Prototyping Soft Devices with Interactive Bioplastics

Marion Koelle*
Saarland University,
Saarland Informatics Campus,
Saarbrücken, Germany and
OFFIS – Institute for
Information Technology,
Oldenburg, Germany
marion.koelle@offis.de

Madalina Nicolae*
Saarland University,
Saarland Informatics Campus,
Saarbrücken, Germany and
Léonard de Vinci Pôle Universitaire,
Research Center,
Paris La Défense, France
madalina.nicolae@devinci.fr

Aditya Shekar Nittala
Saarland University,
Saarland Informatics Campus,
Saarbrücken, Germany and
University of Calgary,
Calgary, Canada
anittala@ucalgary.ca

Marc Teyssier
Léonard de Vinci Pôle Universitaire,
Research Center,
Paris La Défense, France
marc.teyssier@devinci.fr

Jürgen Steimle
Saarland University,
Saarland Informatics Campus,
Saarbrücken, Germany
steimle@cs.uni-saarland.de

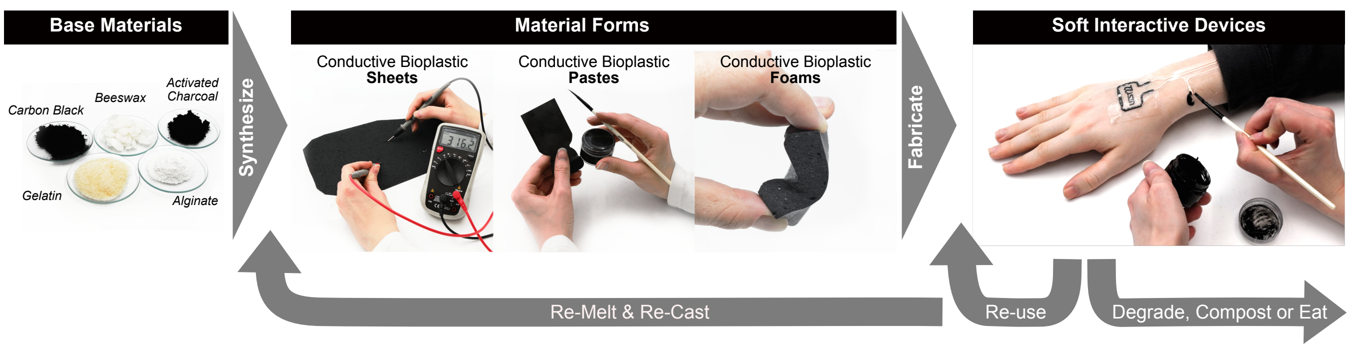

Figure 1: We synthesize conductive bioplastic sheets, pastes, and foams from sustainable base materials. Additive and subtractive fabrication methods allow to combine them with conventional electronics to create soft interactive devices. If no longer used, devices can be disassembled and parts re-used,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

*Both authors contributed equally to this research.

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CCS CONCEPTS

• **Human-centered computing** → **Human computer interaction (HCI)**; • **Hardware** → **Emerging technologies**.

KEYWORDS

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

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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 biodegradable 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, dielectic 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 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 mixtures 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 fablab 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 re-molten 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

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

Alginate Sheets						
Alginate[a]		Dist. Water		Glycerin[b]		Carbon Black[c]
1 (3g)	:	25 (75g)	:	1 (3ml)		2.3% (1.95g)
Gelatin Sheets						
Gelatin[d]		Tap Water		Glycerin[b]		Activated Charcoal[e]
1 (6g)	:	5 (30g)	:	0.6 (3ml)		5% (2g)

[a] Sodium Alginate, Biozoon, 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.

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 cPDMS from silicone and carbon black [112], is increasingly adopted by HCI 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 glycerin (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.

Synthesizing & Casting Sheets. Sheets from *gelatin* are composed from distilled water, glycerin 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 liquified, 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

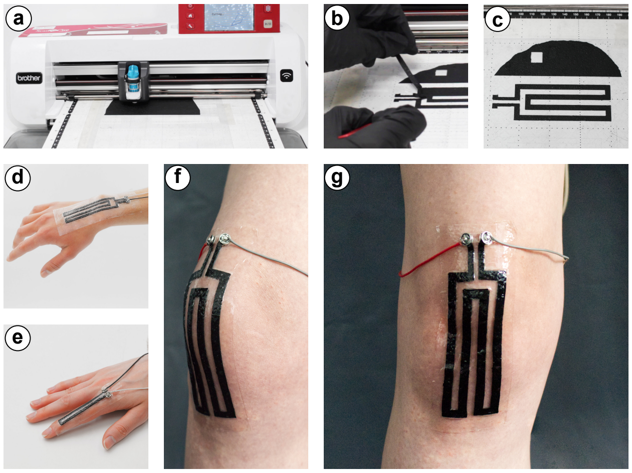

Figure 2: Plotter cutting (a-c) allows to fabricate differently scaled bend sensors, e.g., to be placed on wrist (d), finger (e) and knee (f, g), out of carbon-infused alginate.

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, glycerin 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 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 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 4.39k Ω (extended knee) to 5.44k Ω (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 a new 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

Figure 3: Circuit (a) fabricated from a stack of three conductive alginate sheets using a plotter cutter. A surface-mount LED (a-c) can be driven at as low as 5V and controlled via a capacitive button (b).

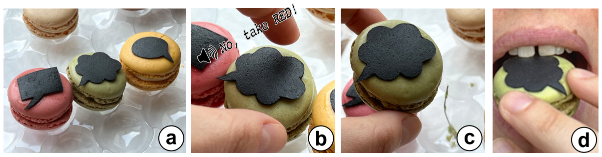

Figure 4: Our pastry application case (a) uses conductive bioplastic sheets from gelatin and activated charcoal for 'speech bubble' capacitive proximity sensors (b-c). They have the potential to be edible (d).

how conductive traces can be created from our conductive alginate sheets and combined with conventional electronics (e.g., LEDs).

We use a plotter cutter to create the circuit (shown in Figure 3) and transfer it to a non-conductive (transparent) alginate sheet. Cut into 1.5mm wide traces of ~65mm length and stacked in three layers, our conductive alginate sheets are sufficiently conductive to drive a surface-mount LED at as low as 5V (no current limiting resistor). We connect LED and traces using a conductive paste (cf., subsequent section) from CléoBio infused with 10% carbon black.

For interactivity, we added a capacitive touch sensing button to turn the LED on or off. We used a MPR121 module connected to an Arduino Uno board to detect capacitive touch and control the LED. The bioplastic circuit is connected to a re-usable adapter from copper traces on acetate and secured with conductive paste. If no longer in use, these 'soldered' connections can be dissolved in water and the LED and adapter retrieved. Alginate sheets can, e.g., be added to the compost.

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, can be deformed, 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 286k$\Omega/\square$ (re-cast sheet) and 350k$\Omega/\square$ (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.

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 micro-controller shields. They also enable skin-exposed electrodes from gelatin that possess self-adhesion to skin.

