Also known as Direct Ink Write (DIW or DW) printing or Robocasting [63], this additive fabrication technique builds objects by extruding material in layers. Instead of extruding a filament like PLA or ABS, we use printers that extrude paste-like materials. This approach has been widely used to print clays [13, 21, 30], foods [43, 51, 56], and hydrogels [31, 55, 65].

We print our biomaterial recipes with a low-cost commercial paste extrusion desktop printer called the Eazao Zero [27]; which resembles other printers such as the PotterBot [66], WASP [80], TRONXY [75] and Lutum [78].

To print with the Eazao, we load the print tube with a given biomaterial. Motor 1 then turns a plunger that pushes the biomaterial through the print tube and connector tube into the print head. Motor 2 turns the auger mechanism within the print head, which pushes the biomaterial out of a 1.5 mm inner diameter nozzle at an extrusion rate of 0.7 mm/mm. The biomaterial is then printed at a speed of 1000 mm/min onto a small wooden board lined with a mesh fabric to enable the easy removal of printed objects from the print bed. As the biomaterial is extruded, it is partially dried by a custom heater system we built that fits around the nozzle.

To control the Eazao, we upload .gcode files designed in Rhino 3D and Grasshopper. We employ open-source software developed by the HCI community for clay 3D printing such as WeaveSlicer [30], CoilCam [13], and Extruder Turtle [64].

Qualities

To develop a biomaterial that is printable (i.e., can be reliably extruded by the printer), usable (i.e., results in a final printed object of high quality), and sustainable (i.e., is derived from renewable sources and degrades naturally in the environment), we identify 10 separate, yet interdependent qualities that recipes should consider. We identified these qualities by first reviewing related literature, notably taking inspiration from Duty et al.'s technical overview of material characteristics for 3D printing [25]. We further surfaced and refined these qualities through our personal recipe development process; selecting final qualities that best guided us in choosing appropriate ingredients and ingredient ratios. Each quality is paired with recommended properties, measurements and tests to gain insight into how the biomaterial aligns with the given quality.

Printability

To achieve a printable biomaterial, its rheology is the biggest consideration. Rheology is the study of how matter deforms and flows when subjected to an applied force [3], which, in our case, describes how the biomaterial flows through the 3D printer. Several qualities play into the rheology of a material, we look at the rheological characteristics of our biomaterials through the qualities of cohesion, hardness, flow, and stability.

Cohesion. The biomaterial forms a uniform paste with no clumps and a consistent texture that holds together by not being too wet or too dry. Test cohesion by looking at and feeling the biomaterial paste. We recommend grinding and sieving all ingredients to a small size before mixing for cohesion.

Hardness. The biomaterial paste is soft enough that it can be pushed through the printer, but hard enough that it is stable on the print bed. Test hardness through feel and with a penetrometer [14]. We aim for hardness penetrometer values between 0.2-0.3 kg/cm^2.

Flow. The biomaterial paste has shear-thinning rheological flow behavior, meaning that it behaves more like a liquid when force is applied and more like a solid when force is removed [57, 85]. Test flow by extruding the biomaterial paste with a hand-held syringe and/or with the 3D printer. We recommend looking for a cohesive paste that requires minimal force to extrude.

Stability. The biomaterial paste is stable on the print bed once extruded, allowing layers to build up on top of each other without collapsing. Test stability by observing how the biomaterial paste holds up as an object is printed. We recommend checking stability by observing how basic cylinders are printed. Find our cylinder .gcode file in supplementary materials.

Usability

To achieve a usable biomaterial, it must dry in a predictable way and lead to a durable object. Shrinkage can be the largest issue; drastic shrinkage can result in biomaterial objects that do not resemble the initially designed form and that are not structurally sound.

Predictability. The printed biomaterial object resembles the designed model, meaning the object does not crack or distort dramatically during drying. Test predictability by observing how a complex form dries and by calculating the shrinkage rate, which is the relative change in size of the object [9]. We recommend observing a how a complex vessel dries and measuring the shrinkage of cylinders in both height and diameter. Find our cylinder and vessel .gcode in supplementary materials.

Durability The printed biomaterial objects is structurally durable, meaning it can be reasonably applied to real-world use cases without breaking, crumbling, or falling apart. Test durability through measuring strength and observing objects in-situ over time. While there are many types of strength, we recommend testing compression strength by following ASTM C773 [1], the standard test method for uniaxial compressive strength of clay materials using a universal testing machine.

Sustainability

To achieve a sustainable biomaterial we select bio-based ingredients and examine modes of circular disposal via recyclability, dissolvability, and biodegradability.

Biobased. The ingredients that make up the biomaterial recipe are grown and derived from renewable, biological sources such as plants, animals, and fungi.

Recyclability. The dried biomaterial, including print waste, failed prints, and no longer wanted objects, can be transformed back into a printable paste. We recommend checking recyclability by grinding up dried biomaterial into a powder and rehydrating it into a printable paste [14].

Dissolvability. The biomaterial breaks down into non-toxic biomass in a water environment. Test dissolvability by submerging a printed biomaterial object in water and observing it over time [68]. We recommend observing the disintegration of a biomaterial tile in room temperature water. Find our tile .gcode in supplementary materials.

Biodegradability. The biomaterial breaks down into non-toxic biomass, carbon dioxide, and water when disposed of in a composting system or the natural environment. Test biodegradation by observing the sample assimilate into the environment and/or measuring the mass loss of a biomaterial over time [6, 7, 72]. To be considered compostable, the biomaterial must biodegrade 90% in less than 180 days, in a composting environment [2]. We recommend following a DIY version of ISO 16929 [29], the standard method for testing the disintegration of a given material within soil, where we observe a printed biomaterial tile biodegrade. Find our tile .gcode file in supplementary materials.

Ingredients

Guided by our past experiments and our qualities for printability, usability, and sustainability, we identified ingredients that we found were necessary to make biomaterials that suited our requirements. We categorize these ingredients into four core groups (fillers, stabilizers, binders, and liquids), as well as two additional groups of optional ingredients (pigments and post-printing ingredients). We note that this is just a starting point to understand what goes into a biomaterial and can be adjusted and expanded upon in the future.

Core Ingredients

Fillers. Solid ingredients that the biomaterial primarily consists of, the ingredient that volumetrically fills up the most space. Fillers can be mineral or cellulose-based. Given the wide range of ingredient options, the filler has the greatest impact on the final characteristics of the biomaterial: texture, color, smell, shrinkage, density, strength, etc. Fillers must be combined with a specific ratio of stabilizers, binders, and liquids to achieve the necessary printability and usability. We use different cellulose-based fillers sourced from local waste streams for each recipe.

