Prototyping Soft Devices with Interactive Bioplastics

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Base Materials
Conductive Bioplastic
Sheets
Conductive Bioplastic
Pastes
Conductive Bioplastic
Foams

Material Forms

Fabricate
Synthesize

Soft Interactive Devices

Re-Melt & Re-Cast
Re-use
Degrade, Compost or Eat

Figure 1: We synthesize conductive bioplastic sheets, pastes, and foams from sustainable base materials. Additive and subtractive fabrication methods allow to combine them with conventional electronics to create soft interactive devices. If no longer used, devices can be disassembled and parts re-used, materials re-molten and re-cast, bio-degraded, composted or eaten.

ABSTRACT

Designers and makers are increasingly interested in leveraging bio-based and bio-degradable ‘do-it-yourself’ (DIY) materials for sustainable prototyping. Their self-produced bioplastics possess compelling properties such as self-adhesion but have so far not been functionalized to create soft interactive devices, due to a lack of DIY techniques for the fabrication of functional electronic circuits and sensors. In this paper, we contribute a DIY approach for creating Interactive Bioplastics that is accessible to a wide audience, making use of easy-to-obtain bio-based raw materials and familiar tools. We present three types of conductive bioplastic materials and their formulation: sheets, pastes and foams. Our materials enable additive and subtractive fabrication of soft circuits and sensors. Furthermore, we demonstrate how these materials can substitute conventional prototyping materials, be combined with off-the-shelf electronics, and be fed into a sustainable material 'life-cycle' including disassembly, re-use, and re-melting of materials. A formal characterization of our conductors highlights that they are even on-par with commercially available carbon-based conductive pastes.

CCS CONCEPTS
• Human-centered computing → Human computer interaction (HCI), • Hardware → Emerging technologies.

KEYWORDS
bioplastics, biomaterials, do-it-yourself, DIY, sustainability

ACM Reference Format:
1 INTRODUCTION

Do-It-Yourself (DIY) prototyping of soft interactive devices has gained traction fueled by a broad set of accessible fabrication techniques contributed by the HCI community. For instance, soft devices of diverse form factors and custom embedded circuitry can be realized with silicone casting [85, 112, 124], cutting and layering techniques [56, 108], by ink-jet or screen printing on soft substrates [58, 96, 119]. They can also be woven [49, 105], knitted [59], or embroidered [45].

So far, these techniques do not address the persistent and timely challenge of sustainability [69, 70, 102], a topic that is of increasing interest to makers and designers [2, 17, 18, 31]. DIY formulations for self-produced, sustainable materials have been explored and popularized under the term ‘bioplastics’ [7, 27, 93, 97, 98]. However, these commonly focus on non-conductive bioplastics; functional properties that are vital for creating bioplastic circuits and sensors remain largely underexplored. This limitation confines designers’ and makers’ experimentation with bioplastics to reactive dyes or pigments, in otherwise passive artifacts and sheet material.

Pioneering work from material science has contributed promising approaches for creating electronics from bio-based and bio-degradable polymers such as gelatin, alginate and agar [40, 46, 72, 78]. Yet, these approaches are inaccessible to makers and designers as they require a high degree of expertise, hard-to-obtain or dangerous materials (e.g., carbon nanotubes), and advanced equipment.

This paper contributes Interactive Bioplastics, the first DIY approach for composing soft interactive devices from bio-based and bio-degradable materials. We self-produce conductive ‘bioplastics’, which we understand as sustainable, bio-based and/or bio-degradable compounds following Endres’ definition [32]. Beyond their promise of sustainability, bioplastics are compelling and well-suited for creating soft sensors and circuits: their material synthesis is highly customizable and can be tuned to create unique properties including transparency, flexibility, malleability and skin-compatibility, offering inherent benefits for soft interactive devices. Our work makes three key main contributions:

First, we contribute an accessible end-to-end approach for DIY fabrication of soft interactive devices from low-cost bio-based and bio-degradable materials. We introduce three types of novel carbon-infused bioplastic materials and their synthesis in the form of conductive sheets, pastes and foams. Customized conductor layouts can be easily realized using widely used additive and subtractive techniques (e.g., stencil painting, plotter cutting). Layering and combining with non-conductive sheets and conventional electronic components enables creating fully functional devices with custom form factors and embedded bio-based (single-layer) circuits and sensors. The entire device can then be fed into a sustainable prototyping ‘life cycle’ where conductive pastes are dissolved in water, conventional electronics retrieved and re-used, and bioplastic sheets or foams re-molten and re-fabricated into other prototypes, or, alternatively, degraded, composted or eaten.

Second, we demonstrate how Interactive Bioplastics can be applied to substitute conventional prototyping materials and show how to re-create various types of soft sensors and soft interactive devices presented in prior HCI literature. We demonstrate the fabrication of six application examples made from Interactive Bioplastics, including bio-based and bio-degradable epidermal devices that feature deformation sensing, and free-form capacitive touch sensing. We showcase functional on-body circuits, an edible capacitive touch sensor, skin-exposed EMG electrodes, and a self-contained computing device that can be disassembled and re-molten.

Third, we contribute a characterization of Interactive Bioplastics’ functional properties including electrical resistance, dielectric behavior, mechanical characteristics and conductivity under strain and pressure. We also selectively report on the sensors’ signal-to-noise-ratio (SNR), and conductivity after re-melting and re-casting. Our results show that the performance of Interactive Bioplastics synthesized in DIY settings is on-par with commercially available, carbon-based but not bio-based products in terms of conductivity and that the sensors’ avg. SNRs meet quality requirements reported in literature.

2 RELATED WORK

Interactive prototypes made from materials that are soft, sustainable, or both have been explored from different angles:

2.1 Crafting Soft Interactive Devices

A number of accessible fabrication techniques for soft electronics has been explored in HCI. A versatile technique is to embed conventional components into silicone elastomers [6, 85]. Conductive traces and circuits can be printed directly on top of stretchable or non-stretchable substrates using screen printing [53, 90, 112, 115] or inkjet printing [57, 58, 96] with conductive ink. Other approaches create circuits from patterns cut from conductive sheets using a laser cutter [43, 85, 108, 112] or vinyl cutter [56, 88]. Foam-type materials can be impregnated with a conductive liquid which turns them into sensors [86, 111]. For this work, we build upon this valuable background, but we introduce a novel class of materials to this research area, functional DIY bioplastics, and evaluate to what extent they integrate with existing DIY bioplastics, and evaluate to what extent they integrate with existing prototyping goals and techniques.