Material Formulation & Synthesis. We present a novel DIY formulation for conductive pastes based on two types of bio-based adhesives that we infuse with carbon black. For an easy production, we decided to use off-the-shelf bio-based adhesives: organic starch glue (CléoBio), made from starch and water, and 'edible glue' (FUNCAKES), made from carboxymethylcellulose (CMC) and water. We achieved sufficiently conductive results using ratios of 10% (10g : 1g) and 16.67% (12g : 2g) carbon black.

Due to its fluid consistency, 'edible glue' requires a filler, i.e., a thickening agent. While non-conductive fillers such as starch are also applicable, we obtained a good viscosity and increased conductivity by combining carbon black (as conductor), with carbon graphite (as filler). The latter is beneficial due to its large particle size, absorption power and (medium) conductivity.

Conductor, adhesive, and filler are hand-mixed by carefully folding in carbon black to prevent dust formation. We furthermore added one drop of clove bud essential oil per 3g of adhesive for its antibacterial and antifungal properties. Other oils such as aegle, citronella, or eucalyptus are applicable as well [92]. We store the

[1] https://www.arduino.cc/reference/en/libraries/talkie/, accessed 26/07/2022

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

Conductive Paste (CléoBio, starch-based)			
Adhesive[a] 12g	Carbon Black[b] 2g (16.67%)		Essential Oil[c] 2-3 drops
Conductive Paste (Edible Glue, CMC-based)			
Adhesive[d] 12g	Carbon Black[c] 2g (16.67%)	Graphite[e,f] 0.6g (5%)	Essential Oil[c] 2-3 drops

[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.*

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[2]) 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. This paste enables, for instance, skin-exposed electrodes on gelatin. Improved results can be achieved by enclosing the painted trace between two layers of non-conductive bioplastic: this sandwich technique (also used by Bell et al. [7]) allows water to evaporate slowly through the hydrophilic sheet during the drying process, therefore reducing the risk of cracks.

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.

[2]containing a 3:1 mixture of Methylchloroisothiazolinone (CIT) and Methylisothiazolinone (MIT) as specified on the package.

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.

Conductive Paste: Adhesive	Conductor	Filler	Alginate □	Alginate ⊡	Gelatin □	Agar □	Acetate □	Beeswax □
Edible Glue	Carbon Black		✗	✓	✗	✗	✗	✓
Edible Glue	Carbon Black	Starch	✗	✓	✗	✗	✓	✓
Edible Glue	Carbon Black	Graphite	✗	✓	✗	✗	✓	✓
CléoBio	Carbon Black		✓*	✓	✓	✓	✓	✓
Craft Glue	Carbon Black		✗	✓	✓*	✓	✓	✓
Bare Conductive Paint			✗	✗	✓	✓	✓	✓

□ single layer; conductive paste exposed.
⊡ sandwiched conductive paste.
(*) only applicable with lower carbon black ratios (tested for 10%).

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 not 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 (Seeed 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].

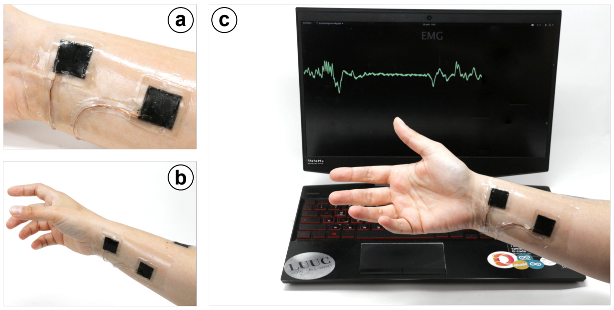

Figure 5: Skin-exposed electrodes stencil painted with conductive paste onto gelatin (a, b) are used for EMG sensing (c).

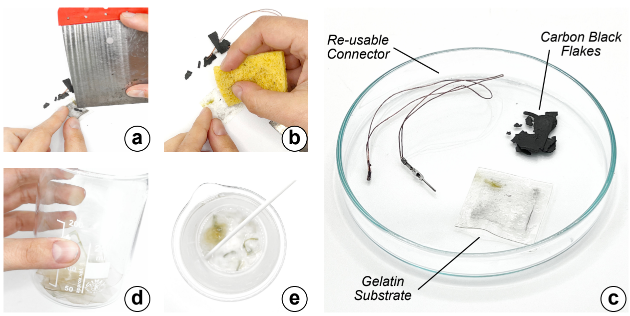

Figure 6: The conductive water-soluble paste facilitates electrode disassembly (a, b) into re-usable connectors, carbon flakes, and gelatin scraps (c), which we can re-melt (d, e).

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.

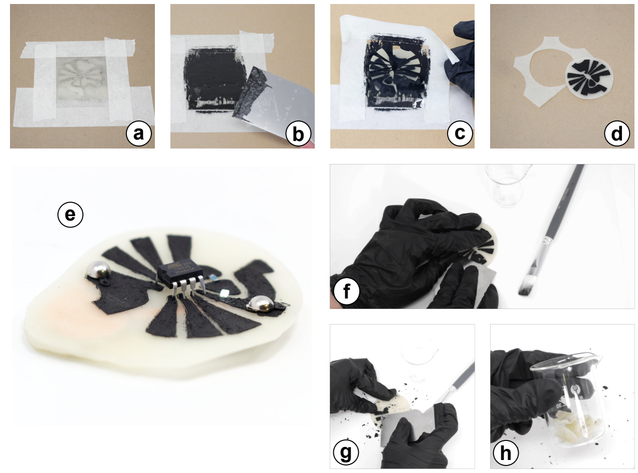

Figure 7: Micro-controller shield (e) from beeswax with stencil painted carbon-based traces (a-d). At its end-of-life electronic components can be easily disassembled (f), traces scratched off (g), and the substrate molten and re-used (h).

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 do 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

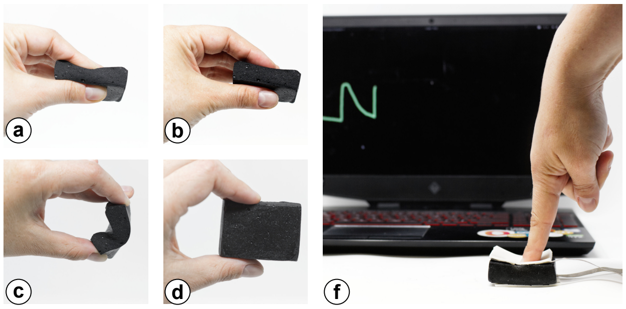

Figure 8: A pressure sensor created from gelatin foam. The pressure sensor can be squeezed and freely deformed, reverting quickly to its original shape (a-d). Resistance changes caused by deformation can be read for pressure sensing (f).

Table 4: Material formulation for conductive foam.

Conductive Gelatin Foam								
Gelatin[a]		Dist. Water		Glycerin[b]		Emulsifier[c]		Carbon Black[d]
1 (45g)	:	1.3 (60g)	:	0.6 (30g)	:	0.13 (6g)		0.7% (1g)

[a] Halal Gelatin, Inka Foods, 250 bloom.
[b] Organic Glycerin, Doktor Klaus, 99.7%.
[c] Organic Dish Soap.
[d] Carbon Black, Vulcan XC 72R.

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 four 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.

7 EVALUATION OF MATERIAL PROPERTIES

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 (Ω/□) 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 (PROGRAPHITE) 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 -Ω/□). Fillers 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 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.