Stabilizers. Non-absorbent ingredients that provide stability and predictability to the biomaterial. Most stabilizers are mineral-based. They are crucial for minimizing shrinkage, thus usability. Bio-based stabilizers are grown from bones, shells, and eggs. Non-bio-based but biodegradable binders include sand and dirt. We use eggshells in all of our recipes as a readily available, bio-based stabilizer.


harvesting eggs from local chicken coops


sawdust from a local furniture artist's woodshop


dirty eggshells sourced from local restaurant


orange peels from our personal consumption


washed eggshells


collecting cottonwood leaves on our university campus


ground eggshell powder

Our recipes present ingredients in terms of their weight for easy reproducibility. However, when developing recipes, we look at ingredients in terms of their volume, especially when identifying the ratio of fillers to stabilizers and dry ingredients to liquid ingredients. While our recipes show that we have more stabilizer by weight, our recipes are primarily filler by volume. This is due to our fillers being less dense than our stabilizers. Meanwhile, all of our recipes have a volume ratio of approximately 100 parts dry ingredients (fillers, stabilizers, and binders) to 80 parts wet ingredients (liquids).

Binders. Absorbent ingredients that bind the filler and stabilizer ingredients together. Binders are required to achieve a cohesive biomaterial paste, with shear-thinning flow behavior. Common bio-based binders include wheat flour, gelatin, agar, alginate, methylcellulose, and xanthan gum. We use a combination of methylcellulose (a powder derived from plant cellulose) and xanthan gum (a powder derived from fermented sugar).

Liquids. Ingredients that transform all the dry powders into a cohesive, wet biomaterial paste. Water is required to activate binder ingredients, however, other liquid ingredients can be employed. For instance, we experimented with oil to improve predictability and vinegar as a preservative.

methylcellulose


water

xanthan gum


vegetable oil

Optional Ingredients

Pigments. Ingredients such as turmeric, beetroot, and activated charcoal that can be added in small quantities to change the color and/or the conductivity of the biomaterial without impacting the biodegradability or bio-based quality.

Post-Printing. Ingredients that are added to the printed biomaterial object to achieve specific qualities and aesthetics, such as coating the object with beeswax for waterproofing or vegetable oil to give a shine.

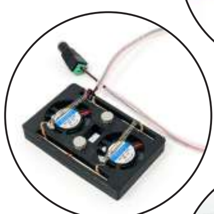
Tools

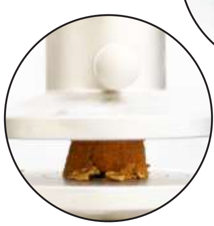
Beyond the required measuring equipment, mixing bowls, stirring utensils, and paste extrusion 3D printer, we identify the following optional tools that can assist in working with these biomaterials.

Specialized Equipment









Grinder. Grind large ingredients to a smaller particle size to ensure the biomaterial paste is cohesive in texture. Electric blenders and coffee grinders are the most efficient, but a mortar and pestle can also work.

Sieve. Use a mesh sieve to get all the ingredients to a small enough particle size for easy extrusion. We use a sieve with a mesh size of 60, which results in particles that are 250 microns in size. The maximum printable particle size is determined by the size of nozzle used when printing.

Stand Mixer. Make large batches of biomaterial quickly and easily by mixing ingredients in an electric stand mixer.

Penetrometer. Measure the hardness of the biomaterial paste before printing it with a hand-held fruit firmness penetrometer. We aim for a hardness between 0.2-0.3 kg/cm^2.

Heater. We use a custom heater that sits around the nozzle of our printer to improve stability of the biomaterial on the print bed. The heater is made up of two fans that blow air across two coils of nichrome heating wire. Find instructions for how to make this open-source heater in our supplementary materials.

Dehydrator. A food dehydrator set to 130°F (55°C) can be used to quickly and evenly dry printed biomaterial objects.

Universal Testing Machine. To test the strength of printed biomaterials, use a universal testing machine. A 50-kilonewton force load cell, at a 10 mm/min rate provides reliable results.

Process

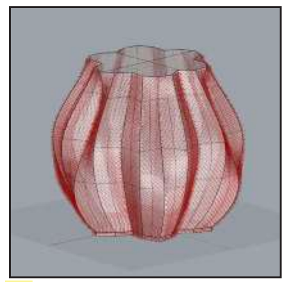
Making Recipes

1. select recipe

2. prepare all tools and ingredients

3. combine ingredients into a cohesive paste

Printing Recipes



4. design and slice model, then upload .gcode to 3D printer

5. fill print tube with biomaterial paste

6. prepare printer by attaching print tube and setting up print bed

7. print model

8. remove printed object from print bed and let it dry

9. once completely dry, use finished object

Sawdust Bio-Paste

Not your typical wood 3D printing! Unlike wood PLA that has the qualities of plastic, this sawdust recipe looks, feels, and behaves like wood.

Recipe

- 25.0 g sawdust
- 34.0 g eggshells
- 1.75 g methylcellulose
- 1.00 g xanthan gum
- 15.0 g vegetable oil
- 85.0 g water

Preparation

1. sieve sawdust to 60 mesh, sawdust waste from sanding is ideal
2. mix sawdust with eggshell powder, xanthan gum, methylcellulose, water, and vegetable oil to form ~75 mL of a cohesive paste
3. print, dry, then use sawdust object

makes one serving size = ~75 mL (1/3 cup) of bio-paste

sawdust

grind + sieve into powder

mix into paste

print object

3 serving sizes

Qualities

shrinkage in height = 6.95%
shrinkage in diameter = 5.28%
strength = 2.23 ± 0.30 MPa
recycle: 50 g biomaterial to 34 g water
dissolve: ~104 hours in water
biodegrade: ~90 days in soil

Notes

This recipe uses a volume ratio of 75 parts sawdust (filler) to 25 parts eggshells (stabilizer). Fine sawdust from sanding was collected from a local furniture artist's woodshop. The sawdust consisted primarily of hardwoods like oak, cherry, and walnut. We imagine the recipe having to be slightly altered to support sawdust from softer woods like fur and pine, or woodflour, which is made from pulverizing dried wood. Of our three recipes, this one has the lowest shrinkage and is the least dense when dried. It also takes the longest to dissolve and biodegrade. Biodegradability was tested using local soil from Albuquerque, NM in a dehydrator set to 130°F (55°C). Environmental factors will impact results.