2.2 Sustainable Prototyping

Functional prototyping plays a significant role in HCI to design interactivity. However, there is a tension between HCI’s traditional practice of prototyping and sustainability goals [102], as the commonly employed materials can have adverse environmental effects. This is due to their provenance and scarcity (e.g., metal mining causing loss of biodiversity [28]), synthesis (e.g., the excess of water needed to produce natural rubber [69]), processing (e.g., toxic effluents from PCB creation [12]), and disposal (e.g., acrylic sheets ending up in landfill [38]). As a result of this tension, makers, designers and HCI researchers have developed approaches making use of scrap materials [107] and explored re-use or upcycling processes [19] as design incentives [26, 60]. Further examples includes the reuse of off-cuts [64] or unused 3D prints [35]. In addition, researchers explored sustainable materials as alternatives to plastic. Arroyos et al. employed a flax fiber-based compound and polyvinylalcohol to create a eco-friendly computer mouse design [3]. Mycelium-based materials have been explored for prototyping enclosures, breadboards and other passive prototype elements [67, 68, 106, 114]. Bell et al. introduced ReClaym [8], a bio-degradable clay-like compound based on alginate and compost...
which they customize by adding color, texture, thermo- and UV-active pigments, and graphite for capacitive touch sensing. The exploration of sustainable alternatives for prototyping also fosters reflections of the after-life of materials used in digital fabrication, examining a product’s environmental impact throughout all stages of its life, from the raw materials acquisition, manufacturing and distribution, use and end-of-life [4, 70]. With this paper, we contribute to this vision of making prototyping more sustainable by introducing Interactive Bioplastics as an accessible approach towards making use of bio-based and bio-degradable materials for prototyping.

2.3 Bio-based and Bio-degradable Electronics

Pioneering research in material science has opened up new opportunities for the creation of bio-based sensors and circuits. These lines of research succeeded in making use of the absorbent properties of bio-polymers such as gelatin or alginate to create sensorized hydrogels [46], and conductive composites with silver fillers [72, 89]. They show high potential for soft electronics. The characteristic molecular structure of gelatin has been leveraged to create ferroelectric [40] and piezoelectric [125] sensors. Won et al. demonstrated tungsten-infused natural wax [120]. Most material science research makes bio-degradable substrates conductive by embedding metals (e.g., silver nano wires [72] or ultra-thin gold coatings [78]).

These procedures require a high level of expertise and are inaccessible to non-material scientists (e.g., makers). Attempts to democratize these approaches towards DIY prototyping are so far very limited.

Carbon conductors made from bio-degradable materials have the potential to be accessible but have only been covered selectively: bio-based on-body sensors have been successfully 3D-printed with inks based on cellulose and carbon nano tubes [48]. Fu et al. demonstrated ink jet printing circuits on transparent wood film with conductive ink containing carbon nano fibers derived from plant lignin [39]. These works share our goal of employing bio-based carbon-infused conductive circuits on bio-based and bio-degradable substrates but are inapplicable to DIY settings, as they require complex chemical treatments and uses carbon nano fibers or nano tubes that have adverse health effects [61].

2.4 Self-produced Materials and DIY Bioplastics

Self-produced materials or ‘DIY Materials’, including re-cycled or re-purposed plastics [2, 94], novel compound materials on mineral basis [44, 99], or re-shaped organic waste and bio-based raw materials [17, 18, 31, 34] gain increasing popularity in design [5]. Focusing on bioplastics, i.e., materials that are either bio-based and/or bio-degradable [32], we situate our work within this context. In DIY settings, bioplastics are typically synthesized or ‘cooked’ from bio-based polymers such as gelatin [25, 80], agar-agar [7, 74], and various types of starch [98]. Prior work contributed manifold open source DIY ‘recipes’ [23, 93, 97]; most notably Dunne’s Bioplastics Cookbook [27], Ribul’s Recipes for Material Activism [98], and The Chemarts Cookbook [55] as well as collaborative databases for biomaterials [24, 74, 75, 80].

Yet, functional or interactive bioplastics, and their applicability for creating circuits and sensors, remain largely underexplored in HCI literature. Here, prior work has mostly focused on chemical sensing, e.g., color-changing gelatin PH sensors [121]. Most closely related, Bell’s Alganyl [7], a DIY bioplastic from agar, demonstrates interactivity through color-change using thermochromic and UV-sensitive pigments. Bell et al. also showcase basic circuits on Alganyl created from Bare Conductive, a petrochemical, commercially-available conductive ink, but they do not extend their line of work towards electrical sensors or interactive electronics. Other bio-based DIY inks have shown to be applicable on paper substrates, e.g., a mix of activated charcoal and vinegar [79]; however, these do not yield satisfactory results on bioplastic sheets.

Previous conductive bioplastics have been limited to sheet material infused with activated charcoal [22], and uses of charcoal only for pigmentation [100] or for air purification [33, 84]. Functional devices have only been demonstrated by Lorenzi, who published an instructional zine for DIY gelatin solar cells [30] and explored hydrated, conductive agar [75], titanium dioxide and activated charcoal for capacitive touch sensing [77]. However, none of these materials has been formally or informally evaluated in terms of its applicability to circuits, sensors or interactive devices.

3 INTERACTIVE BIOPLASTICS

Interactive Bioplastics is a DIY approach that empowers makers and designers to integrate bio-based and bio-degradable materials into their prototyping practice. To this end, Interactive Bioplastics tackles three key challenges:

1. Our approach is accessible to a wide audience. Base materials such as alginate, gelatin or glycerin are easy-to-obtain (e.g., from supermarkets or pharmacies), non-toxic and available at low cost. They are also easy to process: material synthesis only requires kitchen-like setups, using common household or prototyping tools. All materials are safe to process in typical lab environments, requiring only familiar precautionary safety measures, e.g., pot cloths, gloves or respiratory masks.

2. Our approach enables a broad set of functions and allows to replicate well-known form factors and applications of interactive soft devices. We focused on bioplastics due to their compelling mechanical properties: as non-conductive base materials (substrates), they are compatible with human tissue due to their stretchability, self-adhesion, and insulation. Carbon-infused bioplastics, one of our key contributions, act as conductors and enable the creation of soft circuits and different types of sensors, avoiding scarce or harmful metal conductors [28, 69].

3. Our approach enables a sustainable prototyping ‘life cycle’ for soft interactive devices. It introduces materials sourced from bio-based origin into electronics prototyping. Once no longer in use, prototypes can take a set of circular paths: bioplastics can be remolten and re-fabricated into other prototypes, or, alternatively, degraded, composted or eaten. In addition, bio-based conductive pastes can be dissolved allowing non-biodegradable electronic components to be retrieved and re-used.

Addressing above challenges, Interactive Bioplastics introduces a DIY process for creating three different forms of carbon-based conductive bioplastic materials: sheets, pastes, and foams. All three leverage bio-based and bio-degradable base materials as functional alternatives for device prototyping, but also keep the option of integrating conventional electronic components. Furthermore, they
invite a range of familiar, flexible and free-form patterning techniques. We created custom shaped sensors and circuits using both additive and subtractive fabrication methods, ranging from cutting sheets, over layering, to hand or stencil painting with pastes. In the following, we present how sheets, pastes and foams are created and evaluate how they allow to re-create a diverse set of application cases inspired by prior work on soft interactive devices.

Bioplastic materials offer unique properties, including transparency, flexibility, malleability and skin-compatibility, which are inherently well-suited for creating soft sensors and circuits. For many interfaces, actual use time is rather short; examples include temporary tattoo interfaces [56, 87] or conventional items and devices for one-time use (e.g., plastic cutlery or off-the-shelf skin electrodes). Hence, our application cases intentionally sketch out common one-time use scenarios that highlight Interactive Bioplastics’s potential to raise awareness for waste reduction and sustainability.

