RESEARCH-ARTICLE

BioLIG: Functionalizing Biocomposites with Laser-induced Graphene for Bio-Rapid Prototyping of Electronics

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BioLIG: Functionalizing Biocomposites with Laser-induced Graphene for Bio-Rapid Prototyping of Electronics

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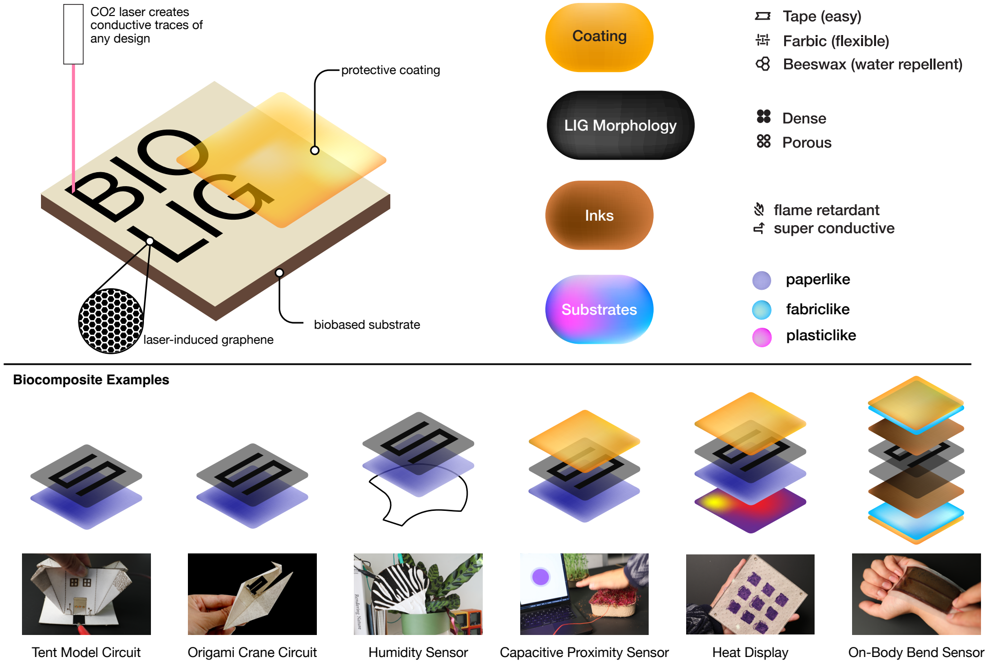

Figure 1: Overview of the BioLIG framework from material formulation design, functionalizing the substrate into sensors and circuits to five applications.

Abstract

In HCI, there is a rapidly growing interest in prototyping with conductive bio-based materials. However, the methods for conductive

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making of bio-based materials to suit the diverse needs of makers remain underexplored. We introduce BioLIG, a fabrication framework that functionalizes affordable and optimized bio-based substrates with a conventional CO2 laser to create highly conductive traces for sensors and circuits. To illustrate the framework, we first contribute five bio-based materials: three sheets (paper-like, fabric-like, plastic-like) and two paints (lignin-ink, chitosan-stain). A formal electrical characterization of our conductors highlight that they surpass activated charcoal, are on par with carbon black, and one ink is even comparable with the most common synthetic material used for laser-induced graphene. Then, we present three biodegradable coatings that ensure functionality and durability and balance protection with controlled degradation. Next, we build upon our sheets, paints, and coatings to form multifunctional biodegradable biocomposites and implement five end-to-end applications. Lastly, we define three strategies of how the framework supports a circular making culture. BioLIG enables accessible, fast, and bio-rapid prototyping, adding new directions for designing sustainable electronics with environmental integration.

CCS Concepts

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

Keywords

prototyping, material, bio-based, sustainability, biocomposite,laser-induced graphene, functionalization

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1 Introduction

In the field of Human-Computer Interaction (HCI), there is a rapidly growing interest in using bio-based materials for prototyping. For example, smart biodegradable textiles and wearables [6, 46], 3D printing with extrudable bio-pastes[9, 62], biofilm actuators triggered by humidity or heat [22, 90, 92, 95] and growing one's own prototyping material using mycelium [32, 86, 87] or bacterial cellulose [8, 55]. These materials are used to address waste production and life-cycle aware making, but also to discuss more-than-human thinking [68] and eco-socio-technical relations through material design [10]. So far, these techniques commonly focus on non-conductive bio-based materials. *Conductive* and *conductive making* of bio-based materials are less explored and dominated by incorporating conductive powder into non conductive bio-based material recipes [11, 47, 55, 69]. However, incorporating activated charcoal or carbon black from a third-party supplier comes with inherent inconsistency in performance from different brands or even the same batch[42]. Patterning existing conductive bio-based materials into sensors is a multi-step process and sometimes requires precise manual labor, including stenciling and hand painting. These fabrication techniques tend to introduce inaccuracies and can challenge the iterative nature of prototyping. Lastly, compared to traditional materials such as wood, metal, or acrylic, bio-based materials as well as their workflows can be unfamiliar to makers, increasing the threshold to entry