Orange Peel Bio-Paste

This fun and fresh recipe is perfect for when you have a citrus craving! Instead of throwing away your orange peels, transform them into this recipe.

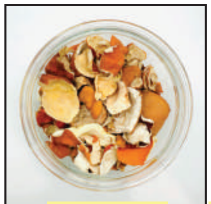
Recipe

- 21.0 g orange peels
- 60.0 g eggshells
- 3.40 g methylcellulose
- 1.00 g xanthan gum
- 85.0 g water

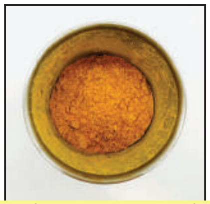
Preparation

1. dehydrate orange peels, grind them into powder, and sieve the powder to 60 mesh
2. mix orange peel powder with eggshell powder, xanthan gum, methylcellulose, and water to form ~75 mL of a cohesive paste
3. print, dry, then use orange peel object

makes one serving size = ~75 mL (1/3 cup) of bio-paste



orange peels



grind + sieve into powder

mix into paste

print object

3 serving sizes

Qualities

shrinkage in height = 10.1%
shrinkage in diameter = 7.91%
strength = 2.24 ± 0.33 MPa
recycle: 50 g biomaterial to 26 g water
dissolve: ~72 hours in water
biodegrade: ~60 days in soil

Notes

This recipe uses a volume ratio of 60 parts orange peels (filler) to 40 parts eggshells (stabilizer). Orange peels were sourced from our personal consumption of mandarin and navel oranges. The peels had to be dehydrated before being ground and sieved to size. In the future, we imagine exchanging orange peels for lemon, lime, or grapefruit skins to get a colorful variety of citrus-based recipes, however, differences in the pith will impact the recipe. Of our three recipes, this one dissolves and biodegrades the fastest, while also being the most dense when dried. Its shrinkage rate falls between the sawdust and tree leaf recipes. Biodegradability was tested using local soil from Albuquerque, NM in a dehydrator set to 130°F (55°C). Environmental factors will impact results.

Tree Leaf Bio-Paste

Be-leaf us when we say you will want to try this recipe! Made from fallen tree leaves around the city, this recipe is best created during the autumn.

Recipe

- 49.0 g fallen tree leaves
- 34.0 g eggshells
- 2.20 g methylcellulose
- 1.30 g xanthan gum
- 15.0 g vegetable oil
- 60.0 g water

Preparation

1. dehydrate leaves (if not already dry), grind into powder, and sieve powder to 60 mesh
2. mix tree leaf powder with eggshell powder, xanthan gum, methylcellulose, and water to form ~75 mL of a cohesive paste
3. print, dry, then use tree leaf object

makes one serving size = ~75 mL (1/3 cup) of bio-paste

tree leaves

grind + sieve into powder

mix into paste

print object

3 serving sizes

Qualities

shrinkage in height = 13.3%
shrinkage in diameter = 8.80%
strength = 2.27 ± 0.32 MPa
recycle: 50 g biomaterial to 32 g water
dissolve: ~82 hours in water
biodegrade: ~75 days in soil

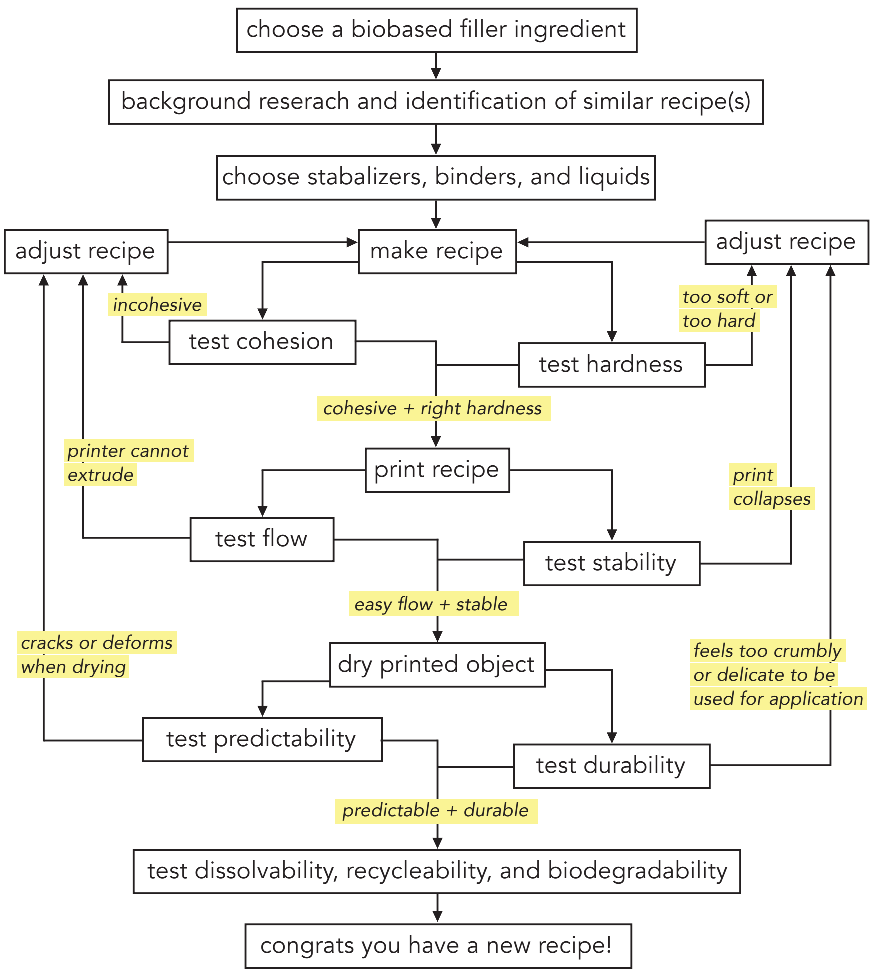
Notes

This recipe uses a volume ratio of 70 parts tree leaves (filler) to 30 parts eggshells (stabilizer). Tree leaves were sourced primarily from cottonwood trees around our university campus and apricot trees from our backyards. Our leaves resulted in an orange-colored biomaterial, but we see a colorful palette of biomaterial being developed from different tree leaves. The type of tree leaf and the amount of time the leaves have been decaying on the ground will impact the recipe. Of our three recipes, this one has the highest shrinkage, but falls between the sawdust and orange peel recipes in terms of density, dissolvability, and biodegradability. Biodegradability was tested using local soil from Albuquerque, NM in a dehydrator set to 130°F (55°C). Environmental factors will impact results.