4 CONDUCTIVE BIOPLASTIC SHEETS

Sheets are a very common form factor of soft and flexible devices [108, 112, 115]. In this section, we demonstrate how to realize soft sensors and circuits with bioplastic sheet material that is shaped into patterned conductive elements. We investigate material formulations for bioplastics that allow to synthesize sheets which are conductive and cohesive, while also remaining soft and flexible. After detailing on material formulation and fabrication, we demonstrate the use of conductive bioplastic sheets for prototyping wearable circuits, on-body sensors and edible interfaces.

Material Formulation. Commonly, bioplastic sheet materials are made with a solvent, a bio-based polymer, a plasticizer and optional fillers or additives [97]. For Interactive Bioplastics we adopt the material formulation of non-functional bioplastic sheets [25, 27, 80] and functionalize them by using a carbon-based conductor as additive. Doping or ‘infusing’ polymers with carbon-based conductors, for instance creating ePDMS from silicone and carbon black [112], is increasingly adopted by HCl prototyping practice. However, the adaptation of existing techniques and ratios for bioplastics is non-trivial, as an optimal balance between conductivity and sheet softness is crucial. Carbon form, type of polymer, additives and amount of plasticizer each affect the sheet’s characteristics. We selected and iteratively improved material formulations that achieve this balance. Our conductive bioplastic sheets are composed as follows:

(1) Polymer: We create two types of bioplastic sheets using either gelatin (INKA FOODS) or alginate (BIOZOON); both can be made conductive or non-conductive.
(2) Solvent: We use distilled water (for all experiments) and tap water (for edible interfaces) as solvent. The amount of solvent affects drying time and how thinly sheets can be cast.
(3) Plasticizer: Our sheets use gelatin (DOKTOR KLAUS) as plasticizer. Increasing the amount of plasticizer in the material formulation increases flexibility at a decrease in strength [7, 52].
(4) Conductor: Our sheets use carbon black (VULCAN) and activated charcoal (GEWÜRZLAND) as conductors. As a rule of thumb, a higher ratio of conductive particles causes the sheet to be more conductive but also more brittle and less flexible.
(5) Fillers and further additives: We explore Transglutaminase (TGase) and Sorbitol (SRB) which are applicable to protein-based polymers, i.e., gelatin. TGase improves tensile strength and elongation at break value [41]. Our detailed evaluation shows that it also increases conductivity (Section 7). SRB has the opposite effect on conductivity.

Choice of Conductor. Conductive materials made of carbon exist in diverse types, with varying properties such as particle size and shape. Most notably, structure and surface functionality influence conductivity and wetting [82]. Thus, making a well-informed choice of carbon type is crucial. We achieved satisfying conductivity and flexibility with carbon black (VULCAN XC 72R, bulk density: 96 kg/m³, avg. particle size: 50nm). We found larger particles, e.g., micro-graphite (PROGRAPHITE, avg. particle size 10 micron), to be less desirable as they cause stiffer and more fragile sheets at lower conductivity. We furthermore tested several types of off-the-shelf, food-grade activated charcoal, finding one type, sold as spice (GEWÜRZLAND), to also be conductive. Notably, food-grade products do typically not report particle size, density or conductivity. Thus, they are likely based on different types of activated charcoal powder which may exhibit different surface structures e.g., due to different provenance or activation method [82]. Hence, their conductivity can only be determined on a trial-and-error basis, and may vary between brands and even batches. Activated charcoal has high absorption power, with a large inner surface (500 - 1500 m²/g [50]) and typically a higher surface-area-to-volume ratio than carbon black (VULCAN XC 72R: 250 m²/g [66, 117]), which causes sheets to be stiffer and more brittle.

We contribute two concrete material formulations (Table 1): one based on alginate and carbon black which is sufficiently conductive to be used in circuits and as deformation sensor, and one based on gelatin and activated charcoal, which has the potential to be eaten and re-molten.

Table 1: Material formulations for conductive sheets. For better comparability, we report conductors as ratio of the compound’s total weight.

<table>
<thead>
<tr>
<th>Material Formulation</th>
<th>Alginate Sheets</th>
<th>Gelatin Sheets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alginatena</td>
<td>Dist. Water</td>
<td>Glycerinb</td>
</tr>
<tr>
<td>1 (3g)</td>
<td>25 (75g)</td>
<td>1 (3ml)</td>
</tr>
<tr>
<td>Gelatinb</td>
<td>Tap Water</td>
<td>Glycerinb</td>
</tr>
<tr>
<td>1 (6g)</td>
<td>5 (30g)</td>
<td>0.6 (3ml)</td>
</tr>
</tbody>
</table>

a Sodium Alginat, Biozoos, with Calcium Lactate as curing agent.
b Organic Glycerin, Doktor Klaus, 99.7%, density 1.26 g/ml.
c Carbon Black, Vulcan XC 72R.
d Halal Gelatin, Inka Foods, 250 bloom.
e Gewürzland.

Synthesizing & Casting Sheets. Sheets from gelatin are composed from distilled water, gelatin and gelatin powder following the procedure described by Dunne [27], using a magnetic stirrer. After heating the bloomed gelatin (~10 min) at medium temperature (~80°C), turning the stirrer on once the gelatin has fully liquefied, the carbon-based conductor is added after ~2.5 min, and (slowly) stirred for ~4.5 min. Non-conductive sheets are also cast after ~4.5 min stirring. We cast our sheets into square laser-cut wooden frames taped onto an acrylic sheet. Glass sheets would cause the gelatin to cool down more rapidly, resulting in uneven sheets. We optimized
the size of our frames (8x8cm inner, 9x9cm outer dimensions) to prevent warping. Sheets are cast up to 3mm thick (before drying) and dried for 24-30h at room temperature, resulting in a sheet thickness ranging from ~0.15mm to ~0.35mm. As a rule of thumb, sheets can be kept for 5-7 days. If stored longer (e.g., months), contained water will slowly evaporate, which impacts elasticity and adhesiveness. Gelatin sheets can be re-molten and re-cast.

Sheets from alginate are composed following Raspanti’s lecture [97] and consist of distilled water, glycercin and sodium alginate powder which we mix in a bowl and set to rest for 1-2h. The resting time supports the formation of a homogeneous, viscous compound. Carbon-based conductors are folded in in small portions before the sheets are cast. We found mixing by hand to be more beneficial in terms of time effort (~5 min) and resulting quality than mixing with a magnetic stirrer or planetary centrifugal mixer. For casting, the compound is coated onto a glass blade with a leveling blade and the sheet is sprayed with a 1:10 mix of calcium lactate and water and set to dry. Calcium acts as curing agent, supporting gel formation without the need for heat. A sheet cast 2mm thick takes ~3 days to dry, reducing the sheets’ thickness by 90% to 0.20mm.

Non-conductive sheets from agar can be created following Bell et al.’s recipe for Alganyl [7]. For our experiments with conductive variants, no material formulations yielded cohesive, planar conductive sheets; all experiments displayed signs of warping or crumbling. There are also, to the best of our knowledge, no successful attempts of conductive agar sheets, not requiring hydration (cf., Hydrated Agar on Materiom [75]), reported in literature.