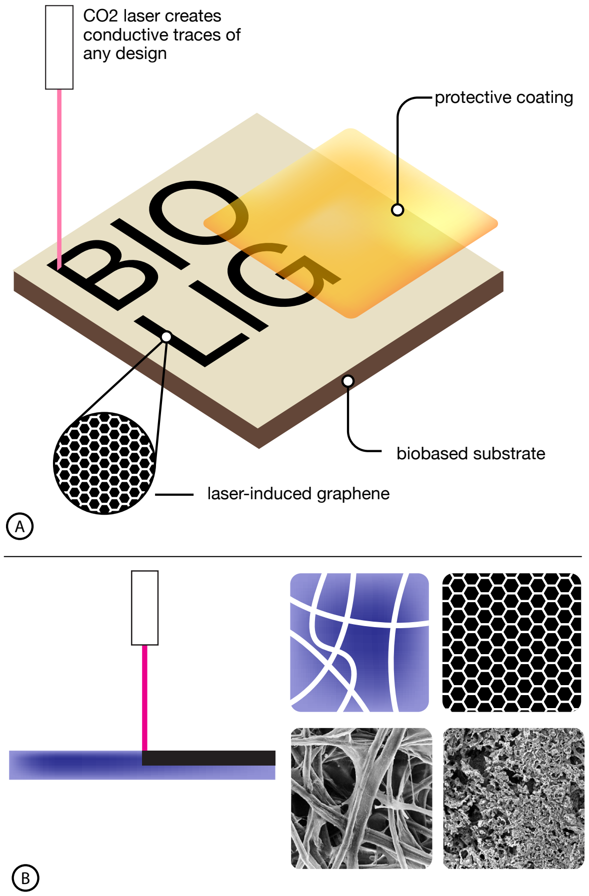


Figure 2: Schematic diagram of BioLIG fabrication. (A) shows an isometric diagram of the graphitization process on bio-based substrate. (B) illustrates the cross-section as the substrate converts into the hexagonal, orderly, conductive graphitic structure, including illustration and Scanning Electron Microscope (SEM) images.

This paper introduces BioLIG, a fabrication framework functionalizing biocomposites with a CO2 laser to make sensors and circuits. BioLIG consists of two parts: **Bio** refers to the bio-based and biodegradable substrate. **LIG** refers to laser-induced graphene (LIG), a carbon conductor directly induced from the substrate using a laser.

The fabrication framework consists of

- (1) **Material Formulation Design** and synthesizing a substrate that is optimal for laser-induced conductivity
- (2) **Functionalizing Substrate to act as Sensors and Circuits** by making the substrate conductive with a CO2 laser. Finalizing sensor or circuit by applying a protective and

biodegradable coating for necessary robustness and reliability.

- (3) **Circular Making** with end-of-life reuse or recycle strategies.

(1) **Material Formulation Design** In the formulation design process, we developed over 40 novel bio-based materials and evaluated their suitability for laser-induced graphene. To effectively meet the diverse prototyping needs of makers, we optimized three sheets with distinct mechanical properties (paper-like, fabric-like, and plastic-like) and two paints (lignin-ink, chitosan stain). Our approach utilizes readily available raw materials and accessible machinery commonly found in maker spaces. The entire fabrication process, from making to drying, to patterning, takes on average 14 hours, which makes it competitive with overnight express delivery of off-the-shelf sensors. The resulting conductors are highly conductive. An electrical characterization demonstrates that the conductivity of *BioLIG Paper* surpasses that of single-layer activated charcoal, one of the most commonly used biodegradable conductors, and has similar electrical performance to carbon black, the state-of-the-art biodegradable conductor in HCI. We even achieved performance comparable to LIG on synthetic substrates with *BioLIG Ink* paint. We also create multiple copies of recipes on different days to evaluate their reliability. The test on sheets stored for six months yielded performance results with fluctuations between 2% and 10%.

(2) **Functionalizing Substrate to Sensors and Circuits** For each BioLIG material, we share the conductive making process in detail, including leanings and laser settings. To finalize the sensor or circuit, we developed three robust yet biodegradable coatings for stable functionality and controlled degradation. These coatings can enhance the everyday usability and protect the LIG layer from environmental factors such as routine abrasion and moisture from the skin. Further, they add additional features to the final biocomposite, such as compliance and water repellency. Although these coatings extend the time of microbial degradation, we believe that having some control over the lifespan and degradation is beneficial for various applications. We tested three types of coatings: beeswax for water-repellent and rigid applications, a *BioLIG Fabric* for flexible applications, and commercially available cellulose tape for quick prototyping and ease of application.

(3) **Circular Making** Building on our sheets, paints, and coatings, we demonstrate the multifunctional biocomposites based on five applications. Each application explores distinctly different advantages, performance characteristics, and limitations. Our implementation include two circuits and four fully biodegradable sensors (input and output), such as a resistive bend sensor, a humidity sensor, a heater, and a capacitive sensor. Lastly, we evaluate three strategies for incorporating BioLIG devices into a material life cycle to minimize waste and advocate for a circular making culture. These strategies include (1) re-blending and re-fabricating material cut-offs generated during a subtractive laser cutting workflow, (2) dissolving circuit board substrates in water to separate conventional electronics from the PCB for reuse, and (3) composting.

2 Related Works

2.1 Sustainable Electronics Fabrication in HCI

Sustainable electronics fabrication has been examined from the perspective of reuse and upcycling [12, 25, 53]. EcoEDA is a software tool that assists users in identifying reusable components in existing printed circuit boards (PCBs) and designing new ones using recycled PCBs [51]. Yan et al. investigate the iterative reuse of PCBs by rerouting [94], while Kim et al. explore innovative reuses of electronic waste [41]. Other researchers advocate for fundamentally rethinking decentralized and lifecycle-aware production and suggest the integration of bio-based materials with digital fabrication [6, 7, 27]. Using the limitations and potentials of bio-based materials, researchers created novel electrical systems [48, 87]. Vim - a decomposable electrical energy storage solution - addresses a critical gap in the development of completely decomposable interactive systems and paves the way for advancements in sustainable material innovation [69]. The Degrade to Function (DfF) technology of Lu et al. uses programmed sequential degradation of biobased materials under various environmental conditions to achieve specific functions [52] and Cheng et al. describe ultilizing the physical transiency of sustainable materials for electronics applications [17]. This paper builds on these innovative and multiple ways to rethink sustainability and making with a focus on combining bio-based materials with computer-controlled fabrication for lowering the barrier to entry.