Adapting Recipes

Developing a new recipe is no small task as it requires significant amounts of research, testing, and iteration. To make the process more approachable, we outline our workflow for adapting recipes. We note that this is the process we followed; it is not optimized for any one quality (e.g., durability, predictability, etc.), but has led to reliably printable, usable, and sustainable recipes that mostly reflect the filler ingredient. As such, this workflow is a starting point that can be adjusted to optimize for specific qualities or user needs. We complement this workflow with other considerations and recommendations for adapting recipes.

Recipe Adaption Workflow



Guidance from Failures

Our recipe adaption workflow relies on understanding "failed" recipe iterations in terms of our qualities. For example, a recipe that is too soft or too hard would be a hardness failure. The simple fix for this failure is to adjust the amount of liquid.

In contrast, an unstable recipe (i.e., a recipe that lacks structural stability and/or lacks a high print quality once extruded) is much more complex. It requires fine-tuning of all ingredients, but often depends on the amount of binders. In our recipes, this requires finding an appropriate ratio of methylcellulose to xanthan gum. This becomes even more complicated when considering flow, which is also often dependent on the binders. It is key to find a recipe that is shear-thinning (i.e., it flows like a liquid when force is applied and acts like a solid when force is removed). Xanthan gum is good at enabling flow, while methylcellulose improves stability.

Finding a balance between predictability and durability was also a complex process. Our stabilizer, eggshells, reduces the durability of printed objects. However, if we do not incorporate any stabilizer, printed objects are subject to significant shrinking, deformation, and cracking.

We also came across more unique "failures" that are not entirely captured by our workflow. For example, some orange peel objects began to grow mold due to slow, room-temperature drying. While the moldy objects are considered unusable from a human perspective, the mold indicated that the recipe is likely to biodegrade rapidly and can serve more-than-human purposes [5, 6].


unstable leaf recipe iteration that needed a different ratio of binder ingredients


unpredictable orange peel recipe iteration that did not have any stabilizer


print that grew mold

Ingredient Exchanges

Anyone who cooks or bakes knows that ingredients cannot always be exchanged (e.g., salt is not a substitute for sugar). Exchanging mussel shells for eggshells, grapefruit peels for orange peels, or carboxymethylcellulose for methylcellulose is not going to be an exact 1 for 1 replacement. However, we see our recipes acting as a solid starting point that can be finely tuned when making these ingredient exchanges. More drastic changes to the ingredients, such as using potato skins, banana peels, or straw as the filler ingredients will require significantly more adjustment to find an appropriate ratio of stabilizer, binder, and liquid ingredients. Along these lines, filler ingredients can also double as stabilizer ingredients or binder ingredients. For example, it is possible to use eggshells as both the filler and stabilizer or wheat flour as the filler and binder. Regardless, one of our recipes can still be used to at least kickstart the recipe adaption workflow.

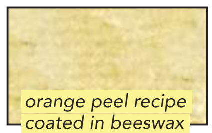
New ingredients also might entail new methods as well. For example, to use agar or gelatin as a binder ingredient, they need to be combined with water and brought to a boil to activate their geling properties. These changes in the ingredients will dramatically change the making process.

Adding optional pigment ingredients such as turmeric or activated charcoal powders to adjust the color and/or electrical conductivity of the biomaterial also might require the recipe to be slightly adjusted; for example adding more water to balance out the incorporation of more dry ingredients. Post-printing ingredients like coating the biomaterial object in beeswax or oil typically have no impact on the recipe, but can change the final aesthetics and qualities.


using dehydrated green tree leaves instead of yellow and orange leaves


using wood flour instead of woodshop sawdust


orange peel recipe with no coating


orange peel recipe coated in beeswax


a recipe in progress that uses eggshells as both the filler and binder

Quality Optimization

We developed our three recipes with the qualities of printability, usability, and sustainability in mind. However, we did not optimize for any of these qualities; instead, we tried to find a balance between them. Because of this, our recipes face certain limitations that we need to account for when it comes to applications. In the future, users might strive to optimize recipes for a specific quality to suit an intended application.

For example, our recipes have notable shrinkage. While the shrinkage of these recipes does not lead to dramatic cracking or deformation of printed objects, we need to account for the amount the object will shrink and design models accordingly. Another solution can be to adjust the recipe by increasing the amount of stabilizer and decreasing the amount of filler to obtain a more predictable recipe with less shrinkage. However, increasing the stabilizer in a recipe will cause the biomaterial to lose some of the aesthetics and properties dictated by the filler (e.g., the orange peel recipe will look more white than orange).

Durability is another limitation of our recipes. While the strength is appropriate for household objects like plant pots and knick-knack bowls, these recipes would not be strong enough to survive being dropped on the ground or bear enough load for furniture or architectural purposes. Increasing the particle size of the ingredients (especially of the stabilizer) could improve strength and reduce shrinkage, as seen with clays and concretes [66]. In some cases, the user might want to optimize for durability, while not constraining themselves to using only bio-based ingredients, in which an ingredient such as white glue (a synthetic resin made of polyvinyl acetate) might be utilized as another binder ingredient to increase strength, as seen with Buechley and Ta's printable play-dough [14].

Along these lines, the dissolvability of these recipes makes them unsuitable for dishware or outdoor paraphernalia. However, a previous coffee-ground biomaterial by Rivera et al. [68], overcomes this limitation by coating the printed objects in a biomaterial like beeswax to improve water resistance.

Qualities for sustainability can be further optimized and expanded on in several ways. For example, choosing biobased ingredients that are considered "waste", thus extending the life cycle of biomaterials through reuse, or sourcing ingredients from local markets, thus reducing the amount of emissions caused by shipping ingredients.

When optimizing for qualities, we emphasize that the goal should not be to necessarily recreate an existing material. These biomaterials will never be clay, nor plastic; and we find that asking these biomaterials to be a perfect substitute for existing materials is not generative for design. While qualities can be better tuned to specific application scenarios, we encourage designers to embrace the unique qualities, properties, and aesthetics of each biomaterial recipe. Understanding and embracing the uniqueness of each biomaterial can in turn inspire new applications previously overlooked, as previously exemplified in other material-centered design practices [10, 40, 73].