Conductive Pastes

Material Formulation				Sheet Resistance
Adhesive	Carbon Type	Ratio	Filler	
CléoBio	Activ. Charcoal	16.67%	-	- Ω/□
Edible Glue	Carbon Black	16.67%	-	- Ω/□
Edible Glue	Activ. Charcoal	16.67%	-	1682.5 Ω/□
Craft Glue*	Carbon Black	10%	-	306.0 Ω/□
CléoBio	Carbon Black	10%	-	94.7 Ω/□
Edible Glue	Carbon Black	10%	-	66.5 Ω/□
Bare*	Carbon Black	n/a	Graphite	70.6 Ω/□
Craft Glue*	Carbon Black	16.67%	-	46.2 Ω/□
CléoBio	Carbon Black	16.67%	-	36.9 Ω/□
Edible Glue	Carbon Black	16.67%	Graphite	28.3 Ω/□

higher conductivity ↓

*) Not bio-based and not bio-degradable baselines: Bare Conductive® and commodity craft glue (STYLEX).

Conductive Sheets

Material	Sheet Resistance		
Conductive Gelatin Sheets	1 Layer	2 Layers	4 Layers
2.3% Carbon Black	6.4M Ω/□	997k Ω/□	511k Ω/□
2.3% Carbon Black, SRB	29.0M Ω/□	1.9M Ω/□	1.8M Ω/□
2.3% Carbon Black, TGase	7.5M Ω/□	733k Ω/□	93.4k Ω/□
4.6% Carbon Black	600k Ω/□	142k Ω/□	98.3k Ω/□
Conductive Alginate Sheets	1 Layer	2 Layers	4 Layers
4.6% Carbon Black	- Ω/□	- Ω/□	- Ω/□
2.3% Activated Charcoal	859k Ω/□	200k Ω/□	69.2k Ω/□
2.3% Carbon Graphite	926k Ω/□	161k Ω/□	36.1k Ω/□
2.3% Carbon Black	162.3 Ω/□	98.1 Ω/□	34.2 Ω/□

higher 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.

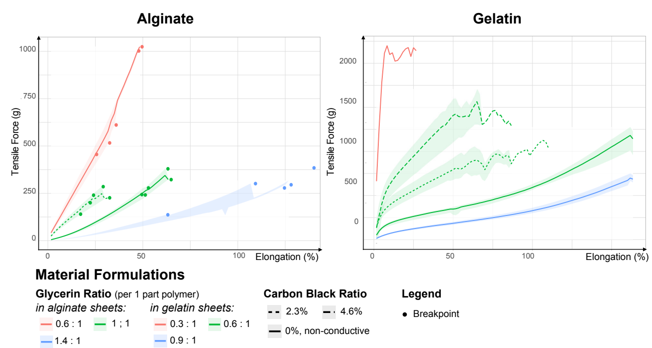

Figure 9: Tensile strength measurements of conductive and non-conductive sheets from alginate (left) and gelatin (right). We compare different ratios of glycerin (stiff to flexible sheets) and carbon black (no, low and medium conductivity).

Foam: Resistance Change under Pressure. We characterized the resistance change under pressure of the conductive foam. We used the following setup: a gelatin foam pressure sensor (cf., Section 6: 8cm by 5.5cm, one electrode each on the top and bottom side, plus non conductive foam sheets for insulation) is placed on a flat surface. To ensure uniform weight distribution we use a leak-proof 3D printed container of equal dimensions and 32g unladen weight. It is placed on top of the sensor. We measure change in resistance at intervals of 20g by adding the corresponding amount of water and performing 10 measurements for each interval. We report repeated measures on the day of casting (D), and after 96h (D+4). In the meantime, we stored the sensor in an airtight container. Our results are shown in Figure 11 and have the following practical implications: the gelatin pressure sensor exhibits a linear decrease in resistance when pressure increases. Our experiments confirm this linear response up to a load of 400g. Beyond this, the sensor may reach its extreme deformation and the signal becomes non-linear. When the sensor dries out, the overall resistance as well

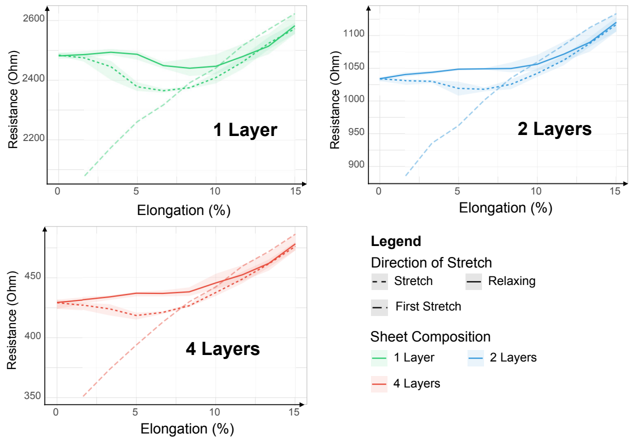

Figure 10: Experimental measurements of resistance change under strain. We show hysteresis cycle graphs for samples of conductive alginate sheets with one, two and four layers.

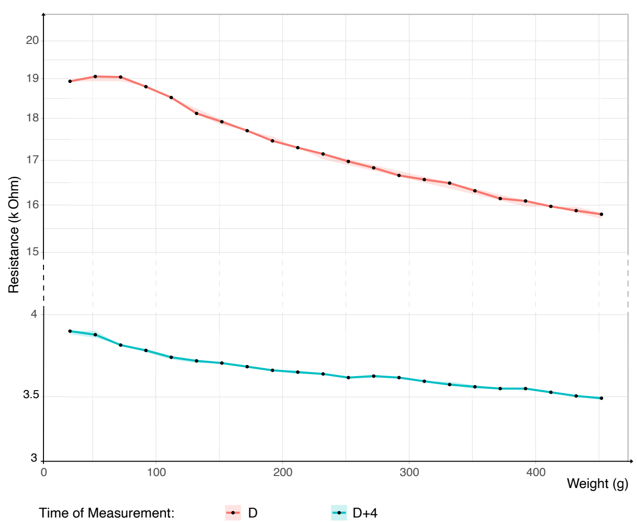

Figure 11: Experimental measurements of resistance change that occurs when pressure is applied to the conductive foam. We report on repeated measurements of the same sensor, on the day of casting (D) and four days later (D+4).

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

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

Polymer	Additive	Thickness	Bulk Resistance
Alginate		0.09 mm	4.119 MΩ
Gelatin		0.30 mm	3.299 MΩ
Gelatin	TGase	0.30 mm	3.398 MΩ
Gelatin	SRB	0.30 mm	2.984 MΩ

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 more suitable as substrate for conductive pastes, e.g., to create electrodes. Here, TGase does not have a notable affect on bulk resistance. In contrast, SRB decreases bulk resistance. Even though micro-thin, alginate sheets (0.09mm) still possess satisfying insulating properties, on-par with 0.3mm thick gelatin sheets. They are most beneficial where 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 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 then 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 alignate, 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 MSDS[3]), 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-)restitivity 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

[3]Vulcan XC72 Material Safety Data Sheet, https://www.fuelcellstore.com/msds-sheets/vulcan-xc72r-msds.pdf, accessed 26/07/2022

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.