2.2 Fabrication of Bio-based Electronics

From advanced materials to robotics, researchers from various disciplines are advancing in green chemistry and electronics. Transient electronics [37] refers to electronic devices that disappear or leave minimal traces after use and explore opportunities for electronics that do not to remain physically invariant , as exemplified by edible robots [4] and degradable transistors [71]. Typically, this research takes place in high-end laboratory environments, utilizing machines and materials that are inaccessible to makers and designers. Besides fully biodegradable electronics, there exists commercially available biodegradable printed circuit board (PCB) substrates, such as Soluboard® [1]. Nonetheless, these boards use copper lamination or silver ink as non-degradable conductors on top of the biodegradable printed circuit board substrate, making them similar to FR1 boards. In the HCI community, most conductive bio-based materials use activated charcoal or carbon black. The “Designing with Alganyl” by Bell et al. paints circuit traces using bare conductive charcoal paste [6], and Vasquez et al. explore biofoams infused with activated charcoal powder [47]. In 2022, Koelle and Nicolae et al. Interactive bioplastics offer a systematic insight into the prototyping of sensors and circuits using interactive bio-based material enriched with activated charcoal and carbon black [42]. Although accessible and easy to use, the authors report that activated charcoal has inherent limitations, such as inconsistencies in particle size, density, or conductivity between brands and batches. In addition, the resulting conductive bioplastic sheets have bulk conductivity, where the desired pattern must be cut out by hand or using a vinyl cutter. This 2nd step is prone to inaccuracies and leaves little room for error correction. Lastly, activated charcoal can be used for selective patterning; however, only by using a brush or stencil, which requires the use of additional materials, increases labor and slows down rapid prototyping. Building upon the innovative work in this area, BioLIG proposes a computational fabrication process that is familiar to many makers and reduces the expenses of learning a new workflow.

2.3 Laser-induced Graphene (LIG)

Unlike activated charcoal, graphitization creates conductive traces through a computer-controlled laser. Laser-induced graphene was introduced in 2014 by Lin et al. as a scalable approach for producing and patterning porous graphitic structures from commercial polymer films using a conventional CO2 infrared laser. The resulting LIG exhibits high electrical conductivity 30 Ω/□ [49]. While it is generally possible to induce graphene on any materials, ones with higher carbon content tend to be the easiest and most efficient. In 2018, Chyan et al., for the first time, showed patterned carbonization on surfaces of substrates based on cellulose and lignin, such as food, cloth, paper and cardboard, with resistance in the megaohm range [19].

We chose laser-induced graphene as the method to make bio-based materials conductive for three reasons:

- LIG has excellent electrical conductivity among accessible and easy-to-make carbon conductors.
- LIG works more effectively on bio-based materials than synthetic materials, therefore giving a practical reason for using sustainable materials.
- Lasers are already widely integrated into prototyping workflows. This makes it easy for makers to build on existing knowledge and incorporate bio-based materials into their workflow.

Table 1: Sheet resistance in Ω/□ of LIG on BioLIG materials compared to state-of-the-art carbon conductors in HCI

Type of Carbon Conductor	Ω/□
activated charcoal [6, 11, 42, 47, 69]	859k
graphite powder [11, 56]	527
carbon black [42, 55, 57]	28.3 - 162.3
LIG on BioLIG materials	**2.4k - 14**

2.4 LIG on Bio-based Materials in HCI

To our knowledge, few HCI papers mention LIG for prototyping. The only work centered around graphitization is CircWood by Ishii et al.[38] Through multi-pass graphitizing of commonly available plywood, the researchers achieved an impressive sheet resistance of 25 Ω/□. However, makers often want to have a variety of form factors to create different affordances. In this sense, wood as a precursor can be limiting. Nicolae et al. also described graphitization in Biohybrid Devices [55]. While these traces were conductive, their resistance was 20x times higher than expected, restraining them to resistive sensors. Even though the authors do not provide a reason for this, in our own experiences with graphitizing bacterial cellulose (BC), we found that BC's surface texture is full of small gaps, causing disconnections that inhibit the circuit's conductivity.

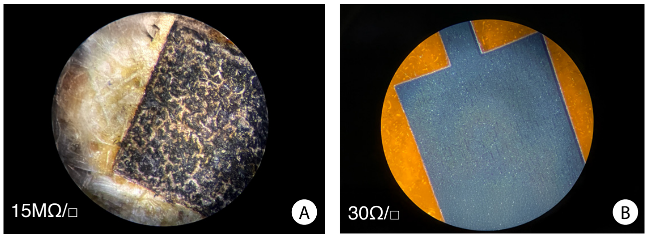


Figure 3: Comparing (A) LIG on bacterial cellulose vs (B) LIG on polyimide under 250x magnification. The induced graphene on BC is coarse, while LIG on polyimide is dense and smooth. Contrast in surface flatness impacts carbonization.

2.5 Preliminary Study on Existing Bio-based Materials and their Suitability for LIG

We started with common prototyping materials rich in lignin and cellulose for inducing graphene. This included (a) off-the-shelf prototyping substrates (e.g., paper, cardboard, biodegradable dishware) and (b) small-scale, market-ready bio-based material, such as bacterial cellulose (BC) from Malai [29] and mycelium-based composites from Redhouse Architecture [61]. Copy paper and biodegradable dishware were burned before LIG was formed. Thicker papers, such as coated postcard paper and corrugated cardboard, exhibited better structural integrity under laser exposure. Grown materials, such as bacterial cellulose and mycelium blocks, are often irregular and produce resistances in the hundreds of megohm range, rendering them unsuitable. The biggest challenge with commercial materials is their unknown ingredients. Some coatings may release harmful fumes or interfere with the carbonization process. In addition, these products might differ from region to region, making it impossible for others to recreate. Our preliminary findings highlight the need for custom bio-based materials engineered for optimal graphitization.

3 Guidelines

The current guiding principles for prototyping with bio-based materials in HCI include affordability, accessibility, minimal use of exotic machines and components, and compatibility with off-the-shelf electronic components [9, 55, 62, 67]. BioLIG meets these guidelines, and in addition, we recognize two additional guidelines - prioritizing Speed and Consistency, and Multifunctional Biocomposites for Prototyping - that could enhance material usability and bridge the vision of sustainable prototyping with the realities faced by most prototypers.