Conclusion

Future Vision

With rising interest in the materiality of physical computing and tangible interfaces [35, 39, 76, 82], developing and deploying new materials that have a minimal impact on the environment and in some cases even promote environmental regeneration [17, 41] is crucial for planetary wellbeing—environmental damage caused by material sourcing and disposal being linked to climate change, species extinction, and human health. In this light, our biomaterial recipes are designed from renewable sources and can be disposed of circularly through recycling and/or biodegradation.

We present our recipes through a cookbook, an instructional format that poses information in a familiar and unintimidating way. By doing so, we hope to emphasize that these recipes can be easily and readily implemented by other researchers, artists, and makers who have access to a paste extrusion 3D printer. We also encourage these recipes to be adapted to suit specific needs, applications, machines, and ingredients that might be abundantly available in different locations and cultures around the world. In supporting grass-roots actions of making, printing, and using biomaterials, we hope to not only expand the library of creative materials currently available to us, but to foster more widespread, sustainable making practices.

In the future, we envision expanding this cookbook by developing more biomaterial recipes for 3D printing and encouraging others to develop their

own recipes. We imagine creating an online, open-source version of the cookbook—similar to other accessible biomaterial resources [24, 53]—to improve its reach and to enable other practitioners to submit recipes they have adapted to be added.

Through continuously adding to the cookbook, we hope it grows to exemplify other perspectives and experiences that take place in different environments and ecologies, with different printing setups and ingredients, and different guiding qualities and contexts in mind. By expanding the cookbook in this way, we hope it becomes more applicable to a wider range of people, and thus holds a wider impact on how we as humans approach sustainability in terms of our built environment.

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References

[1] ASTM. 2020. Standard Test Method for Compressive (Crushing) Strength of Fired Whiteware Materials. https://www.astm.org/c0773-88r20.html

[2] ASTM. 2022. Standard Specification for Labeling of Plastics Designed to be Aerobically Composted in Municipal or Industrial Facilities. https://www.astm.org/d6400-21.html

[3] Howard A. Barnes, John Fletcher Hutton, and K. Walters. 1989. An Introduction to Rheology. Elsevier. Google-Books-ID: B1e0uxFg4oYC.

[4] Fiona Bell, Latifa Al Naimi, Ella McQuaid, and Mirela Alistar. 2022. Designing with Alganyl. In Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction. ACM, Daejeon Republic of Korea, 1–14. https://doi.org/10.1145/3490149.3501308

[5] Fiona Bell and Leah Buechley. 2024. Directions for Degradation: Multispecies Entanglements with 3D Printed Biomaterials. In Halfway to the Future Symposium 2024. ACM, Santa Cruz, CA, USA, 1–14. https://doi.org/10.1145/3686169.3686181

[6] Fiona Bell, Nadia Campo Woytuk, Marie Louise Juul Søndergaard, and Mirela Alistar. 2024. Biodegradation as More-Than-Human Unmaking. ACM Trans. Comput.-Hum. Interact. (Aug. 2024). https://doi.org/10.1145/3685526

[7] Fiona Bell, Derrek Chow, Hyelin Choi, and Mirela Alistar. 2023. SCOBY BREASTPLATE: SLOWLY GROWING A MICROBIAL INTERFACE. In Proceedings of the Seventeenth International Conference on Tangible, Embedded, and Embodied Interaction. ACM, Warsaw Poland, 1–15. https: // doi.org/10.1145/3569009.3572805

[8] Fiona Bell, Joshua Coffie, and Mirela Alistar. 2024. Bio-Digital Calendar: Attuning to Nonhuman Temporalities for Multispecies Understanding. In Proceedings of the Eighteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '24). Association for Computing Machinery, New York, NY, USA, 1–15. https://doi.org/10.1145/3623509.3633386

[9] 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 CHI Conference on Human Factors in Computing Systems (CHI '24). Association for Computing Machinery, New York, NY, USA, 1–19. https://doi.org/10.1145/3613904.3642246

[10] Fiona Bell, Netta Ofer, and Mirela Alistar. 2022. ReClaym our Compost: Biodegradable Clay for Intimate Making. In CHI Conference on Human Factors in Computing Systems. ACM, New Orleans LA USA, 1–15. https://doi.org/10.1145/3491102.3517711

[11] Fiona Bell, Shanel Wu, Nadia Campo Woytuk, Eldy S. Lazaro Vasquez, Mirela Alistar, and Leah Buechley. 2024. Making Biomaterials for Sustainable Tangible Interfaces. In Proceedings of the Eighteenth International Conference on Tangible, Embedded, and Embodied Interaction. ACM, Cork Ireland, 1–5. https://doi.org/10.1145/3623509.3634740

[12] Eli Blevis. 2007. Sustainable interaction design: invention & disposal, renewal & reuse. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '07). Association for Computing Machinery, New York, NY, USA, 503–512. https://doi.org/10.1145/1240624.1240705

[13] Samuelle Bourgault, Pilar Wiley, Avi Farber, and Jennifer Jacobs. 2023. CoilCAM: Enabling Parametric Design for Clay 3D Printing Through an Action-Oriented Toolpath Programming System. In Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems. ACM, Hamburg Germany, 1–16. https://doi.org/10.1145/3544548.3580745

[14] Leah Buechley and Ruby Ta. 2023. 3D Printable Play-Dough: New Biodegradable Materials and Creative Possibilities for Digital Fabrication. In Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23). ACM, Hamburg, Germany, 15 pages. https://doi.org/10.1145/3544548.3580813

[15] Michelle Chang, Chenyi Shen, Aditi Maheshwari, Andreea Danielescu, and Lining Yao. 2022. Patterns and Opportunities for the Design of Human-Plant Interaction. In Proceedings of the 2022 ACM Designing Interactive Systems Conference (DIS '22). Association for Computing Machinery, New York, NY, USA, 925–948. https://doi.org/10.1145/3532106.3533555

[16] Julia Child, Louisette Bertholle, and Simone Beck. 1961. Mastering the Art of French Cooking.