**Patterning.** Conductive bioplastic sheets can be patterned using a plotter cutter or manually using a surgical knife. For ease of moving micro-thin sheets (e.g., alginate) to the cutting bed, they are first put onto an acetate sheet (so-called ‘transparency’) that acts as a handling substrate. Minimum trace width depends on the plotter cutter; we achieved traces as thin as 1mm testing on a on a Cricut Maker 3 and a Brother ScanNCut CM350. Both require a so-called ‘deep point’ or ‘deep cut’ blade to prevent creases when cutting conductive sheets with an uneven surface. After cutting, surplus material is removed with sharp tweezers and the circuit can be peeled and transferred to the desired substrate, e.g., a non-conductive bioplastic sheet (Figure 2a-c).

**Layering.** Stacking multiple sheets on top of each other enables combining different types of sheets and also improves stability. Layering also increases conductivity, as shown by our experiments (cf., Section 7). Casting thicker sheets is less beneficial, as thicker sheets take longer to dry which increases the risk of mold, cracks or warping. Electric dehydrators can alleviate this issue but increase the cost of equipment and are only applicable to alginate, due to gelatin’s low melting point. Thus, we present layering as a novel and beneficial alternative.

### 4.1 Alginate Bend Sensor

Soft motion sensors positioned directly on the user’s body joints have been explored and popularized by prior work in HCI [47, 71, 73, 81, 104]. From a (bio-)materials perspective, these applications are challenging, as they require a sheet material that is firm but flexible, ideally with a elastic modulus similar to human tissue [81] and exhibits variable resistance under strain [104]. This application case demonstrates how our conductive and non-conductive alginate sheets can combined to create skin-compatible, ultra-thin skin-mount sensors, that can be worn on finger, wrist and knee.

Each skin-worn bend sensor consists of five layers. The layer most closely to the epidermis is a micro-thin, non-conductive and transparent alginate sheet (0.10mm) that possesses the ability to adhere to skin and offers insulation. On top, we added a sensor composed from 3 stacked layers of conductive alginate (each ~0.15mm thick); each with a ratio of 2.3% carbon black (VULCAN). Finally, a layer of non-conductive alginate bioplastic seals the interface. We created bend sensors from simplified horseshoe patterns at three different scales: 5mm (knee), 4mm (wrist) and 3mm (finger), all shown in Figure 2. The conductive traces are connected with snap buttons to a commodity microcontroller board (Arduino).

Our knee sensor exhibits a resistance change from 4.39kΩ (extended knee) to 5.44kΩ (75° knee flexion) resulting in an SNR value of ~25.56 (SD=2.97) which is higher than the squeeze sensors made out of strain gauges in prior work [113]. Our characterization below further details on the electro-mechanical response of the material and the video figure presents how a knee’s motion is picked up by our bio-based deformation sensor. As the sensor can be easily detached from the snap connectors, it can be exchanged for anew one (if desired) and added to the compost for sustainable disposal.

Sodium alginate cured with calcium lactate offers benefits such as long pot-life, skin compatibility, or water- and heat-resistance that are desirable for on-skin applications. The resulting bioplastic (i.e., calcium alginate) is water-insoluble and can only be biodegraded [8, 65, 101] or re-used in synthesized form. We demonstrate in our video figure how carbon-infused alginate can be repurposed as decorative elements in other, freshly prepared or re-molten bioplastics.

### 4.2 Circuit Example

Decorative on-body ornaments including LEDs have been explored and popularized by prior work [73, 95]. Here, we demonstrate...
Conductive inks or pastes are widely used for prototyping soft circuits and devices. Not only can they be used to create circuits and sensors on diverse substrate materials, but they are also compatible with diverse patterning techniques, ranging from the ease and flexibility of hand painting or drawing [15, 83] to making use of stencils or silk screens [90] for high resolution and precise control.

In this section, we introduce conductive pastes that are applicable for hand painting and stencil painting on bioplastics from alginate, gelatin and agar, as well as beeswax sheets. They are sufficiently conductive to create functional circuits and simple self-contained circuits and devices. Not only can they be used to create circuits and

## 4.3 Edible Gelatin Capacitive Sensor

Edible artifacts are a vibrant research area [1, 101, 122]. In this application case, we demonstrate the use of a variant of our conductive sheets that is entirely made of food-grade ingredients and works as a capacitive touch sensor on top of dry but soft pastry, a macaron.

We created 1mm thick conductive sheets from 6g gelatin, 4g glycerin, and 30g tap water infused with 2g food-grade activated charcoal (5% carbon ratio). The resulting sheet is sufficiently conductive for capacitive touch sensing, but is not stretchable. We manually cut decorative shapes (‘speech bubbles’) using a surgical knife and attached them to the pastry’s (macaron’s) upper side. We used roulade needles to connect these sensing electrodes to a circuit positioned underneath the pastry. Capacitive sensing and sound output are implemented on an Arduino Uno using a 8 Ω/0.2W mini speaker and the Talkie library\(^1\). When a user attempts at taking one of the pastries, a sound utterance tells them to take one of the other pastries (Figure 4b).

For consumption, the macaron could be picked up and lifted from the pierced connector (Figure 4c-d). Our conductive gelatin ‘speech bubble’ can be removed, re-molten, and re-cast. For this application case, we compared two strips of conductive gelatin (5% carbon ratio): one cut from the same sheet as our ‘speech bubbles’ (10mm x 70mm, 0.4g) and one created by re-melting 0.4g of left-over pieces. Gelatin scraps were molten in a beaker together with a few drops of water (less than 0.1g) and cast into a 10mm x 70mm wooden frame. The resulting strip’s visual appearance is glossier than the original sheet. Yet, the conductivity of both strips is comparable with a sheet resistance (cf., method in section 7.1) between 286kΩ/□ (re-cast sheet) and 350kΩ/□ (original sheet).

Moreover, this application example has the potential to be fully edible: each ‘speech bubble’ weighs 0.4g-0.6g. Based on our material formulation, we estimate the amount of activated charcoal in the dried pieces at approx. 16.7%, i.e., less than 0.1g per macaron. For comparison, EFSA (European Food Safety Authority) approved dosage of activated charcoal is 1g as a food supplement [29].

## 5 CONDUCTIVE BIOPLASTIC PASTES

Conductive inks or pastes are widely used for prototyping soft circuits and devices. Not only can they be used to create circuits and sensors on diverse substrate materials, but they are also compatible with diverse patterning techniques, ranging from the ease and flexibility of hand painting or drawing [15, 83] to making use of stencils or silk screens [90] for high resolution and precise control.

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resulting paste in an airtight container, yielding an extended lifespan of 6-8 days (vs. 3 days without) during which the paste remains sufficiently stable for stencil painting circuits.