3.1 Prioritizing Speed and Consistency

A recent holistic examination of sustainable prototyping revealed that makers do not like to be wasteful [93]. Many would appreciate the recyclability and circularity of bio-based materials. However, they must also consider performance, accessibility, and cost. Although bio-based materials are generally accessible and affordable, they often require more time to achieve optimal performance. Compared to standard materials like wood, metal, or acrylic, bio-based materials present challenges for makers. Self-made bio-based materials tend to shrink, curl, and crack as they dry unevenly, leading to frustrating experiences. Patterning conductive bio-based materials into sensors requires manual labor, such as stenciling and hand painting. These fabrication techniques tend to introduce inaccuracies and do not align with the iterative nature of prototyping. While it is understandable that natural materials will not behave exactly the same, to incentivize prototypers bio-rapid prototyping needs to consider speed and offer materials that have predictability, and reliability to a certain extent. In our work, we prioritize usability over achieving the highest performance. By reducing the time and effort required to make the substrate, bio-materials can gain attraction.

3.2 Multifunctional Biocomposites for Prototyping

A 2020 study revealed that while some participants value the biodegradability of bio-based materials for prototyping, others feel constrained by the limitations of these materials. In particular, the inability of many bio-based materials to withstand prolonged exposure to water is a characteristic they wish to change [48]. However, meeting all requirements with a single material can be challenging; therefore, we focus on layered biocomposites - combinations of sheets, inks and coatings to form multifunctional biocomposites that offer a range of mechanical and electrical properties. While composites sound counterintuitive for biodegradability, by focusing on the biodegradability of raw materials, we expand the potential of bio-rapid prototyping, e.g., water-resistant, and encourage makers to create innovative combinations of materials specific to their applications and workflows.

4 Novel Sheets for Laser-induced Conductivity

Non-functional bio-based sheet materials are commonly made with a polymer, a binder, a plasticizer, a solvent, and optional fillers or additives [2]. For BioLIG, we adopted the formulation and optimized it around the cellulose-based polymer. As the most abundant polymer on Earth, the type of cellulose not only determines the mechanical properties of the material but also, most importantly, influences the conductivity and morphology of the LIG.

4.1 *BioLIG Paper* - a paper-like material for laser-induced conductivity

Papers are one of the most well-known and appreciated materials for low-fidelity prototyping of interactive devices [14, 59, 98, 100]. This section demonstrates how to make a paper-like bio-based material optimized for laser-induced conductivity. We investigated material formulations that synthesize robust sheets while remaining flexible. After material formulation and fabrication, we discuss the CO2 laser graphitization process for sensor and circuit prototyping.

Material Formulation

Making a well-informed choice of cellulose is crucial. We tested a range of cellulose products, including pulp from hardwoods, softwoods, hemp, and cotton; paper products such as office paper, newsprint, paper towels, and cardboard; bacterial cellulose from living organisms; processed cellulose derivatives such as microcrystalline cellulose (MCC), cellulose nanocrystals (CNC) and cellulose nanofibers (CNF). For the *BioLIG Paper*, we found *hardwood pulp* and *newsprint* to be the most suitable polymer. *Hardwood pulp* is commonly used in papermaking. Hardwood pulp has short fibers (0.6 - 1.5mm) and produces a smoother paper surface than cotton (1-3mm) or softwoods (2-5mm). The smooth surface makes it easier to induce graphene layers that are densely connected with fewer cracks. Furthermore, the higher lignin content in hardwood pulp compared to softwood or cotton allows us to yield more consistent results. The resulting sheets resemble cardstock or cardboard, common materials for low-fidelity prototyping. *Newsprint* is a thin grayish paper that is recycled and is often used to print newspapers and magazines. Although it depends on the source of the cellulose, newsprint fibers are often shorter because of the mechanical grinding process. It is cost-effective while demonstrating similar suitability of LIG to pulp. The resulting sheet is more flexible and similar to that of copy paper. For all sheet materials, we kept the source of binder (sodium alginate), plasticizer (glycerin), and solvent (distilled water) consistent to evaluate the difference in the cellulose-based polymer better.

Synthesizing and Casting Sheets

BioLIG Paper is a cellulose-based composite developed using distilled water, shredded pulp or newsprint, sodium alginate, and glycerin. The mixture is processed in a high-powered blender (1000W Ninja) to create a homogeneous slurry, ensuring a uniform distribution of fibers. The pulp or newsprint is cut into small pieces and blended at medium power for one minute before sodium alginate and glycerin are added and mixed for another two minutes. The mixture rests for 2–3 hours before casting to reduce air bubbles. Sheets are formed by evenly spreading the slurry on a plastic tray (38 × 25 cm) using a flexible scraper, achieving an initial thickness of up to 5mm before drying. We do not use a curing agent for the mixture and rely solely on air drying. Drying can be carried out at room temperature for two days or accelerated in an oven at 40 ° C for 12 hours, reducing the final thickness to 0.5 to 1.5mm.

Inducing Conductivity through Laser

The laser power, scanning speed, and number of passes are crucial factors that affect the quality and morphology of LIG. If the laser power is too low, the graphitization will be incomplete. If the power is too high, it overburns the substrate and can result in holes in the precursor. In addition, the quality of LIG depends on the number of passes, with a higher number resulting in thicker and more uniform graphene films. Lastly, we observed that (de)focus can be crucial for LIG formation on bio-based materials; more details can be found in Section 6. On *BioLIG Paper* using pulp we used 8% power, 16% speed, -2mm defocus to achieve 85 $\Omega/\square$. On *BioLIG Paper* using newsprint, we used 10% power, 18% speed, and -3mm defocus to achieve 75 $\Omega/\square$.

Material Property

BioLIG Paper is a fibrous, robust paper-like material. Naturally, it is white or beige, but can be easily dyed using natural dyes. Due to its fibrous nature, the dried material shows a craft paper-like texture, offering structural stability and fold retention. The LIG