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REFERENCES

[1] Jekaterina Aleksejeva, Paul Biedermann, Iulia Gavriliuc, Ona Orlovaite, and Danielle Wilde. 2019. Crafting Bioplastics: Materially Reconfiguring Everyday Food Practices. In *Proceedings of the 4th Biennial Research Through Design Conference 19–22/03/2019*. RTD Conference. https://doi.org/10.6084/m9.figshare.7855796.v2

[2] Agustín Arroyo. 2021. Plastic Smoothie. Retrieved July 26, 2022 from https://plasticsmoothie.com

[3] Vicente Arroyos, Maria L K Viitaniemi, Nicholas Keehn, Vaidehi Oruganti, Winston Saunders, Karin Strauss, Vikram Iyer, and Bichlien H Nguyen. 2022. A Tale of Two Mice: Sustainable Electronics Design and Prototyping. In *Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI EA '22)*. Association for Computing Machinery, New York, NY, USA, Article 263, 10 pages. https://doi.org/10.1145/3491101.3519823

[4] Michael F Ashby. 2012. *Materials and the Environment: Eco-informed Material Choice*. Elsevier.

[5] Camilo Ayala-Garcia, Valentina Rognoli, and Elvin Karana. 2017. Five Kingdoms of DIY-Materials for Design. In *EKSIG 2017 Alive Active Adaptive: International Conference on Experiential Knowledge and Emerging Materials*. TU Delft Open, 222–234.

[6] Moritz Bächer, Benjamin Hepp, Fabrizio Pece, Paul G. Kry, Bernd Bickel, Bernhard Thomaszewski, and Otmar Hilliges. 2016. DefSense: Computational Design of Customized Deformable Input Devices. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI '16)*. Association for Computing Machinery, New York, NY, USA, 3806–3816. https://doi.org/10.1145/2858036.2858354

[7] Fiona Bell, Latifa Al Naimi, Ella McQuaid, and Mirela Alistar. 2022. Designing with Alganyl. In *International Conference on Tangible, Embedded, and Embodied Interaction* (Daejeon, Republic of Korea) *(TEI '22)*. Association for Computing Machinery, New York, NY, USA, Article 2, 14 pages. https://doi.org/10.1145/3490149.3501308

[8] Fiona Bell, Netta Ofer, and Mirela Alistar. 2022. ReClaym Our Compost: Biodegradable Clay for Intimate Making. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 454, 15 pages. https://doi.org/10.1145/3491102.3517711

[9] European Bioplastics. 2015. EN 13432 Certified Bioplastics Performance in Industrial Composting. Retrieved July 26, 2022 from https://docs.european-bioplastics.org/publications/bp/EUBP_BP_En_13432.pdf

[10] Paolo Bonato, Tommaso D'Alessio, and Marco Knaflitz. 1998. A Statistical Method for the Measurement of Muscle Activation Intervals from Surface Myoelectric Signal during Gait. *IEEE Transactions on biomedical engineering* 45, 3 (1998), 287–299.

[11] Anne-Marie Bonneau. 2019. "We don't need a handful of people doing zero waste perfectly. We need millions of people doing it imperfectly.". Retrieved July 26, 2022 from https://twitter.com/ZeroWasteChef/status/1098682500237254656 [Tweet].

[12] Walter C Bosshart, Arvind Shah, and SR Bhat. 1983. *Printed Circuit Boards: Design and Technology*. Tata McGraw-Hill.

[13] Leah Buechley. 2010. MAS.962 Special Topics: New Textiles. Spring 2010. Massachusetts Institute of Technology: MIT OpenCourseWare. Retrieved July 26, 2022 from https://ocw.mit.edu/courses/media-arts-and-sciences/mas-962-special-topics-new-textiles-spring-2010/ [Course, License: Creative Commons BY-NC-SA.].

[14] Leah Buechley, Mike Eisenberg, Jaime Catchen, and Ali Crockett. 2008. The LilyPad Arduino: Using Computational Textiles to Investigate Engagement, Aesthetics, and Diversity in Computer Science Education. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Florence, Italy) *(CHI '08)*. Association for Computing Machinery, New York, NY, USA, 423–432. https://doi.org/10.1145/1357054.1357123

[15] Leah Buechley and Hannah Perner-Wilson. 2012. Crafting Technology: Reimagining the Processes, Materials, and Cultures of Electronics. *ACM Trans. Comput.-Hum. Interact.* 19, 3, Article 21 (oct 2012), 21 pages. https://doi.org/10.1145/2362364.2362369

[16] Sergio Calixto, Nina Ganzherli, Sergey Gulyaev, and Susana Figueroa-Gerstenmaier. 2018. Gelatin as a photosensitive material. *Molecules* 23, 8 (2018), 2064.

[17] Lara Campos. 2021. EN(DES)USO – A Poetic Approach to Materialities using Eggshells and Yerba Mate for Design Artefacts. Retrieved July 26, 2022 from https://ars.electronica.art/newdigitaldeal/en/el-barrio-food-waste-biomaterial/ Ars Electronica, Remix el Barrio, Food Waste Biomaterial Makers [Exhibition].

[18] Silvana Catazine and Josean Vilar of Naifactory. 2021. RE-OLIVAR – Creating Design Objects such as Lamps, Chairs, and Tiles from Olive Pits. Retrieved July 26, 2022 from https://ars.electronica.art/newdigitaldeal/en/el-barrio-food-waste-biomaterial/ Ars Electronica, Remix el Barrio, Food Waste Biomaterial Makers [Exhibition].

[19] Kyung Yun Choi and Hiroshi Ishii. 2021. Therms-Up!: DIY Inflatables and Interactive Materials by Upcycling Wasted Thermoplastic Bags. In *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Salzburg, Austria) *(TEI '21)*. Association for Computing Machinery, New York, NY, USA, Article 51, 8 pages. https://doi.org/10.1145/3430524.3442457

[20] Ad van Oorschot Chris Twigg and Patricia Geelen. 2017. Eco-Friendly Carbon Black Provides 'Green' Future for Black Pigments. Retrieved July 26, 2022 from https://www.pcimag.com/articles/103148-eco-friendly-carbon-black

[21] Pencho Dalev, Ekaterina Staromanova, Dimitar Dalev, RD Patil, James E Mark, Elena Vassileva, and Stoyko Fakirov. 2001. Biodegradation of Chemically Modified Gelatin Films in a Simulated Natural Environment. *Biotechnology & Biotechnological Equipment* 15, 2 (2001), 116–123.