Substrate Compatibility. In contrast to textile- or paper-substrates, printing delicate conductive patterns on bioplastic substrates is challenging due to the contained polymers’ hydrophilic nature. For robust end-to-end conductivity, the prevention of cracks is essential, which demands for a careful analysis of the interaction between the paste and the substrate. Table 3 summarizes the results of our experiments and guides the reader in choosing compatible combinations of pastes and substrate materials. For comparison, we contrast with not bio-based alternatives, namely Bare Conductive and a paste using common craft glue (STYLEX®) as adhesive. Our results show that at least one of our bio-based conductive pastes is compatible with any of the tested substrates. CléoBio with up to 16.67% carbon black (no filler) can be used directly on a single layer of substrate. CleoBio with up to 16.67% carbon black (no filler) can be used directly on a single layer of substrate. CléoBio with up to 16.67% carbon black (no filler) can be used directly on a single layer of substrate. CléoBio with up to 16.67% carbon black (no filler) can be used directly on a single layer of substrate. CléoBio with up to 16.67% carbon black (no filler) can be used directly on a single layer of substrate. CléoBio with up to 16.67% carbon black (no filler) can be used directly on a single layer of substrate. CléoBio with up to 16.67% carbon black (no filler) can be used directly on a single layer of substrate. CléoBio with up to 16.67% carbon black (no filler) can be used directly on a single layer of substrate.

Hand Painting. Hand painting with conductive paste allows for more creative freedom and control (Figure 1 right), similar to the processes frequently used to create soft devices with conductive ink [15, 83, 95]. Our conductive pastes are viscous enough to be applied with a brush (e.g., 3mm). We observed that, to avoid cracks, it is necessary to paint 2-5 times superimposing layers of conductive paste with intervals of ~5 to 10 min drying time in between. Incremental painting also increases conductivity.

Stencil Painting. Inspired by stencil or screen printing techniques for soft circuits [73, 90, 113], we use stencils cut from 0.11mm thick acetate sheets using a vinyl cutter. We found that the self-adhesion of most bioplastic sheets is sufficient to keep the stencil firmly fixed in place. Conductive pastes are spread thinly across the stencil using Japanese spatulas, before the stencil is peeled off. Stencil painted circuits dry at room temperature (~25°C) within ~30 min.

Table 2: Material formulation for conductive pastes. We report conductors and fillers as ratio of the adhesive’s weight.

<table>
<thead>
<tr>
<th>Conductive Paste (CléoBio, starch-based)</th>
<th>Adhesive^a</th>
<th>Carbon Black^b</th>
<th>Essential OIl^c</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>12g 2g (16.67%) 2g-3 drops</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Conductive Paste (Edible Glue, CMC-based)</th>
<th>Adhesive^d</th>
<th>Carbon Black^e</th>
<th>Graphite^f</th>
<th>Essential Oil^g</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>12g 2g (16.67%) 0.6g (5%) 2-3 drops</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

^a CléoBio, Cléopatre, based on starch and water.
^b Carbon Black, Vulcan XC 72R.
^c Clove bud essential oil.
^d Edible Glue, Funcakes, based on carboxymethylcellulose (CMC).
^e Prographite, avg. particle size 10 micron.
^f optional, improves conductivity and compatibility with substrates.

5.1 EMG Sensor

Electrophysiological sensors are challenging to fabricate because they require low-impedance electrodes that adhere to skin [62, 87]. In this application example, we demonstrate the applicability of Interactive Bioplastics for EMG (Electromyogram) sensing and demonstrate how skin-exposed electrodes can be stenciled onto gelatin substrate. The gelling (or ‘melting’) point of gelatin is close to human body temperature (35°C), which allows our gelatin electrodes to act as bio-compatible adhesive that can be used directly on skin. Gelatin is also fully bio-degradable, which is particularly promising for components such as electrodes that are discarded after one-time use for hygienic or functional reasons.

We synthesized non-conductive (transparent) gelatin bioplastic (1:5:0.6, cf., Table 1) and combined it with the conductive paste from CléoBio and 16.67% carbon black, which offers a good compatibility (see Table 3). We designed three electrodes (20x20mm) by stencil painting a conductive paste onto gelatin substrate (25x25mm, ~0.5mm thick). Connectors are made from flexible anti-oxidation conductive silver thread (S0703FX-100GH by Suzhou TEK Silver Fiber Technology Co., Ltd) and attached using conductive paste.

We placed a reference electrode and two measurement electrodes on the flexor carpi radialis muscle line, each with the conductive paint in direct skin contact. Our self-adhesive electrodes are robust enough to be picked up (e.g., with fingers or tweezers) and repositioned until the desired alignment is reached. Finally, we applied non-conductive alginate sheets as outermost layer to keep the non-bio-based connectors firmly in place and as wrapping to insulate the silver thread from the wearer’s skin.

To interface the electrodes, we used an off-the-shelf EMG sensing kit (Seed Studio Groove) with a sampling rate of 250Hz without any additional fine-tuning or tweaking of hardware parameters. Silver thread connectors are connected using standardized 0.1” (2.54mm) crimp connectors. The bio-based electrodes succeed in picking up muscle activity including gestures such as hand turning or flexing. Our results show that the electrodes can capture EMG signals with an average SNR of 21.84 dB, exceeding the required SNR of 10 dB [10].

Table 3: Compatibility of different types of substrate sheets with bio-based carbon-infused pastes. Carbon-infused craft glue (STYLEX®) and Bare Conductive® added for comparison.

<table>
<thead>
<tr>
<th>Conductive Paste</th>
<th>Adhesive</th>
<th>Conductor</th>
<th>Filler</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edible Glue</td>
<td>Carbon Black</td>
<td>✓ ✓ ✓ ✓ x x x</td>
<td></td>
</tr>
<tr>
<td>Edible Glue</td>
<td>Carbon Black</td>
<td>✓ ✓ ✓ ✓ x x x</td>
<td></td>
</tr>
<tr>
<td>Edible Glue</td>
<td>Carbon Black</td>
<td>✓ ✓ ✓ ✓ x x x</td>
<td></td>
</tr>
<tr>
<td>CléoBio Carbon Black</td>
<td>✓ ✓ ✓ ✓ ✓ ✓ ✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Craft Glue</td>
<td>Carbon Black</td>
<td>✓ ✓ ✓ ✓ ✓ ✓ ✓</td>
<td></td>
</tr>
<tr>
<td>Bare Conductive</td>
<td>✓ ✓ ✓ ✓ ✓ ✓ ✓</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

x single layer; conductive paste exposed.
□ sandwiched conductive paste.
(*) only applicable with lower carbon black ratios (tested for 10%).
At the electrodes’ end-of-life they can be degraded (e.g., composted) or disassembled and re-molten. An example process is shown in Figure 6. The conductive water-soluble paste facilitates re-melting of the non-conductive gelatin substrate: larger flakes can be scraped off and removed with a spatula, any remaining residue is then washed off with cold water.

5.2 Micro-controller Shield
In this example, we demonstrate how our approach allows to create self-contained sustainable devices, by combining a bio-based substrate with conventional electronic components. We show how at its end-of-life, the device can be disassembled and components reused by melting the substrate. Using beeswax as a sustainable and re-shapeable substrate, we stencil painted a simple micro-controller shield inspired by Buechley et al.’s ‘micro-controller patches’ [14]. It contains an ATTiny45, a LED, and a resistor (cf., Figure 7a-e).

The beeswax substrate was prepared 1.1mm thick by sandwiching beeswax pellets between two sheets of baking parchment and melting them using a household iron. No additives or fillers are required. We used edible glue with 16.67% carbon as conductive paste. We stencil painted a board layout (loosely based on one of Buechley’s [13]) with the conductive paste. An ATTiny controller was pierced through the beeswax substrate. Then, we added surface-mount components (LED, resistor, and cell-coin battery, metal studs as connectors) and secured them in place with conductive paste.