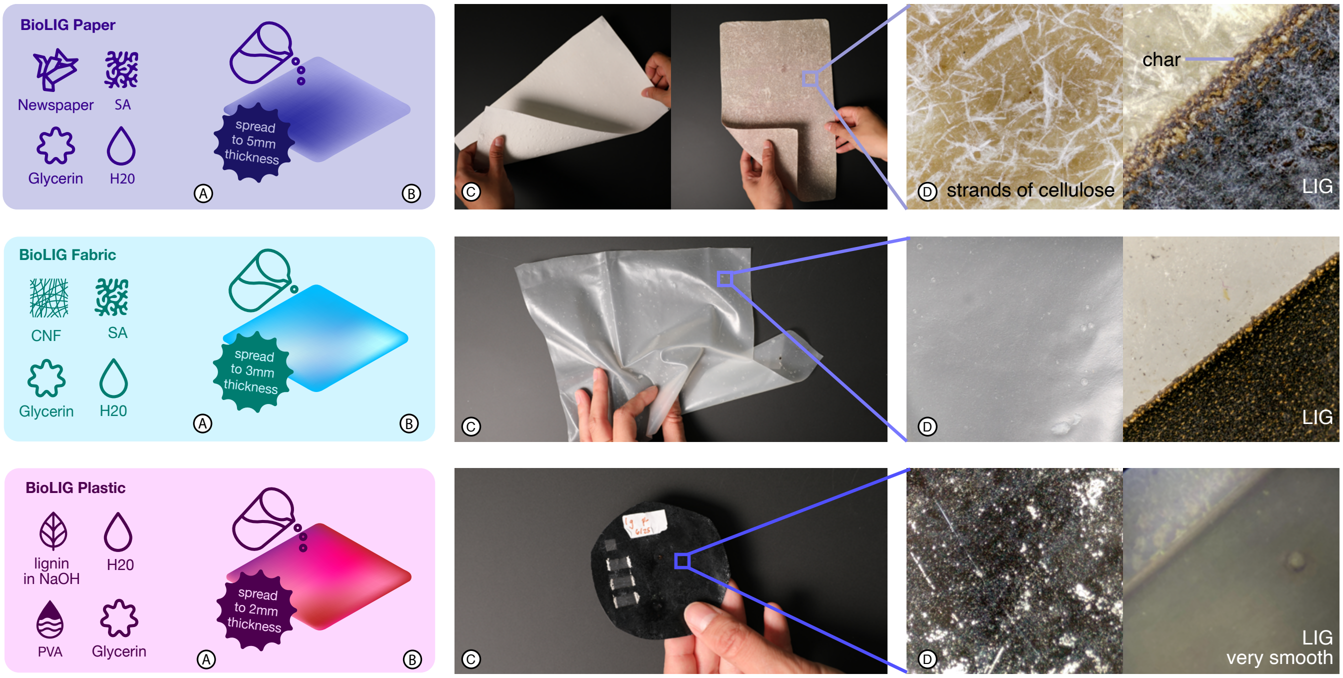


Figure 4: A set of BioLIG sheets with different mechanical, electrical, and visual properties for electronics prototyping. (A) shows the material formulation. SA stands for sodium alginate. (B) the synthesis, (C) the materials before LIG, and (D) zoom in using a 250x microscope to observe substrate and generated LIG. From top to bottom: *BioLIG Paper, BioLIG Fabric, BioLIG Plastic.*

created on BioLIG Paper is gray with small gaps that are visible under a microscope. The material holds LIG well meaning it will not easily flake off upon bending. We performed a preliminary tensile strength test on a 10mm x 20mm x 0.9mm *BioLIG Paper*, resulting in 6.67MPa or 6kN/m according to TAPPI/ANSI T494 om-01, making it stronger than copy paper and comparable with Kraft Sack Paper [97].

Storage
Sealed in an airtight bag, the paper-like material can be easily stored and maintain usability for at least 6 months.

4.2 *BioLIG Fabric* - a fabric-like material for laser-induced conductivity

E-textiles are a common prototyping material for wearables, soft sensors, and interactive garments [23, 40, 58]. The unique properties of the fabric-like material, including flexibility, malleability, and skin compatibility, make it inherently well suited for creating soft, on-skin sensors and circuits. In this section, we introduce *BioLIG Fabric*, a biobased fabric-like material optimized for LIG. We investigated material formulations and synthesis sheets that are flexible and tear-resistant. After material formulation and fabrication, we discuss the CO2 laser graphitization process for sensor and circuit prototyping.

Material Formulation
For *BioLIG Fabric*, we used cellulose nanofiber (CNF). Processed cellulose derivatives have orders of magnitude shorter fiber lengths compared to pulp or paper products. We tested microcrystalline cellulose (MCC), cellulose nanocrystals (CNC), and cellulose nanofiber (CNF) and achieved a satisfying conductivity with all three. However, for more affordable production, CNF was the most suitable. Even in small amounts (as little as 5%), CNF-based *BioLIG Fabric* exhibited high tear resistance, minimal warping, and smooth surfaces, making it ideal for soft and flexible sensors.

Synthesizing and Casting Sheets
BioLIG Fabric is formulated from distilled water, dispersed CNF, sodium alginate, and glycerin. The components are blended into a high-viscosity compound, then evenly cast onto a plastic tray (38 × 25 cm) to form a sheet with an initial thickness of 3mm. Over three days, the sheet air dried, reducing to 0.3mm in thickness while maintaining its mechanical strength and elasticity.

Inducing Conductivity through Laser
BioLIG Fabric with 8% power, 16% speed, and -2mm defocus achieved 2.4 kΩ/□. While this is orders of magnitude higher than our other materials, electrical performance was not our only guideline, but also a diverse variety of prototyping materials with different affordances. The thin, flexible, semi-transparent *BioLIG Fabric* covers a wide range of material properties and, if necessary, can be significantly enhanced through *BioLIG Ink*, discussed in Section 5.1.

Material Property

The material is semitransparent, flexible, and self-adherent. Self-adherent meaning that *BioLIG Fabric* is slightly tacky, allowing it to adhere to flat surfaces without the need for additional adhesives. This property makes it suitable for peelable applications and on-skin sensors. Our preliminary findings also show that *BioLIG Fabric* has tensile strength, such as shearing, bending, and twisting. We were able to use the CNF-infused material with a sewing machine and create a semi-heavy-duty bag. This makes *BioLIG Fabric* ideal to incorporate into fabric-oriented electronics prototyping such as wearables, bags, or garments.

Storage
BioLIG Fabric stored in a sealed container, e.g., zip lock bag, remains soft and compliant for at least nine months. We observed that the self-adhesive property remains effective for six months.