[22] Clara Davis. 2017. Bioplastic + Activated Charcoal. Retrieved July 26, 2022 from https://clara-davis.com/albums/research/

[23] Clara Davis. 2017. The Secrets of Bioplastics. Retrieved July 26, 2022 from https://issuu.com/nat_arc/docs/the_secrets_of_bioplastic_

[24] Clara Davis. 2018. Agar bioplastic (heated) Ag02. Retrieved July 26, 2022 from https://materiom.org/recipe/208

[25] Clara Davis. 2020. BIOPLASTIC RECIPE [Fablab Barcelona]. Retrieved July 26, 2022 from https://class.textile-academy.org/tutorials/BIOPLASTIC-RECIPE.pdf

[26] Kristin N. Dew and Daniela K. Rosner. 2019. Designing with Waste: A Situated Inquiry into the Material Excess of Making. In *Proceedings of the 2019 on Designing Interactive Systems Conference* (San Diego, CA, USA) *(DIS '19)*. Association for Computing Machinery, New York, NY, USA, 1307–1319. https://doi.org/10.1145/3322276.3322320

[27] Margaret Dunne. 2018. Bioplastic cook book. Retrieved July 26, 2022 from http://fabtextiles.org/bioplastic-cook-book/

[28] David P Edwards, Sean Sloan, Lingfei Weng, Paul Dirks, Jeffrey Sayer, and William F Laurance. 2014. Mining and the African Environment. *Conservation Letters* 7, 3 (2014), 302–311.

[29] Nutrition EFSA Panel on Dietetic Products and Allergies (NDA). 2011. Scientific Opinion on the Substantiation of Health Claims related to Activated Charcoal and Reduction of Excessive Intestinal Gas Accumulation (ID 1938) and Reduction of Bloating (ID 1938) pursuant to Article 13 (1) of Regulation (EC) No 1924/2006. *EFSA Journal* 9, 4 (2011), 2049. https://doi.org/10.2903/j.efsa.2011.2049

[30] Jeffrey Yoo Warren Elisabeth Lorenzi. 2020. DIY Gelatin Solar Cell. Retrieved July 26, 2022 from https://issuu.com/elisabethlorenzi/docs/gelatin_solar_cell_issu

[31] Susana Jurado Gavino Elisenda Jaquemot and Nuria Bonet Roca. 2021. SQUEEZE THE ORANGE – A Jacket made of Vegan Fruit Leather based on Orange Peel. Retrieved July 26, 2022 from https://ars.electronica.art/newdigitaldeal/en/el-barrio-food-waste-biomaterial/ Ars Electronica, Remix el Barrio, Food Waste Biomaterial Makers [Exhibition].

[32] Hans-Josef Endres. 2017. Bioplastics. *Biorefineries* (2017), 427–468.

[33] Fabtextiles. 2018. Bio Filter: Bioplastic + Activated Charcoal. Retrieved July 26, 2022 from http://fabtextiles.org/bio-filter-bioplastic-activated-charcoal/

[34] Fabtextiles. 2019. Coffee Bio-Leather Bag. Retrieved July 26, 2022 from http://fabtextiles.org/coffee-leather-bag/

[35] Yusheng Feng, Aidan Kennedy, Erika Miyajima, Tsuiyee Ng, and Sydney Seo. 2020. Reuse Plastic for 3D Printing.

[36] Bente Foereid, Johannes Lehmann, and Julie Major. 2011. Modeling Black Carbon Degradation and Movement in Soil. *Plant and Soil* 345, 1 (2011), 223–236.

[37] Paul Forsythe. 2011. Bare Conductive Safety Data Sheet. Retrieved July 26, 2022 from https://cdn.sparkfun.com/datasheets/E-Textiles/Materials/MSDS_Bare%20Conductive%20Paint.pdf

[38] Kate Franklin and Caroline Till. 2018. *Radical Matter: Rethinking Materials for a Sustainable Future*. Thames & Hudson Incorporated.

[39] Qiliang Fu, Yi Chen, and Mathias Sorieul. 2020. Wood-based Flexible Electronics. *ACS nano* 14, 3 (2020), 3528–3538.

[40] Sujoy Kumar Ghosh, Jonghwa Park, Sangyun Na, Minsoo P Kim, and Hyunhyub Ko. 2021. A Fully Biodegradable Ferroelectric Skin Sensor from Edible Porcine Skin Gelatine. *Advanced Science* (2021), 2005010. https://doi.org/10.1002/advs.202005010

[41] C Valeria L Giosafatto, Antonio Fusco, Asmaa Al-Asmar, and Loredana Mariniello. 2020. Microbial Transglutaminase as a Tool to Improve the Features of Hydrocolloid-based Bioplastics. *International Journal of Molecular Sciences* 21, 10 (2020), 3656.

[42] Daniel Groeger and Jürgen Steimle. 2018. ObjectSkin: Augmenting Everyday Objects with Hydroprinted Touch Sensors and Displays. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 1, 4, Article 134 (Jan 2018), 23 pages. https://doi.org/10.1145/3161165

[43] Daniel Groeger and Jürgen Steimle. 2019. *LASEC: Instant Fabrication of Stretchable Circuits Using a Laser Cutter*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3290605.3300929

[44] Marco Guazzini. 2015. Marwoolus. Retrieved July 26, 2022 from http://marcoguazzini.com/marwoolus/

[45] Nur Al-huda Hamdan, Simon Voelker, and Jan Borchers. 2018. Sketch&Stitch: Interactive Embroidery for E-Textiles. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3173574.3173656

[46] David Hardman, Josie Hughes, Thomas George Thuruthel, Kieran Gilday, and Fumiya Iida. 2021. 3D Printable Sensorized Soft Gelatin Hydrogel for Multi-Material Soft Structures. *IEEE Robotics and Automation Letters* 6, 3 (2021), 5269–5275.

[47] Cedric Honnet, Hannah Perner-Wilson, Marc Teyssier, Bruno Fruchard, Jürgen Steimle, Ana C. Baptista, and Paul Strohmeier. 2020. *PolySense: Augmenting Textiles with Electrical Functionality Using In-Situ Polymerization*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3313831.3376841

[48] Jieyu Huang, Dawei Li, Min Zhao, Pengfei Lv, Lucian Lucia, and Qufu Wei. 2019. Highly Stretchable and Bio-based Sensors for Sensitive Strain Detection of Angular Displacements. *Cellulose* 26, 5 (2019), 3401–3413.

[49] Kunpeng Huang, Ruojia Sun, Ximeng Zhang, Md. Tahmidul Islam Molla, Margaret Dunne, Francois Guimbretiere, and Cindy Hsin-Liu Kao. 2021. WovenProbe: Probing Possibilities for Weaving Fully-Integrated On-Skin Systems Deployable in the Field. In *Designing Interactive Systems Conference 2021*. Association for Computing Machinery, New York, NY, USA, 1143–1158. https://doi.org/10.1145/3461778.3462105

[50] IFA. 2022. Active Carbon. Retrieved July 26, 2022 from https://gestis-database.dguv.de/data?name=004340

[51] Syed H Imam, SH Gordon, Randal L Shogren, TR Tosteson, NS Govind, and RV Greene. 1999. Degradation of Starch–poly (β-hydroxybutyrate-co-β-hydroxyvalerate) Bioplastic in Tropical Coastal Waters. *Applied and environmental microbiology* 65, 2 (1999), 431–437.

[52] Inayati, Damar Jati Pamungkas, and Maudy Pratiwi Novia Matovanni. 2019. Effect of Glycerol Concentration on Mechanical Characteristics of Biodegradable Plastic from Rice Straw Cellulose. In *AIP Conference Proceedings*, Vol. 2097. AIP Publishing LLC, 030110.