At its end-of-life, the device’s substrate can be recycled (cf., Figure 7f-h) and electronic components can be re-used.

6 CONDUCTIVE BIOPLASTIC FOAM
Foams have a form factor that is of great interest for soft devices, due to its volumetric geometry, its deformability, and compelling tactile ‘feel’. Prior work has demonstrated non-conductive bioplastic foams (short ‘biofoams’) created by inserting an emulsifier into the material formulation for bioplastic [67, 97]. We contribute a DIY approach for the creation of (piezo-)resistive biofoam using Carbon Black, and demonstrate its use as a pressure sensor.

Material Formulation & Synthesis. Non-conductive DIY biofoams have been reported from gelatin and agar [27, 97]. Foams from alginate have been addressed in material science research [54], but are not easily accessible in DIY settings: alginate requires to be cured, i.e., sprayed with a calcium lactate solution. In the case of volumetric shapes, gel formation does not permeate and the inside remains liquid. Starch-based bioplastics have also been reported inapplicable as they form non-Newtonian materials (dilatants) that do not yield foam [27]. We thus decided to make use of gelatin.

We extend existing formulations for gelatin foam [27, 97] by adding carbon black as conductor. Carbon black has to be added after adding the emulsifier (e.g., biodegradable dish soap). We prepared our foam using the ratios and off-the-shelf materials presented in Table 4. We mixed gelatin with glycerin and water using a commodity hand mixer. Then, the emulsifier is added, and the mixture is whisked to create a foam. After whisking, carbon black is folded in carefully and the foam is poured into the desired shape. It is ready to be used after ~30 min of drying time. The sensor dries out slightly over time, reducing its softness and dimensions. We observed that foam shrinks considerably in the first 5 - 10h (e.g. 10 to 15%). When completely dry, the foam is no longer deformable enough for pressure sensing. However, fully dried out sensors (~6
We characterize the electrical and mechanical behavior of our conductive bioplastic materials.

7.1 Electrical Resistance

We analyze our conductive sheets’ and pastes’ sheet resistance (also known as surface resistivity). Following prior work [42, 57, 95], we obtain sheet resistance ($\Omega/\square$) through division by the trace area, which establishes comparability independently of trace width, and by averaging the results for each material.

Conductive Sheets. We cut evenly sized strips (10mm x 70mm) using a plotter cutter from alginate (0.15mm thick) and gelatin sheets (0.30mm thick) of different compositions, each with 1, 2 and 4 layers. We used a multimeter and 4 repeated measurements to determine sheet resistance as describe above. Our results (Table 5 right) have several practical implications: Alginate sheets exhibit higher conductivity than sheets with gelatin as polymer but otherwise identical material formulation. For both polymers, conductivity can be improved when multiple layers of thin sheets are stacked on top of each other. Carbon black (VULCAN) outperforms activated charcoal (GEWÜRZLAND) and carbon graphite (PRO-GRAPHITE) as conductor. Increasing the carbon ratio (e.g., to 4.6%) can increase conductivity, but also cause the sheet to crack during drying. Furthermore, conductivity of gelatin sheets increases when transglutaminase (TGase, 3.4%) is added as additional binding agent, whereas adding sorbitol (SRB, 3.4%) has the opposite effect.

Conductive Pastes. We determined the sheet resistance for stencil painted traces of 20mm, 5mm, and 1mm width using a multimeter and four repeated measurements. The traces were created by stencil painting on a substrate of 0.11mm thick acetate. Our results (Table 5 left) have practical implications as follows: Carbon black (VULCAN) outperforms activated charcoal (GEWÜRZLAND). Higher carbon ratios (e.g., 16.67%) improve conductivity but also decrease the paste’s viscosity which may impair end-to-end conductivity, i.e., cause traces to crack. For illustration, we selectively report on failed samples (denoted -) with large particle size can alleviate this issue. Best results are obtained using carbon graphite as filler. Following this strategy, our most conductive bio-based paste, composed from ‘edible glue’ (FUNCAKES), carbon black and carbon graphite, is even on-par with Bare Conductive – a commercially available, conductive paint containing carbon black and carbon graphite [91]. Although Bare Conductive paint is considered safe to handle, non-toxic, and contains natural resin [37], it also contains petrochemical humectants, processing aids and preservatives some of which may release formaldehyde. Thus, it is well-suited for baseline comparison but does not fully meet our requirements for sustainable DIY bioplastics.

7.2 Mechanical Characteristics

We analyze mechanical characteristics of sheets, both conductive and non-conductive. For those experiments, we cut evenly sized samples of 10mm x 80mm size using a plotter cutter. For measurement, we used a linear guide machine based on a Nanotec ST4118L1804-A stepper motor with a maximum elongation of 100mm moving at 1.3mm/sec (300 steps/sec) and a ARCELI HX711 : 2kg load cell setup. 60mm of the sample length is exposed during measurement. In addition, we report on resistance change under pressure for the conductive foam.

Table 4: Material formulation for conductive foam.

<table>
<thead>
<tr>
<th>Conductive Gelatin Foam</th>
<th>Gelatin&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Dist. Water</th>
<th>Glycerin&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Emulsifier&lt;sup&gt;c&lt;/sup&gt;</th>
<th>Carbon Black&lt;sup&gt;d&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (45g) : 1.3 (60g) : 0.6 (30g) : 0.13 (6g) : 0.7% (1g)</td>
<td>Halal Gelatin, Inka Foods, 250 bloom.</td>
<td>Organic Glycerin, Doktor Klaus, 99.7%.</td>
<td>Organic Dish Soap.</td>
<td>Carbon Black, Vulcan XC 72R.</td>
<td></td>
</tr>
</tbody>
</table>

months after being cast) can be re-hydrated any time by soaking for ~3h in cold water.

6.1 Gelatin Foam Pressure Sensor

Inspired by the literature on “foamy” or “squishy” sensors [86, 111] we created a pressure sensor from conductive gelatin foam that acts as squeezable sensor for physical user interfaces. For pressure sensors, like the one shown in Figure 8, we used 45g gelatin, adapting the amounts of glycerin (30g), water (60g), and dish soap (6g) accordingly. We added 1g of carbon black. The mixture was then poured into two compartments of a silicone form (each 3x8cm). After ~30 min, we removed the pieces and cut them in half. Each of the resulting sensors is ~8 by 6cm wide and 3cm high.

One electrode (Silver Nylon Tape, 8 by 6cm wide) is attached to the top, and one to the bottom of the sensor. We added one thinner sheet of non-conductive gelatin foam for insulation on top of each electrode. Both electrodes are connected to an Arduino Uno board using a voltage divider scheme, where the foam acts as a variable resistor. We demonstrate satisfying performance ~12h after being cast. Figure 8a-d illustrates its ability to deform with a sampling rate of 250Hz, the bio-based pressure sensor succeeds in picking up gestures such as slight touches and firm presses.

Our conductive biofoam pressure sensor can be hydrated, remolten, and whisked again to create fresh bioplastic foam.