4.3 *BioLIG Plastic* - a plastic-like material for laser-induced conductivity

Stiff, waterproof, plastic-like materials are common in prototyping. In the following section, we demonstrate how to make a carbon-rich, plastic-like bio-based material optimized for laser-induced conductivity. We investigate material formulations that make stiff and water-resistant sheets while increasing the conductivity compared to those of cellulose-based materials. After material formulation and fabrication, we discuss the CO2 laser graphitization process for sensor and circuit prototyping.

Material Formulation
Lignin has a very high carbon content (up to 60% [96]) compared to many other biopolymers, making it an ideal precursor for carbonisation and one of the most effective raw ingredients for converting biopolymer into LIG [13]. The biggest challenge with lignin is how brittle it is. We experimented with various cellulose-to-lignin ratios and polymer binders to overcome this challenge, such as 5 - 30% sodium alginate and 2 - 10% glycerin. Ultimately, we optimized our *BioLIG Plastic* and mixed pure lignin with PVA (Polyvinyl Alcohol) as the binder instead of sodium alginate.

Synthesizing and Casting Sheets
BioLIG Plastic is made from distilled water, polyvinyl alcohol (PVA), pure lignin powder, and sodium hydroxide (NaOH). We prepared the mixture using a magnetic stirrer, which helps prevent air bubbles and ensures a uniform blend. The process starts by dissolving PVA in distilled water at 90 ° C for one hour with continuous stirring to create a stable polymer solution. Separately, we dissolve 1.5g lignin in a 2% NaOH solution before being combined with the PVA mixture in a 1:1 ratio. Once blended, the solution is poured into a 5 × 5 cm mold at a thickness of 2mm and left to dry at room temperature for 24 hours. The dried sheets are stiff and water resistant, offering high electrical conductivity and making them suitable for biodegradable circuits. However, the brittle nature of lignin makes it difficult to scale up production, since larger sheets often warp or crack during drying. Despite these challenges, *BioLIG Plastic* is industrially compostable, making it a viable option for sustainable electronics while maintaining strong electrical performance.

Inducing Conductivity through Laser
BioLIG Plastic sheets achieved 2x higher electrical performance 30 Ω/□ compared to *BioLIG Paper* (newsprint). We used 8% power, 16% speed, -2mm defocus.

Material Property
BioLIG Plastic is a rigid, dark brown material. The surface is smooth and even. The LIG induced on the material is uniform, and under the microscope, very few gaps can be observed, resulting in a highly conductive and densely connected carbon layer.

Storage
BioLIG Plastic can be stored in room conditions, but can easily become brittle after 3 months.

BioLIG Paper (pulp)				
synthesize		functionalization		Ω/□
hardwood pulp	20%	power	8	85
sodium alginate	4-8%	speed	16	
glycerin	4-8%	defocus	-2mm	
dist. water	200ml			
BioLIG Paper (np)				
synthesize		functionalization		Ω/□
newsprint	10%	power	10	75
sodium alginate	4-8%	speed	18	
glycerin	4-8%	defocus	-3mm	
dist. water	200ml			
BioLIG Fabric				
synthesize		functionalization		Ω/□
CNF (5% dispersion)	8-12%	power	8	2.4k
sodium alginate	4-8%	speed	16	
glycerin	4-8%	defocus	-2mm	
dist. water	200ml			
BioLIG Plastic				
synthesize		functionalization		Ω/□
Lignin in 2% NaOH	10-15%	power	8	30
PVA	6-9%	speed	16	
glycerin	4-6%	defocus	-2mm	
dist. water	200ml			

Table 2: Hardwood pulp[5], Newsprint Paper (np) [79], CNF[84]), Sodium Alginate [31], Vegetable Glycerin[20], Lignin[65], NaOH[66], PVA[80]

5 Two Novel Paints Optimized for Laser-induced Conductivity

Bio-based materials are commonly used in fixed shapes, such as sheets, foam, threads, and we expand the existing library of bio-based liquids and pastes to allow for electrical interactions with an ink and a stain.

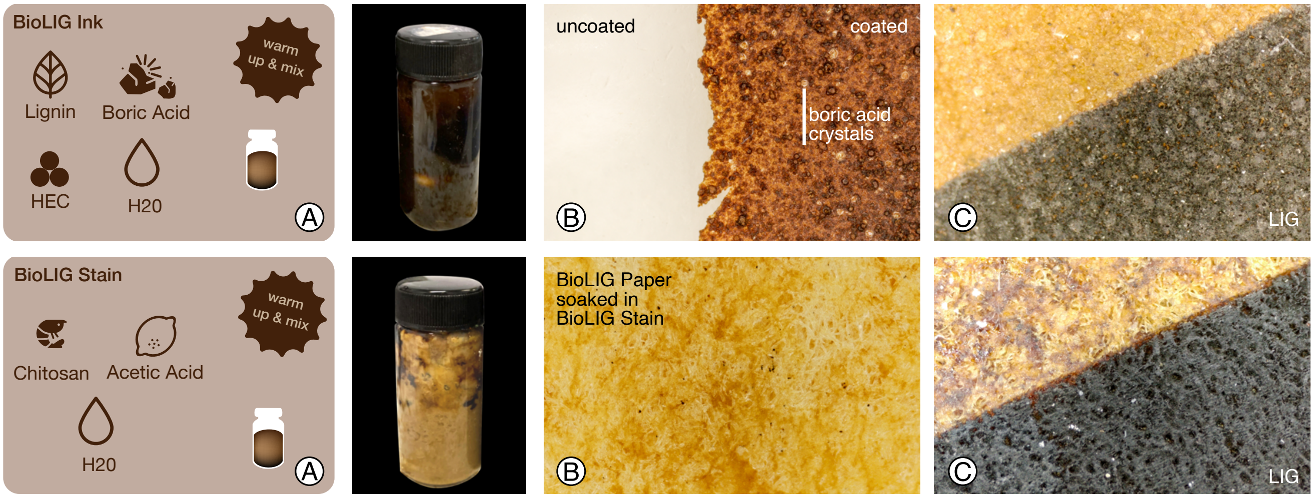


Figure 5: Two BioLIG paints, from top to bottom *BioLIG Ink* and *BioLIG Stain.* 1(A) and 2(A) show the material formulation and synthesis; 1(B) an Ink coated material and 2(B) a Stain coated under a 250x microscope, and 1(C) and 2(C) the visual cues of generated LIG.