[17] Raymond J. Cole, Amy Oliver, and John Robinson. 2013. Regenerative design, socio-ecological systems and co-evolution. Building Research & Information 41, 2 (April 2013), 237–247. https://doi.org/10.1080/09613218.2013.747130

[18] Val M. Cushing. 1994. Cushing's handbook : a compilation of papers concerning glazes, glaze calculation & formulation, clay bodies, raw materials with clay body, slip and glaze formulas, firing, pottery making tips and other useful information. (No Title) (1994). https://cir.nii.ac.jp/crid/1130000796241143424

[19] [Matthew A. Dalton, Audrey Desjardins, and Ron Wakkary. 2014. From DIY tutorials to DIY recipes. In CHI '14 Extended Abstracts on Human Factors in Computing Systems (CHI EA '14). Association for Computing Machinery, New York, NY, USA, 1405–1410. https://doi.org/10.1145/2559206.2581238

[20] Audrey Desjardins, Cayla Key, Heidi R. Biggs, and Kelsey Aschenbeck. 2019. Bespoke Booklets: A Method for Situated Co-Speculation. In Proceedings of the 2019 on Designing Interactive Systems Conference (DIS '19). Association for Computing Machinery, New York, NY, USA, 697–709. https://doi.org/10.1145/3322276.3322311

[21] Audrey Desjardins and Timea Tihanyi. 2019. ListeningCups: A Case of Data Tactility and Data Stories. In Proceedings of the 2019 on Designing Interactive Systems Conference (DIS '19). Association for Computing Machinery, New York, NY, USA, 147–160. https://doi.org/10.1145/3322276.3323694

[22] Laura Devendorf, Sasha de Koninck, and Etta Sandry. 2022. An Introduction to Weave Structure for HCI: A How-to and Reflection on Modes of Exchange. In Proceedings of the 2022 ACM Designing Interactive Systems Conference (DIS '22). Association for Computing Machinery, New York, NY, USA, 629–642. https://doi.org/10.1145/3532106.3534567

[23] DIYbio. 2024. DIYbio. https://diybio.org/

[24] Margaret Dunne. 2018. Bioplastic Cook Book. https://issuu.com/nat_arc/docs/bioplastic_cook_book_3

[25] Chad Duty, Christine Ajinjeru, Vidya Kishore, Brett Compton, Nadim Hmeidat, Xun Chen, Peng Liu, Ahmed Arabi Hassen, John Lindahl, and Vlastimil Kunc. 2018. What makes a material printable? A viscoelastic model for extrusion-based 3D printing of polymers. Journal of Manufacturing Processes 35 (Oct. 2018), 526–537. https://doi.org/10.1016/j.jmapro.2018.08.008

[26] Thomas Dylan, Mark Blythe, Jayne Wallace, James Thomas, and Tim Regan. 2016. RtD Comics: A Medium for Representing Research Through Design. In Proceedings of the 2016 ACM Conference on Designing Interactive Systems (DIS '16). Association for Computing Machinery, New York, NY, USA, 971–982. https://doi.org/10.1145/2901790.2901821

[27] Eazao. 2022. Eazao Zero - Eazao. https://www.eazao.com/product/eazao-zero/

[28] Jeremy Faludi, Corrie M. Van Sice, Yuan Shi, Justin Bower, and Owen M. K. Brooks. 2019. Novel materials can radically improve whole-system environmental impacts of additive manufacturing. Journal of Cleaner Production 212 (March 2019), 1580–1590. https://doi.org/10.1016/j.jclepro.2018.12.017

[29] International Organization for Standardization. 2021. ISO 16929:2021. https://www.iso.org/standard/80302.html

[30] Camila Friedman-Gerlicz, Deanna Gelosi, Fiona Bell, and Leah Buechley. 2024. WeaveSlicer: Expanding the Range of Printable Geometries in Clay. In Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems (CHI '24). Association for Computing Machinery, New York, NY, USA, 1–19.

[31] Silvan Gantenbein, Emanuele Colucci, Julian Käch, Etienne Trachsel, Fergal B. Coulter, Patrick A. Rühs, Kunal Masania, and André R. Studart. 2023. Three-dimensional printing of mycelium hydrogels into living complex materials. Nature Materials 22, 1 (Jan. 2023), 128–134. https://doi.org/10.1038/s41563-022-01429-5 Number: 1 Publisher: Nature Publishing Group.

[32] Çağlar Genç, Emilia Launne, and Jonna Häkkilä. 2022. Interactive Mycelium Composites: Material Exploration on Combining Mushroom with Off-the-shelf Electronic Components. In Nordic Human-Computer Interaction Conference. ACM, Aarhus Denmark, 1–12. https://doi.org/10.1145/3546155.3546689

[33] Glazy. 2024. Glazy Ceramic Glaze and Pottery Recipes. https://glazy.org/

[34] 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, Hamburg Germany, 1–15. https://doi.org/10.1145/3544548.3580958
[35] Shad Gross, Jeffrey Bardzell, and Shaowen Bardzell. 2014. Structures, forms, and stuff: the materiality and medium of interaction. Personal and Ubiquitous Computing 18, 3 (March 2014), 637–649. https://doi.org/10.1007/s00779-013-0689-4
[36] Karey Helms. 2021. Entangled Reflections on Designing with Leaky Breastfeeding Bodies. In Proceedings of the 2021 ACM Designing Interactive Systems Conference (DIS '21). Association for Computing Machinery, New York, NY, USA, 1998–2012. https://doi.org/10.1145/3461778.3462048
[37] David Hidalgo-Carvajal, Álvaro Hortal Muñoz, José J. Garrido-González, Ruth Carraco-Gallego, and Victoria Alcázar Montero. 2023. Recycled PLA for 3D Printing: A Comparison of Recycled PLA Filaments from Waste of Different Origins after Repeated Cycles of Extrusion. Polymers 15, 17 (Jan. 2023), 3651. https://doi.org/10.3390/polym15173651 Number: 17 Publisher: Multidisciplinary Digital Publishing Institute.
[38] Yuhan Hu, Jasmine Lu, Nathan Scinto-Madonich, Miguel Alfonso Pineros, Pedro Lopes, and Guy Hoffman. 2024. Designing Plant-Driven Actuators for Robots to Grow, Age, and Decay. In Proceedings of the 2024 ACM Designing Interactive Systems Conference (DIS '24). Association for Computing Machinery, New York, NY, USA, 2481–2496. https://doi.org/10.1145/3643834.3661519
[39] Hiroshi Ishii and Brygg Ullmer. 1997. Tangible bits: towards seamless interfaces between people, bits and atoms. In Proceedings of the ACM SIGCHI Conference on Human factors in computing systems (CHI '97). Association for Computing Machinery, New York, NY, USA, 234–241.https://doi.org/10.1145/258549.258715
[40] Elvin Karana, Bahar Barati, Valentina Rognoli, and Anouk Zeeuw van der Laan. 2015. Material Driven Design (MDD): A Method to Design for Material Experiences. International Journal of Design in press (May 2015).
[41] Elvin Karana, Holly McQuillan, Valentina Rognoli, and Elisa Giaccardi. 2023. Living artefacts for regenerative ecologies. Research Directions: Biotechnology Design 1 (Jan. 2023), e16. https://doi.org/10.1017/btd.2023.10
[42] Awais Hameed Khan, Samar Sabie, and Dhaval Vyas. 2023. The Pragmatics of Sustainable Unmaking: Informing Technology Design through e-Waste Folk Strategies. In Proceedings of the 2023 ACM Designing Interactive Systems Conference (DIS '23). Association for Computing Machinery, New York, NY, USA, 1531–1547. https://doi.org/10.1145/3563657.3596056
[43] Rohit Ashok Khot, Deepti Aggarwal, Ryan Pennings, Larissa Hjorth, and Florian 'Floyd' Mueller. 2017. EdiPulse: Investigating a Playful Approach to Self-monitoring through 3D Printed Chocolate Treats. In Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems. ACM, Denver Colorado USA, 6593–6607. https://doi.org/10.1145/3025453.3025980
[44] Sunyoung Kim and Eric Paulos. 2011. Practices in the creative reuse of e-waste. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11). Association for Computing Machinery, New York, NY, USA, 2395–2404. https://doi.org/10.1145/1978942.1979292
[45] Marion Koelle, Madalina Nicolae, Aditya Shekhar Nittala, Marc Teyssier, and Jürgen Steimle. 2022. Prototyping Soft Devices with Interactive Bioplastics. In Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology. ACM, Bend OR USA, 1–16. https://doi.org/10.1145/3526113.354562
[46] Jeffrey J. Kolstad, Erwin T. H. Vink, Bruno De Wilde, and Lies Debeer. 2012. Assessment of anaerobic degradation of Ingeo™ polylactides under accelerated landfill conditions. Polymer Degradation and Stability 97, 7 (July 2012), 1131–1141. https://doi.org/10.1016/j.polymdegradstab.2012.04.003
[47] Stacey Kuznetsov, Alex S. Taylor, Tim Regan, Nicolas Villar, and Eric Paulos. 2012. At the seams: DIYbio and opportunities for HCI. In Proceedings of the Designing Interactive Systems Conference (DIS '12). Association for Computing Machinery, New York, NY, USA, 258–267. https://doi.org/10.1145/2317956.2317997