Figure 8: A pressure sensor created from gelatin foam. The pressure sensor can be squeezed and freely deformed, reverting quickly to its original shape (a-d). Resistance changes caused by deformation can be read for pressure sensing (f).
Table 5: Experimental measurements of sheet resistance for various conductive pastes (left) and single- and multi-layered sheets (right). Samples without end-to-end conductivity denoted as - Ω/□. Our top-performing bio-based paste (last row) is on-par with petrochemical off-the-shelf products. Stacking multiple sheets allows to reach a similarly satisfactory conductivity.

Sheets: Tensile Strength. We determine tensile strength of conductive and non-conductive samples (gelatin and alginate) by measuring stress (tensile force in g) in relation to strain (elongation in %) for 5 samples per each material. Testing multiples allows to map out the variability of behavior to be expected when sheets are produced in DIY settings (e.g., resulting in impurities). Our results are shown in Figure 9 and have the following practical implications: for both gelatin and alginate sheets, increasing the amount of glycerin increases maximum strain (i.e. elongation) but decreases strength. Adding carbon black to obtain conductive sheets decreases maximum strain and stress, i.e. the sheet becomes less stretchable and breaks earlier. This substantiates our (tactile) observation that carbon-infused sheets are more brittle, and less flexible.

Sheets: Resistance Change under Strain. We chose to measure the resistance change under mechanical deformation of the alginate sheets, as their stretchability (e.g., compared to gelatin) affords use as variable resistor. To this end, we analyze alginate conductive sheets (1 : 1 : 25 with 2.3% carbon black) and in layers of 1, 2 and 4. We measured using our custom device (as described above), and executed 5 deformation cycles under 15% strain (elongation), taking 3 measures of force and resistance at every 1mm without any waiting time between cycles. We report on our observations in Figure 10. The practical implications are as follows: a higher number of layers decreases the hysteresis effect in resistance, i.e., behavior under stretch and relaxation start to converge. The graphs also show that the behavior of the first deformation cycle differs from the other four measured cycles. This is caused by the material’s elastic retraction being slower than the cycle duration.

In summary, conductive sheets tend to be more fragile than non-conductive sheets with otherwise equal composition (e.g., ~200g vs. ~280g for 9% elongation and alginate) and display effects of hysteresis. In consequence, circuits and sensors (particularly stretch or bend), should ideally be composed from multiple layers. Layering increases (1) tensile strength, (2) helps to minimize hysteresis, and (3) improves conductivity, as shown in the previous section.

Figure 9: Tensile strength measurements of conductive and non-conductive sheets from alginate (left) and gelatin (right). We compare different ratios of glycerin (stiff to flexible sheets) and carbon black (no, low and medium conductivity).

Figure 10: Resistance change under strain of conductive and non-conductive sheets from alginate and gelatin. Sheets: resistance change under strain of alginate and gelatin under 15% elongation.
We report on repeated measurements of the same sensor, on acetate. We then placed a 50g load on top to ensure firm contact between two plate electrodes created from adhesive copper tape material. Using the parallel plate method, we placed each of them evenly sized samples (20mm x 20mm) from each (fully dried) sheet. We used a plotter cutter to cut non-conductive sheets in Table 6. We report on repeated measurements of the same sensor, on annealed, and four days later (D+4).

Table 6: Characterization of bulk resistance for non-conductive bioplastic sheets.

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Additive</th>
<th>Thickness</th>
<th>Bulk Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alginate</td>
<td>0.09 mm</td>
<td>4.119 MΩ</td>
<td></td>
</tr>
<tr>
<td>Gelatin</td>
<td>0.30 mm</td>
<td>3.299 MΩ</td>
<td></td>
</tr>
<tr>
<td>Gelatin</td>
<td>TGase</td>
<td>0.30 mm</td>
<td>3.398 MΩ</td>
</tr>
<tr>
<td>Gelatin</td>
<td>SRB</td>
<td>0.30 mm</td>
<td>2.984 MΩ</td>
</tr>
</tbody>
</table>

between substrate and electrodes. We measure bulk resistance using a multimeter and two repeated measurements separated by a 1 min interval.

Our results have the following practical implications: gelatin sheets (when dry) exhibit good dielectric properties which makes them even more suitable as substrate for conductive pastes, e.g., to create electrodes. Here, TGase does not have a notable effect on bulk resistance. In contrast, SRB decreases bulk resistance. Even though micro-thin, alginate sheets (0.9mm) still possess satisfying insulating properties, on-par with 0.3mm thick gelatin sheets. They are most beneficial when a stretchable and conformable insulation (e.g., against skin) is desired.

8 DISCUSSION

We believe that our approach can benefit HCI by expanding the horizon of prototyping activities and by adding bio-based and bio-degradable materials to the available range of sustainable alternatives. Our goal is to open up a space to be used and explored complimentarily and in combination with conventional materials and existing techniques, not (yet) to fully substitute all conventional electronic components at once. In this, our vision falls in line with a common view on the zero waste movement: “We don’t need a handful of people doing zero waste perfectly. We need millions of people doing it imperfectly” [11]. To this end, we believe that by opening up a space for prototyping electronics with bioplastics, this work can act as valuable starting point for sustainable prototyping.

Yet, it is also not without its limitations, on which we reflect in the following.

8.1 Practical Impact & Sustainability

Using DIY bioplastics for prototyping does not entirely solve sustainability problems. Instead, our approach lowers the entry barrier for using bio-based and bio-degradable materials for prototyping.

Choice of Materials. In order to boost the accessibility of our DIY approach to Interactive Bioplastics, we made use of non-laboratory grade products. This is an essential quality for non-experts and hobbyist makers but also comes at the cost product variability (e.g., Bloom strength of gelatin) and imprecise declarations, e.g., activated charcoal as food supplement might give nutritional values but no particle size. In addition, while food-grade materials offer benefits in terms of accessibility and low toxicity, there may still be a risk of inducing allergies as medium-to-long-term effects when brought in contact with skin [110]. Similarly, the provenance of plant-based polymers is not always disclosed by the manufacturers, which may challenge sustainability claims in terms of transport emissions. Gelatin, while bio-based and fully bio-degradable, can raise ethical questions, as it is typically a by-product of the meat and leather

Figure 10: Experimental measurements of resistance change under strain. We show hysteresis cycle graphs for samples of conductive alginate sheets with one, two and four layers.

Figure 11: Experimental measurements of resistance change that occurs when pressure is applied to the conductive foam. We report on repeated measurements of the same sensor, on the day of casting (D) and four days later (D+4).

as the amplitude of resistance change under pressure decreases. Yet, measurable differences in resistance remain large enough to distinguish different pressure levels: 763.8 Ω per 100g for D and 82.5 Ω per 100g for D+4.

7.3 Dielectric Behavior

We present a characterization of the dielectric behavior of different non-conductive sheets in Table 6. We used a plotter cutter to cut evenly sized samples (20mm x 20mm) from each (fully dried) sheet material. Using the parallel plate method, we placed each of them between two plate electrodes created from adhesive copper tape on acetate. We then placed a 50g load on top to ensure firm contact

![Figure 10: Experimental measurements of resistance change under strain. We show hysteresis cycle graphs for samples of conductive alginate sheets with one, two and four layers.](image)

![Figure 11: Experimental measurements of resistance change that occurs when pressure is applied to the conductive foam. We report on repeated measurements of the same sensor, on the day of casting (D) and four days later (D+4).](image)
industry [27], i.e., derived from animal bones and tissue. Off-the-shelf dish soaps, as used as emulsifier in our conductive foams, are awarded the label biodegradable even with a residue of up to 10% after biodegradation (e.g., containing problematic phosphates) [63].