5.1 *BioLIG Ink* - a lignin solution for Laser-induced Conductivity

As we recognized the brittleness of lignin in sheet materials, we shifted our attention to a paint-oriented approach. *BioLIG Ink* is a carbon-rich lignin solution that can be painted on surfaces to impart laser-induced conductivity to existing objects.

Material Formulation

First, we used 99% pure lignin with minimal residual by-products for optimal performance. To bind lignin, we used hydroxyethyl cellulose, a cellulose-based thickening agent, to improve the adhesion and increase carbon content in the ink for conductive making. We then added boric acid, a mineral and natural flame retardant, to allow the material to be graphitized at a higher point temperature without burning. The heat stability of *BioLIG Ink* allows for more effective conversion from carbon to graphene. This approach also allowed for better scalability, reproducibility, and consistency.

Synthesizing

To synthesize the *BioLIG Ink*, we dissolved pure lignin in distilled water. Hydroxyethylcellulose (HEC) acts as a binder, improving adhesion and flexibility, while boric acid is an environmentally friendly flame retardant. We significantly reduced brittleness and improved surface smoothness by applying lignin as a thin ink layer instead of incorporating it into the bulk material. This coating method was the most effective for enhancing the precursor's mechanical and electrical properties.

Inducing Conductivity through Laser

The process is to apply the ink, let it dry (15 - 30min) and then laser treat. By incorporating boric acid as a flame retardant, we were able to graphitize the *BioLIG Ink* at almost double power, while lowering the speed 14% power, 10% speed, -3mm defocus. Our observations under the microscope (60x) and electrical characterizations show the higher power resulted in a more complete, efficient conversion of biopolymer into a conductive graphitic structure. We were able to achieve sheet resistances as low as 14 Ω/□, which is comparable to synthetic polyimide films that range from 5 Ω/□ to 50 Ω/□[99].

Storage

The ink can be stored in an airtight bottle. In our observation, it is usable for up to six months. The ink is water-soluble and easily washed off from applied surfaces.

5.2 *BioLIG Stain* - a chitosan stain for Laser-induced conductivity

Material Formulation

Due to its natural flame-retardant properties, chitosan helps regulate heat distribution during the graphene conversion process, reducing the spread of flames and improving efficiency. Chitosan is water-soluble at a pH lower than 6 [43, 60]. We could confirm through preliminary measurements of water contact angles. *BioLIG Stain* on Paper achieved an average of 112°, which classifies it as hydrophobic (>90°).

Synthesis We prepared the *BioLIG Stain* by dissolving 8% chitosan powder into 0.2% acetic acid to provide a total volume of 100 ml, creating a solution that enhances structural integrity and heat resistance. This stain is best suited for porous materials such as *BioLIG Paper.*

Inducing Conductivity through Laser

Similar to *BioLIG Ink*, we graphitized materials dipped into *BioLIG Stain* at a higher power setting without burning. However, the biggest improvement came from defocusing. By using 9% power, 15% speed, and -2mm defocus, we achieved a sheet resistance of 500 Ω/□. In comparison, at the same power and speed settings but with 4 mm defocus, the resistance was reduced by 5x to 100 Ω/□.

Storage

The stain can be stored in an airtight bottle. In our observation, it is usable for up to six months.

BioLIG Ink				
synthesize		functionalization		Ω/□
lignin	10-15%	power	10	14
Hydroxyethylcell. (HEC)	10-15%	speed	14	
boric acid	8-10%	defocus	-3mm	
dist. water	40ml			
BioLIG Stain				
synthesize		functionalization		Ω/□
chitosan	8-12%	power	9	100
acetic acid	0.2%	speed	15	
dist. water	40ml%	defocus	-4mm	

Table 3: HEC[78], Boric Acid[75], Chitosan[77], Acetic Acid[73]

6 Electrical Characterization of BioLIG

We analyzed the laser-induced conductivity of sheets by evaluating the sheet resistance of LIG induced on them. Using a laser cutter for fabrication means that power and speed settings might not be directly transferable, even between the same machine models. Therefore, we provide details as a starting point for others to replicate, along with guidelines as to how to fine-tune the settings for their setup. We used a 30W 10.6microns CO2 laser cutter (GCC Spirit GLS 30). In tests, *BioLIG Ink* was tested on a conventional ceramic plate, and *BioLIG Stain* was tested on *BioLIG Paper* (pulp). Laser-induced graphene is a process about finding a narrow window rather than hitting a perfect endpoint. We first determined the upper and lower limits of the laser settings. The lower limit is defined by the transition from substrate to amorphous carbon (not conductive to conductive), and the upper limit of laser settings is defined by the transition from graphene to char (highly conductive to less conductive). After determining the maximum and minimum settings, we carefully tuned the scanning speed, laser power, and focus distance to maximize conductivity. We used the following setup: a 3x3 grid of squares of 5mm x 10mm. Along the X-axis, we graphitized with two-step incremental power; along the Y-axis, we graphitized with two-step incremental scanning speed. This grid was repeated at defocusing levels of -1mm, -2mm, -3mm, and -4mm and for 1 and 2 passes. For each material, we collected 54 resistance values. Finally, we repeated the most promising settings three times and took the average as the sheet resistance value of the material. The biggest reduction in sheet resistance is caused by defocusing, see figure 8.

We summarized electrical characterization in a sheet resistance graph. The graph presents the set of materials, as well as, slight variations, e.g., different amounts of newsprint. We grouped similar raw materials by color to highlight the strong influence of raw materials on the graphitization process. In conclusion, our observations show that lignin sheets outperform cellulose sheets, and the paints show the best performance overall.