[48] Pirjo (editor) Kääriäinen, Liisa (editor) Tervinen, Tapani (editor) Vuorinen, and Nina (editor) Riutta. 2020. The CHEMARTS cookbook. Aalto University. https://aaltodoc.aalto.fi/handle/123456789/44165 ISSN: 1799-4985 (electronic).
[49] Eldy S. Lazaro Vasquez, Lily M Gabriel, Mikhaila Friske, Shanel Wu, Sasha De Koninck, Laura Devendorf, and Mirela Alistar. 2023. Designing Dissolving Wearables. In Adjunct Proceedings of the 2023 ACM International Joint Conference on Pervasive and Ubiquitous Computing & the 2023 ACM International Symposium on Wearable Computing (UbiComp/ISWC '23 Adjunct). Association for Computing Machinery, New York, NY, USA, 286–290. https://doi.org/10.1145/3594739.3610781
[50] 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 (DIS '20). Association for Computing Machinery, New York, NY, USA, 1301–1312. https://doi.org/10.1145/3357236.3395510
[51] Alain Le-Bail, Bianca Chieregato Maniglia, and Patricia Le-Bail. 2020. Recent advances and future perspective in additive manufacturing of foods based on 3D printing. Current Opinion in Food Science 35 (Oct. 2020), 54–64. https://doi.org/10.1016/j.cofs.2020.01.009
[52] 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 (UIST '23). Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3586183.3606745
[53] Materiom. 2024. Materials Database. https://commons.materiom.org/data-commons
[54] Harold McGee. 2007. On Food and Cooking: The Science and Lore of the Kitchen. Simon and Schuster. Google-Books-ID: bKVCtH4AjwgC.
[55] Mako Miyatake, Koya Narumi, Yuji Sekiya, and Yoshihiro Kawahara. 2021. Flower Jelly Printer: Slit Injection Printing for Parametrically Designed Flower Jelly. In Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems. ACM, Yokohama Japan, 1–10. https://doi.org/10.1145/3411764.3445346
[56] Yamato Miyatake, Parinya Punpongsanon, Daisuke Iwai, and Kosuke Sato. 2022. interiqr: Unobtrusive Edible Tags using Food 3D Printing. In Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology. ACM, Bend OR USA, 1–11. https://doi.org/10.1145/3526113.3545669
[57] Pauline L. Nasatto, Frédéric Pignon, Joana L. M. Silveira, Maria Eugênia R. Duarte, Miguel D. Noseda, and Marguerite Rinaudo. 2015. Methylcellulose, a Cellulose Derivative with Original Physical Properties and Extended Applications. Polymers 7, 5 (May 2015), 777–803. https://doi.org/10.3390/polym7050777 Number: 5 Publisher: Multidisciplinary Digital Publishing Institute.
[58] Audrey Ng. 2017. Grown microbial 3D fiber art, Ava: fusion of traditional art with technology. In Proceedings of the 2017 ACM International Symposium on Wearable Computers. ACM, Maui Hawaii, 209–214. https://doi.org/10.1145/3123021.3123069
[59] Madalina Nicolae, Vivien Roussel, Marion Koelle, Samuel Huron, Jürgen Steimle, and Marc Teyssier. 2023. Biohybrid Devices: Prototyping Interactive Devices with Growable Materials | Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology. In Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology (UIST '23). Association for Computing Machinery, New York, NY, USA, 1–15. https://doi.org/10.1145/3586183.3606774
[60] Netta Ofer and Mirela Alistar. 2023. Felt Experiences with Kombucha Scoby: Exploring First-person Perspectives with Living Matter. In Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23). Association for Computing Machinery, New York, NY, USA, 1–18. https://doi.org/10.1145/3544548.3581276
[61] Jukka Pakkanen, Diego Manfredi, Paolo Minetola, and Luca Iuliano. 2017. About the Use of Recycled or Biodegradable Filaments for Sustainability of 3D Printing. In Sustainable Design and Manufacturing 2017 (Smart Innovation, Systems and Technologies), Giampaolo Campana, Robert J. Howlett, Rossi Setchi, and Barbara Cimatti (Eds.). Springer International Publishing, Cham,