**Bio-Degradability.** Our approach advocates for simple, easy-to-access materials and tools. To facilitate replicability we also opted for experiments that can be repeated in common fablab environments. We did not determine biodegradability experimentally due to the need for specialized equipment and controlled conditions, and as it is already comprehensively covered in prior work [8, 46, 101, 103]: Gelatin films are reported to biodegrade within ~20-35 days depending on the concentration of plasticizer [21]. Prior work reports sodium alginate to take 7 days for 60-70% of degradation [65]. Carboxymethylcellulose is biodegradable and non-toxic, with a degradation time of 7-10 days [123]. The degradation time of starch has been reported to be ~174 days [51]. All indicate sustainability benefits over conventional prototyping materials [69].

**Carbon Black as a Conductor.** The use of carbon black as a conductor allows us to reach conductivity that is on-par with commercially available but not bio-based products. Yet, carbon black (like activated charcoal or graphite) is not bio-degradable but inert, i.e., those carbon types do not fully bio-degrade. Literature suggests that carbon black may decompose slowly over time, with a large portion of decomposition (47%) within the first two years [36]. The rate of degradation depends on various factors such as soil moisture, temperature, or soil erosion. Furthermore, carbon black and activated charcoal have shown to only have negligible or even beneficial effects on the environment [103, 118]. Lastly, our application cases all contain less than 10% carbon black proportionate to the other bio-degradable raw materials, i.e., they can still qualify as biodegradable (defined by EN 13432 [9]). Novel approaches promise eco-friendly production of (petrochemical) carbon black from recycled waste materials [20]. Alternatively, future work might explore food-grade carbon black, a purified form produced from vegetable matter with larger particle sizes, known as vegetable carbon, E153.

### 8.2 Challenges in the Prototyping Process

Working with bio-based and bio-degradable materials is fun, exciting and ideally suited to raise awareness for sustainability issues, but also poses a variety of challenges to HCI prototyping practice:

**Environmental Conditions:** DIY bioplastics are more susceptible to environmental conditions than conventional prototyping materials. Air flow and pressure, temperature or UV exposure during drying can have desired and undesired effects by accelerating or slowing down water evaporation. We (re-)produced our application cases at two different locales, once in a fablab environment (~24°C, 60% humidity), and once in an open space office (~25°C, 30% humidity). Despite those different environmental conditions, our material formulations allowed us to consistently produce functional prototypes. Yet, precise reproducibility is still limited by the extent to which environment conditions can be documented or re-created.

**Time and Production Management:** The time required for materials to dry after synthesis causes prototyping with DIY bioplastics to be more time intensive than working with conventional materials. For instance, sheets cast from silicone may require minutes or hours to reticulate. In contrast, a similar sheet cast from alginate, agar, or gelatin may take 1 to 4 days to dry under otherwise equal environmental conditions.

**Familiarization with the Material:** Material formulations require adaptation if raw materials are substituted or fabrication spaces switched. This requires makers to perform hands-on experimentation to understand the effect of materials quantities and processing. Our systematic analysis of mechanical and electrical properties provides a starting point supporting this familiarization process.

**Material Storage:** Biodegradability comes at the cost of storage challenges. Conductive sheets are ideally stored on a carrier material (e.g., acetate) and protected from humidity and sun exposure. So far, we stored unused and pre-cut conductive sheets as well as our beeswax microcontroller for approx. 9 months. All remained functional. We expect pre-cut bend sensors to show similar behavior: here the limitation is rather the number of times a sensor can be re-applied and re-used. Pastes have limited pot-life, due to risk of contamination, and need to be freshly prepared. Stored gelatin foam hardens over time, requiring rehydration after several months. In our observation, the latter may come at the risk of contamination, this is why we recommend re-melting and re-casting.

**Safety Measures:** Carbon black has to be handled carefully which might lead to a slow processing time. Its manipulation requires measures to prevent dust formation and inhalation, such as wearing safety equipment (e.g., masks). Hence, Interactive Bioplastics including carbon black are not ideally suited for educational purposes, e.g., use in (secondary) schools. Due to the risk of combustion at temperatures larger than 300 Deg (cf., VULCAN MSDS⁵), we also advise against laser cutting carbon-infused bioplastics.

### 8.3 Inherent Technical Limitations

Our focus on sustainable materials comes at the cost of inherent technical limitations.

**Shapes and Scalability:** Our prototypes comprise single-layer circuits. We expect it should be possible to use the bio-materials as dielectric separator layer to create multi-layer circuits; this should be investigated in future work. Furthermore, scalability beyond the dimensions of the prototypes presented here remains an open question: long carbon traces have a high electric resistance, which impacts conductivity and capacitance. Complex 3D foam shapes need to be further characterized.

**Performance and Durability:** Our organic, carbon-based conductors are in the same ballpark as conventional formulations of carbon-infused soft conductive materials. While they are naturally less conductive than silver or copper, our work does not aim to compete with these metal-based conductors. On the opposite, one can even take advantage of the materials’ (piezo-)resistivity to create sensors. Substrates made from bio-based, hydrophilic polymers are less robust than e.g., silicone elastomers. This is not surprising, as naturally, bio-degradability comes at the cost of our materials being

susceptible to microorganisms (e.g., fungi), heat, moisture or UV exposure.

Last but not least, our DIY approach towards creating functional interactive devices relies on the combination with conventional electronics, e.g., semiconductors and microcontrollers, and requires a power supply. While this lowers the entry hurdle for making use of our materials, it is also a limitation that may be addressed by future work. Emerging material science works, including the use of gelatin as photosensitive material [16], or fruit-based transient batteries [109], are promising, but their transfer to DIY fabrication remains a challenge. Nevertheless, there are options to extend the present work within these limits: future work might build upon the bio-based substrates and conductors presented in this work to explore the fabrication of bio-based capacitors modeled after paper capacitors [116] or expand upon DIY gelatin-based solar cells for power supply [76].

9 CONCLUSION

We presented Interactive Bioplastics as a DIY approach towards creating soft interactive devices from bio-based and bio-degradable materials. In this work, we contributed (1) conductive bioplastic sheets, pastes and foams along with an accessible end-to-end approach for material synthesis and device fabrication. We (2) evaluated the applicability of our bioplastic materials as part of HCI prototyping practice by re-implementing a set of representative examples from prior work. We furthermore conducted (3) a systematic characterization of mechanical and physical properties, including our pastes’ and sheets’ conductivity and tensile strength. Our results demonstrate that it is possible to create bio-based conductors that are on-par with commercially available, and not bio-based products. Functional soft devices can be created using bio-based and bio-compatible materials in combination with conventional electronic components. These promising results highlight that it is possible to gradually replace conventional materials with more sustainable alternatives which may broaden the field’s perspective on sustainable prototyping.

ACKNOWLEDGMENTS

This project received funding from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (grant agreement No. 714797 ERC Starting Grant InteractiveSkin).

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Prototyping Soft Devices with Interactive Bioplastics