[53] Walther Jensen, Ashley Colley, Jonna Häkkilä, Carlos Pinheiro, and Markus Löchtefeld. 2019. TransPrint: A method for fabricating flexible transparent free-form displays. *Advances in Human-Computer Interaction* 2019 (2019).

[54] Yuhuan Jiang, Xuening Pang, Yujia Deng, Xiaolu Sun, Xihui Zhao, Peng Xu, Peiyuan Shao, Lei Zhang, Qun Li, and Zichao Li. 2019. An Alginate Hybrid Sponge with High Thermal Stability: its Flame Retardant Properties and Mechanism. *Polymers* 11, 12 (2019), 1973.

[55] Pirjo Kääriäinen, Liisa Tervinen, Tapani Vuorinen, Nina Riutta, et al. 2020. The CHEMARTS cookbook. Retrieved July 26, 2022 from https://aaltodoc.aalto.fi/bitstream/handle/123456789/44165/isbn9789526088037.pdf

[56] Hsin-Liu (Cindy) Kao, Christian Holz, Asta Roseway, Andres Calvo, and Chris Schmandt. 2016. DuoSkin: Rapidly Prototyping on-Skin User Interfaces Using Skin-Friendly Materials. In *Proceedings of the 2016 ACM International Symposium on Wearable Computers* (Heidelberg, Germany) *(ISWC '16)*. Association for Computing Machinery, New York, NY, USA, 16–23. https://doi.org/10.1145/2971763.2971777

[57] Yoshihiro Kawahara, Steve Hodges, Benjamin S. Cook, Cheng Zhang, and Gregory D. Abowd. 2013. Instant Inkjet Circuits: Lab-Based Inkjet Printing to Support Rapid Prototyping of UbiComp Devices. In *Proceedings of the 2013 ACM International Joint Conference on Pervasive and Ubiquitous Computing* (Zurich, Switzerland) *(UbiComp '13)*. Association for Computing Machinery, New York, NY, USA, 363–372. https://doi.org/10.1145/2493432.2493486

[58] Arshad Khan, Joan Sol Roo, Tobias Kraus, and Jürgen Steimle. 2019. Soft Inkjet Circuits: Rapid Multi-Material Fabrication of Soft Circuits Using a Commodity Inkjet Printer. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology* (New Orleans, LA, USA) *(UIST '19)*. Association for Computing Machinery, New York, NY, USA, 341–354. https://doi.org/10.1145/3332165.3347892

[59] Jin Hee (Heather) Kim, Kunpeng Huang, Simone White, Melissa Conroy, and Cindy Hsin-Liu Kao. 2021. KnitDermis: Fabricating Tactile On-Body Interfaces Through Machine Knitting. In *Designing Interactive Systems Conference 2021*. Association for Computing Machinery, New York, NY, USA, 1183–1200. https://doi.org/10.1145/3461778.3462007

[60] 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* (Vancouver, BC, Canada) *(CHI '11)*. Association for Computing Machinery, New York, NY, USA, 2395–2404. https://doi.org/10.1145/1978942.1979292

[61] ER Kisin, AR Murray, L Sargent, D Lowry, M Chirila, KJ Siegrist, D Schwegler-Berry, S Leonard, V Castranova, B Fadeel, et al. 2011. Genotoxicity of Carbon Nanofibers: Are They Potentially More or Less Dangerous than Carbon Nanotubes or Asbestos? *Toxicology and applied pharmacology* 252, 1 (2011), 1–10.

[62] Jarrod Knibbe, Rachel Freire, Marion Koelle, and Paul Strohmeier. 2021. SkillSleeves: Designing Electrode Garments for Wearability. In *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Salzburg, Austria) *(TEI '21)*. Association for Computing Machinery, New York, NY, USA, Article 33, 16 pages. https://doi.org/10.1145/3430524.3440652

[63] Ana Carolina Kogawa, Beatriz Gamberini Cernic, Leandro Giovanni Domingos do Couto, and Hérida Regina Nunes Salgado. 2017. Synthetic Detergents: 100 Years of History. *Saudi Pharmaceutical Journal* 25, 6 (2017), 934–938.

[64] Cindy Kohtala. 2017. Making "Making" Critical: How Sustainability is Constituted in Fab Lab Ideology. *The Design Journal* 20, 3 (2017), 375–394.

[65] Jagoda Kurowiak, Agnieszka Mackiewicz, Tomasz Klekiel, and Romuald Będziński. 2022. Evaluation of Selected Properties of Sodium Alginate-Based Hydrogel Material—Mechanical Strength, μDIC Analysis and Degradation. *Materials* 15, 3 (2022), 1225.

[66] MJ Lázaro, L Calvillo, V Celorrio, JI Pardo, S Perathoner, and R Moliner. 2011. Study and application of carbon black Vulcan XC-72R in polymeric electrolyte fuel cells. *Carbon black: production, properties and uses* 41 (2011).

[67] Eldy S Lazaro Vasquez, Netta Ofer, Shanel Wu, and Mary Etta West. 2021. Smart Biofoam. Retrieved July 26, 2022 from https://www.youtube.com/watch?v=JhTXW12DovU

[68] 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* (London, United Kingdom) *(ISWC '19)*. Association for Computing Machinery, New York, NY, USA, 306–311. https://doi.org/10.1145/3341163.3346938

[69] Eldy S Lazaro Vasquez, Hao-Chuan Wang, and Katia Vega. 2020. The Environmental Impact of Physical Prototyping: a Five-Year CHI Review. *Workshop on SelfSustainableCHI at CHI 2020* (2020).

[70] 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*. Association for Computing Machinery, New York, NY, USA, 1301–1312. https://doi.org/10.1145/3357236.3395510

[71] An Liang, Rebecca Stewart, Rachel Freire, and Nick Bryan-Kinns. 2021. Knit Stretch Sensor Placement for Body Movement Sensing. In *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Salzburg, Austria) *(TEI '21)*. Association for Computing Machinery, New York, NY, USA, Article 10, 7 pages. https://doi.org/10.1145/3430524.3440629

[72] Chanhyuk Lim, Yoonsoo Shin, Jaebong Jung, Ji Hoon Kim, Sangkyu Lee, and Dae-Hyeong Kim. 2019. Stretchable Conductive Nanocomposite based on Alginate Hydrogel and Silver Nanowires for Wearable Electronics. *APL Materials* 7, 3 (2019), 031502. https://doi.org/10.1063/1.5063657

[73] Joanne Lo, Doris Jung Lin Lee, Nathan Wong, David Bui, and Eric Paulos. 2016. Skintillates: Designing and Creating Epidermal Interactions. In *Proceedings of the 2016 ACM Conference on Designing Interactive Systems* (Brisbane, QLD, Australia) *(DIS '16)*. Association for Computing Machinery, New York, NY, USA, 853–864. https://doi.org/10.1145/2901790.2901885

[74] Elisabeth Lorenzi. 2018. Agar bioplastic (heated) Ag02. Retrieved July 26, 2022 from https://materiom.org/recipe/152

[75] Elisabeth Lorenzi. 2018. Conductive Agar Ag03. Retrieved July 26, 2022 from https://materiom.org/recipe/152

[76] Elisabeth Lorenzi. 2020. DIY Gelatin Solar Cell. Retrieved July 26, 2022 from https://issuu.com/elisabethlorenzi/docs/gelatin_solar_cell_issu