776–785. https://doi.org/10.1007/978-3-319-57078-5_73
[62] Jeroen Peeters, Rosa van der Veen, and Ambra Trotto. 2020. Pictorial Unleashed: Into the Folds of Interactive Qualities. In Proceedings of the 2020 ACM Designing Interactive Systems Conference (DIS '20). Association for Computing Machinery, New York, NY, USA, 925–938. https://doi.org/10.1145/3357236.3395570
[63] Erwin Peng, Danwei Zhang, and Jun Ding. 2018. Ceramic Robocasting: Recent Achievements, Potential, and Future Developments. Advanced Materials 30, 47 (2018), 1802404. https://doi.org/10.1002/adma.201802404
[64] Franklin Pezutti-Dyer and Leah Buechley. 2022. Extruder-Turtle: A Library for 3D Printing Delicate, Textured, and Flexible Objects. In Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '22). Association for Computing Machinery, New York, NY, USA, 1–9. https://doi.org/10.1145/3490149.3501312
[65] Valentin Postl, Wolfgang Schwendtbauer, Thomas Preindl, and Kathrin Probst. 2024. Mold Printer: Creating Living Self-Revealing Artworks. In Proceedings of the Eighteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '24). Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3623509.3633396
[66] 3D Potter. 2024. 3D PotterBot 10 PRO | 3D Potter. https://3dpotter.com/product/3d-potterbot-10-pro/
[67] Anton Reijnders. 2005. The Ceramic Process: A Manual and Source of Inspiration for Ceramic Art and Design. University of Pennsylvania Press.
[68] 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 (DIS '23). Association for Computing Machinery, New York, NY, USA, 294–311. https://doi.org/10.1145/3563657.3595983
[69] Mariet Sauerwein and Zjenja Doubrovski. 2018. Local and recyclable materials for additive manufacturing: 3D printing with mussel shells. Materials Today Communications 15 (2018), 214–217. https://doi.org/10.1016/j.mtcomm.2018.02.028
[70] Eugene Soh, Zhi Yong Chew, Nazanin Saeidi, Alireza Javadian, Dirk Hebel, and Hortense Le Ferrand. 2020. Development of an extrudable paste to build mycelium-bound composites. Materials & Design 195 (Oct. 2020), 109058. https://doi.org/10.1016/j.matdes.2020.109058
[71] Katherine W Song, Fiona Bell, Himani Deshpande, Ilan Mandel, Tiffany Wun, Mirela Alistar, Leah Buechley, Wendy Ju, Jeeeun Kim, Eric Paulos, Samar Sabie, and Ron Wakkary. 2024. Sustainable Unmaking: Designing for Biodegradation, Decay, and Disassembly. In Extended Abstracts of the 2024 CHI Conference on Human Factors in Computing Systems (CHI EA '24). Association for Computing Machinery, New York, NY, USA, 1–7. https://doi.org/10.1145/3613905.3636300
[72] Katherine W Song, Aditi Maheshwari, Eric M Gallo, Andreea Danielescu, and Eric Paulos. 2022. Towards Decomposable Interactive Systems: Design of a Backyard-Degradable Wireless Heating Interface. In Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems (CHI '22). Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3491102.3502007
[73] 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, Yokohama Japan, 1–12. https://doi.org/10.1145/3411764.3445529
[74] Marie Louise Juul Søndergaard and Nadia Campo Woytuk. 2023. Feminist Posthumanist Design of Menstrual Care for More-than-Human Bodies. In Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems. ACM, Hamburg Germany, 1–18. https://doi.org/10.1145/3544548.3581083
[75] Tronxy. 2024. Tronxy 3D Printers Official Store. https://www.tronxy3d.com/products/tronxy-moore-2-pro-ceramic-clay-3d-printer
[76] Anna Vallgårda and Johan Redström. 2007. Computational composites. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. ACM, San Jose California USA, 513–522. https://doi.org/10.1145/1240624.1240706

[77] Eldy S. Lazaro Vasquez and Katia Vega. 2019. Myco-accessories: sustainable wearables with biodegradable materials. In Proceedings of the 23rd International Symposium on Wearable Computers. ACM, London United Kingdom, 306–311. https://doi.org/10.1145/3341163.3346938
[78] VormVrij. 2024. The Lutum Clay 3D Printer. https://vormvrij.nl/lutum/
[79] 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 (CHI '21). Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3411764.3445187
[80] WASP. 2024. Clay 3D Printers. https://www.3dwasp.com/en/
[81] Jennifer Weiler, Piyum Fernando, Nipuni Siyambalapitiya, and Stacey Kuznetsov. 2019. Mycelium Artifacts: Exploring Shapeable and Accessible Biofabrication. In Companion Publication of the 2019 on Designing Interactive Systems Conference 2019 Companion. ACM, San Diego CA USA, 69–72. https://doi.org/10.1145/3301019.3325156
[82] Mikael Wiberg, Hiroshi Ishii, Paul Dourish, Anna Vallgårda, Tobie Kerridge, Petra Sundström, Daniela Rosner, and Mark Rolston. 2013. Materiality matters—experience materials. Interactions 20, 2 (March 2013), 54–57. https://doi.org/10.1145/2427076.2427087
[83] Shanel Wu and Laura Devendorf. 2020. Unfabricate: Designing Smart Textiles for Disassembly. In Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20). Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3313831.3376227
[84] Clement Zheng, HyunJoo Oh, Laura Devendorf, and Ellen Yi-Luen Do. 2019. Sensing Kirigami. In Proceedings of the 2019 on Designing Interactive Systems Conference (DIS '19). Association for Computing Machinery, New York, NY, USA, 921–934. https://doi.org/10.1145/3322276.3323689
[85] L. Zhong, M. Oostrom, M. J. Truex, V. R. Vermeul, and J. E. Szecsody. 2013. Rheological behavior of xanthan gum solution related to shear thinning fluid delivery for subsurface remediation. Journal of Hazardous Materials 244-245 (Jan. 2013), 160–170. https://doi.org/10.1016/j.jhazmat.2012.11.028
[86] Jingwen Zhu, Lily Winagle, and Hsin-Liu (Cindy) Kao. 2024. EcoThreads: Prototyping Biodegradable E-textiles Through Thread-based Fabrication. In Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems (CHI '24). Association for Computing Machinery, New York, NY, USA, 1–17. https://doi.org/10.1145/3613904.3642718

Supplementary Materials

Pictorial Assembly Instructions

https://handandmachine.org/index.php/2024/10/15/biomaterial-cookbook-for-3d-printing/

Heater Design

https://handandmachine.org/index.php/eazao-heater/

Print Files

https://handandmachine.org/index.php/biomaterial-test-prints/