[77] Elisabeth Lorenzi. 2021. Bioplastics as proximity sensor. Testing biodegradable electronics. Retrieved July 26, 2022 from https://www.youtube.com/watch?v=rMoaorPdTyc

[78] Piera Maccagnani, Monica Bertoldo, Franco Dinelli, Mauro Murgia, Caterina Summonte, Luca Ortolani, Giulio Pizzochero, Roberto Verucchi, Cristian Collini, and Raffaella Capelli. 2019. Flexible Conductors from Brown Algae for Green Electronics. *Advanced Sustainable Systems* 3, 6 (2019), 1900001. https://doi.org/10.1002/adsu.201900001

[79] MakerBoat. 2014. $1 DIY Conductive Ink and Paint From Fire! (non Toxic, Homemade, Cheap). Retrieved July 26, 2022 from https://www.instructables.com/1-DIY-Conductive-Ink/

[80] Evangelos Pantazis Manuel Kretzer, Miro Roman. 2021. Bioplastics – Cooking Bioplastics from Gelatine. Retrieved July 26, 2022 from http://materiability.com/bioplastics-2/

[81] Eric Markvicka, Guanyun Wang, Yi-Chin Lee, Gierad Laput, Carmel Majidi, and Lining Yao. 2019. ElectroDermis: Fully Untethered, Stretchable, and Highly-Customizable Electronic Bandages. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–10. https://doi.org/10.1145/3290605.3300862

[82] Harry Marsh and Francisco Rodríguez Reinoso. 2006. *Activated Carbon*. Elsevier.

[83] David A. Mellis, Sam Jacoby, Leah Buechley, Hannah Perner-Wilson, and Jie Qi. 2013. Microcontrollers as Material: Crafting Circuits with Paper, Conductive Ink, Electronic Components, and an "Untoolkit". In *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction* (Barcelona, Spain) *(TEI '13)*. Association for Computing Machinery, New York, NY, USA, 83–90. https://doi.org/10.1145/2460625.2460638

[84] Anya Muangkote. 2019. BioScreen - Milan Design Week 2019. Retrieved July 26, 2022 from https://anyamuangkote.info/bioscreen

[85] Steven Nagels, Raf Ramakers, Kris Luyten, and Wim Deferme. 2018. Silicone Devices: A Scalable DIY Approach for Fabricating Self-Contained Multi-Layered Soft Circuits Using Microfluidics. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3173574.3173762

[86] Satoshi Nakamaru, Ryosuke Nakayama, Ryuma Niiyama, and Yasuaki Kakehi. 2017. FoamSense: Design of Three Dimensional Soft Sensors with Porous Materials. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology* (Québec City, QC, Canada) *(UIST '17)*. Association for Computing Machinery, New York, NY, USA, 437–447. https://doi.org/10.1145/3126594.3126666

[87] Aditya Shekhar Nittala, Arshad Khan, Klaus Kruttwig, Tobias Kraus, and Jürgen Steimle. 2020. *PhysioSkin: Rapid Fabrication of Skin-Conformal Physiological Interfaces*. Association for Computing Machinery, New York, NY, USA, 1–10.

[88] Aditya Shekhar Nittala, Anusha Withana, Narjes Pourjafarian, and Jürgen Steimle. 2018. Multi-Touch Skin: A Thin and Flexible Multi-Touch Sensor for On-Skin Input. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3173574.3173607

[89] Yunsik Ohm, Chengfeng Pan, Michael J Ford, Xiaonan Huang, Jiahe Liao, and Carmel Majidi. 2021. An Electrically Conductive Silver–Polyacrylamide–Alginate Hydrogel Composite for Soft Electronics. *Nature Electronics* 4, 3 (2021), 185–192.

[90] Simon Olberding, Michael Wessely, and Jürgen Steimle. 2014. PrintScreen: Fabricating Highly Customizable Thin-Film Touch-Displays. In *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology* (Honolulu, Hawaii, USA) *(UIST '14)*. Association for Computing Machinery, New York, NY, USA, 281–290. https://doi.org/10.1145/2642918.2647413

[91] Electric Paint. 2021. What Is Electric Paint: The Composition and Application of Conductive Paints. Retrieved July 26, 2022 from https://www.bareconductive.com/blogs/blog/what-is-electric-paint-the-composition-and-application-of-conductive-paints

[92] Smaranika Pattnaik, Vemulpad R Subramanyam, and Chittaranjan Kole. 1996. Antibacterial and Antifungal Activity of ten Essential Oils in Vitro. *Microbios* 86, 349 (1996), 237–246.

[93] Juliette Pepin. 2014. Research Book Bioplastics. Retrieved July 26, 2022 from https://issuu.com/juliettepepin/docs/bookletbioplastic

[94] Precious Plastic. 2022. Precious Plastic. Retrieved July 26, 2022 from https://preciousplastic.com

[95] Narjes Pourjafarian, Marion Koelle, Bruno Fruchard, Sahar Mavali, Konstantin Klamka, Daniel Groeger, Paul Strohmeier, and Jürgen Steimle. 2021. BodyStylus: Freehand On-Body Design and Fabrication of Epidermal Interfaces. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 504, 15 pages. https://doi.org/10.1145/3411764.3445475

[96] Narjes Pourjafarian, Marion Koelle, Fjolla Mjaku, Paul Strohmeier, and Jürgen Steimle. 2022. Print-A-Sketch: A Handheld Printer for Physical Sketching of Circuits and Sensors on Everyday Surfaces. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 270, 17 pages. https://doi.org/10.1145/3491102.3502074

[97] Cecilia Raspanti. 2021. Fabricademy 2021-22 Week 06 Bio-fabricating Materials. Retrieved July 26, 2022 from https://vimeo.com/639230954/58e599f00d

[98] Miriam Ribul. 2014. Recipes for Material Activism. Retrieved July 26, 2022 from https://issuu.com/miriamribul/docs/miriam_ribul_recipes_for_material_a

[99] Luisa Rubisch and Rasa Weber. 2022. Urban Terrazzo. Retrieved July 26, 2022 from https://www.urbanterrazzo.com/contact

[100] Beatriz Sandini. 2020. Ephermeral Fashion Lab, Charcoal Bio Leather Bag. Retrieved July 26, 2022 from https://class.textile-academy.org/2020/beatriz.sandini/projects/0-final-project/

[101] Alina S Sharova, Filippo Melloni, Guglielmo Lanzani, Christopher J Bettinger, and Mario Caironi. 2021. Edible Electronics: The Vision and the Challenge. *Advanced Materials Technologies* 6, 2 (2021), 2000757.

[102] M. Six Silberman, Lisa Nathan, Bran Knowles, Roy Bendor, Adrian Clear, Maria Håkansson, Tawanna Dillahunt, and Jennifer Mankoff. 2014. Next Steps for Sustainable HCI. *Interactions* 21, 5 (Sept. 2014), 66–69. https://doi.org/10.1145/2651820

[103] Henry Y Sintim, Sreejata Bandopadhyay, Marie E English, Andy Bary, José E Liquet y González, Jennifer M DeBruyn, Sean M Schaeffer, Carol A Miles, and Markus Flury. 2021. Four Years of Continuous Use of Soil-biodegradable Plastic Mulch: Impact on Soil and Groundwater Quality. *Geoderma* 381 (2021), 114665.

[104] Paul Strohmeier, Narjes Pourjafarian, Marion Koelle, Cedric Honnet, Bruno Fruchard, and Jürgen Steimle. 2020. Sketching On-Body Interactions Using Piezo-Resistive Kinesiology Tape. In *Proceedings of the Augmented Humans International Conference* (Kaiserslautern, Germany) *(AHs '20)*. Association for Computing Machinery, New York, NY, USA, Article 29, 7 pages. https://doi.org/10.1145/3384657.3384774

[105] Ruojia Sun, Ryosuke Onose, Margaret Dunne, Andrea Ling, Amanda Denham, and Hsin-Liu (Cindy) Kao. 2020. *Weaving a Second Skin: Exploring Opportunities for Crafting On-Skin Interfaces Through Weaving*. Association for Computing Machinery, New York, NY, USA, 365–377. https://doi.org/10.1145/3357236.3395548

[106] Eldy S. Lazaro Vasquez and Katia Vega. 2019. From Plastic to Biomaterials: Prototyping DIY Electronics with Mycelium. In *Adjunct Proceedings of the 2019 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2019 ACM International Symposium on Wearable Computers* (London, United Kingdom) *(UbiComp/ISWC '19 Adjunct)*. Association for Computing Machinery, New York, NY, USA, 308–311. https://doi.org/10.1145/3341162.3343808

[107] 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* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 665, 12 pages. https://doi.org/10.1145/3411764.3445187

[108] Yanan Wang, Shijian Luo, Yujia Lu, Hebo Gong, Yexing Zhou, Shuai Liu, and Preben Hansen. 2017. AnimSkin: Fabricating Epidermis with Interactive, Functional and Aesthetic Color Animation. In *Proceedings of the 2017 Conference on Designing Interactive Systems* (Edinburgh, United Kingdom) *(DIS '17)*. Association for Computing Machinery, New York, NY, USA, 397–401. https://doi.org/10.1145/3064663.3064687

[109] Zifeng Wang, Xue Li, Zijie Yang, Hongchen Guo, Yu Jun Tan, Glenys Jocelin Susanto, Wen Cheng, Weidong Yang, and Benjamin Chee Keong Tee. 2021. Fully Transient Stretchable Fruit-based Battery as Safe and Environmentally Friendly Power Source for Wearable Electronics. *EcoMat* 3, 1 (2021), e12073. https://doi.org/10.1002/eom2.12073

[110] Christopher Wanjek. 2012. Facial Soap's Surprise Wheat Ingredient Triggers Allergies. Retrieved April 6, 2022 from http://materiability.com/bioplastics-2/

[111] Keisuke Watanabe, Ryosuke Yamamura, and Yasuaki Kakehi. 2021. Foamin: A Deformable Sensor for Multimodal Inputs Based on Conductive Foam with a Single Wire. In *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, Article 189, 4 pages. https://doi.org/10.1145/3411763.3451547

[112] Martin Weigel, Tong Lu, Gilles Bailly, Antti Oulasvirta, Carmel Majidi, and Jürgen Steimle. 2015. ISkin: Flexible, Stretchable and Visually Customizable On-Body Touch Sensors for Mobile Computing. In *SIGCHI Conference on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI'15)*. Association for Computing Machinery, New York, NY, USA, 2991–3000. https://doi.org/10.1145/2702123.2702391

[113] Martin Weigel, Aditya Shekhar Nittala, Alex Olwal, and Jürgen Steimle. 2017. SkinMarks: Enabling Interactions on Body Landmarks Using Conformal Skin Electronics. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 3095–3105. https://doi.org/10.1145/3025453.3025704

[114] 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* (San Diego, CA, USA) *(DIS '19 Companion)*. Association for Computing Machinery, New York, NY, USA, 69–72. https://doi.org/10.1145/3301019.3325156

[115] Michael Wessely, Theophanis Tsandilas, and Wendy E. Mackay. 2016. Stretchis: Fabricating Highly Stretchable User Interfaces. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology* (Tokyo, Japan) *(UIST '16)*. Association for Computing Machinery, New York, NY, USA, 697–704. https://doi.org/10.1145/2984511.2984521

[116] Working & Applications What is a Paper Capacitor Construction. 2021. ElProCus. Retrieved July 26, 2022 from https://www.elprocus.com/what-is-a-paper-capacitor-construction-working-applications/

[117] Kjell Wikander, Henrik Ekström, AEC Palmqvist, Anders Lundblad, Krister Holmberg, and Göran Lindbergh. 2006. Alternative catalysts and carbon support material for PEMFC. *Fuel Cells* 6, 1 (2006), 21–25.

[118] WikiHow. 2021. How to Use Horticultural Charcoal. Retrieved July 26, 2022 from https://www.wikihow.com/Use-Horticultural-Charcoal

[119] Anusha Withana, Daniel Groeger, and Jürgen Steimle. 2018. Tacttoo: A Thin and Feel-Through Tattoo for On-Skin Tactile Output. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology* (Berlin, Germany) *(UIST '18)*. Association for Computing Machinery, New York, NY, USA, 365–378. https://doi.org/10.1145/3242587.3242645

[120] Sang Min Won, Jahyun Koo, Kaitlyn E Crawford, Aaron D Mickle, Yeguang Xue, Seunghwan Min, Lisa A McIlvried, Ying Yan, Sung Bong Kim, Seung Min Lee, et al. 2018. Natural Wax for Transient Electronics. *Advanced Functional Materials* 28, 32 (2018), 1801819.

[121] Nadia Campo Woytuk and Marie Louise Juul Søndergaard. 2021. Biomenstrual. Retrieved July 26, 2022 from https://files.persona.co/108249/Biomenstrual-spellbook.pdf

[122] Humphrey Yang, Danli Luo, Kuanren Qian, and Lining Yao. 2021. Freeform Fabrication of Fluidic Edible Materials. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 620, 10 pages. https://doi.org/10.1145/3411764.3445097

[123] Jayachandra S Yaradoddi, Nagaraj R Banapurmath, Sharanabasava V Ganachari, Manzoore Elahi M Soudagar, NM Mubarak, Shankar Hallad, Shoba Hugar, and H Fayaz. 2020. Biodegradable Carboxymethyl Cellulose Based Material for Sustainable Packaging Application. *Scientific reports* 10, 1 (2020), 1–13.

[124] Sang Ho Yoon, Ke Huo, Yunbo Zhang, Guiming Chen, Luis Paredes, Subramanian Chidambaram, and Karthik Ramani. 2017. ISoft: A Customizable Soft Sensor with Real-Time Continuous Contact and Stretching Sensing. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology* (Québec City, QC, Canada) *(UIST '17)*. Association for Computing Machinery, New York, NY, USA, 665–678. https://doi.org/10.1145/3126594.3126654

[125] Hui Yuan, Tianmin Lei, Yong Qin, and Rusen Yang. 2019. Flexible Electronic Skins based on Piezoelectric Nanogenerators and Piezotronics. *Nano Energy* 59 (2019), 84–90.