BioLIG	0mm	-1mm	-2mm	-3mm	-4mm
Paper pulp (8%P 16%S)	/	435	85	650	2k
Paper np (10%P 18%S)	/	375	145	75	345
Fabric (8%P 16%S)	/	30k	2.4k	3k	/
Plastic (8%P 16%S)	2.6k	465	30	50	80
Ink (10%P 14%S)	2k	1.2	300	14	24
Stain (9%P 15%S)	/	2.5M	210	160	95

Table 4: The table highlights shows optimal defocus values for lowest sheet resistance across six BioLIG materials. *BioLIG Ink* was tested on conventional ceramic plate and *BioLIG Strain* was tested on *BioLIG Paper* (pulp)

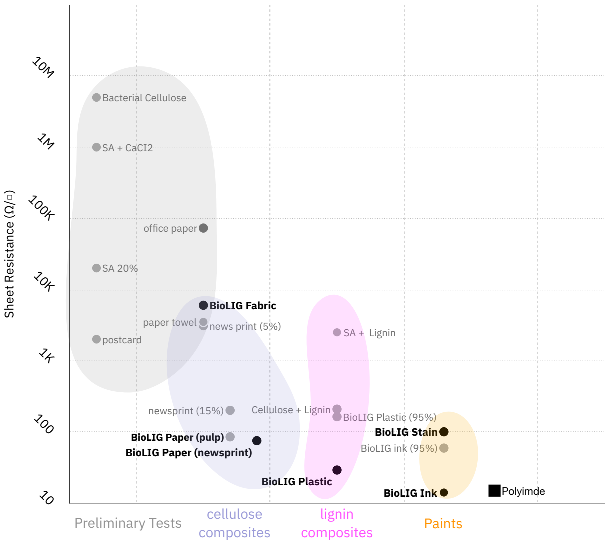


Figure 6: Sheet resistances of raw material groups: Preliminary tests, cellulose composites, and lignin composites and paints.

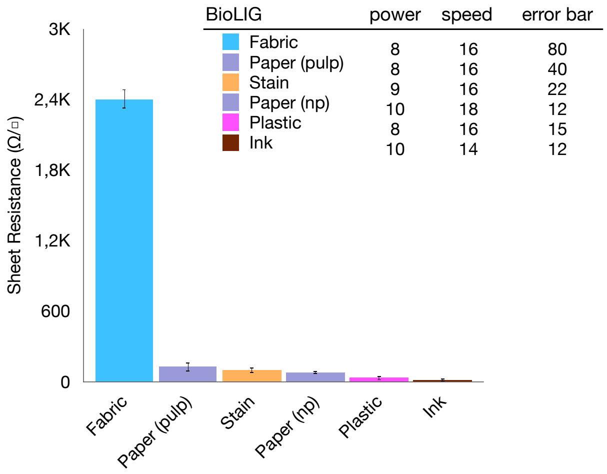


Figure 7: Sheet resistances of BioLIG materials with the error bar to indicating low variability and demonstrating reliability across batch production.

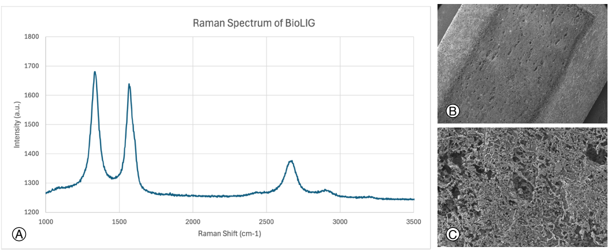


Figure 8: (A) shows the Raman spectroscopy with peaks typical for LIG. (B) shows the LIG electrode, the darker material is LIG and the brighter material is cellulose. (C) shows the SEM of a porous network of LIG.

In order to confirm the successful formation of laser-induced graphene using our laser settings on the bioderived substrate, we conducted Raman spectroscopy. The *BioLIG Paper* example's spectrum clearly exhibits three prominent peaks that are typical of graphitic material. Further, the SEM images shows distinct nature of generated LIG. At the edges of the electrode in image (C), the electrode maintains a morphology similar to the native cellulose material [44, 72]. The SEM images clearly confirm the transformation of the material from the native cellulose structure to a conductive porous network of LIG. Other sample images confirm the presence of LIG as well.

7 Three Robust Coatings for Stable Functionality

The coating protects the graphene from moisture from the hands or day-to-day abrasion common in interaction design prototyping. Robustness is often a limitation seen with many bio-based conductive material approaches. In this section, we present three coatings and analyze their properties regarding robustness to touch, changes in electrical conductivity, and hydrophobic behavior.

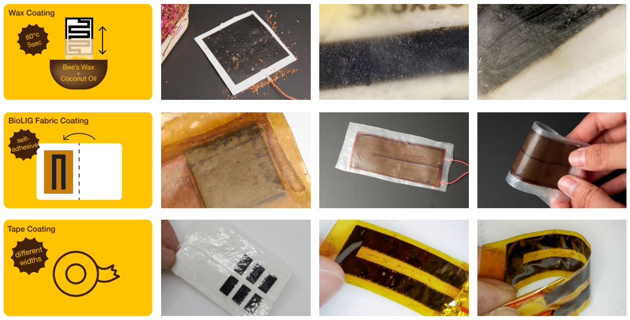


Figure 9: From top to bottom: water-repellent Wax coating, multi-functional fabric coating and easy-to-use tape coating for a quick and rapid flexible protection

Beeswax is a natural product commonly used as a bio-based coating due to its water-repellent properties, which protect against environmental degradation. We heated beeswax pellets to 80°C, dipped the LIG-patterned bio-based material for three seconds, and then dried it vertically. This process resulted in a 20% increase in conductivity, likely due to the beeswax compressing the LIG and enhancing layer interconnectivity. Beeswax is best suited for rigid applications where significant bending is unlikely. To improve the stiffness and flexibility of the coating, we might consider adding natural oils like coconut oil.

***BioLIG Fabric* used as a coating**, a single sheet of *BioLIG Fabric* can be used as the substrate and then folded on itself to serve as a coating. With the fabric-like material as the coating, we observe an increase in resistance of 60%. However, when we created mirrored LIG traces and layered them, the increased surface area reduced the resistivity by 50%. Moreover, the non-LIG backside of the fabric-like material acts as protection against abrasion or rubbing.

Cellophane Tape is a commercially available product consisting of cellulose film with natural rubber adhesive. Cellophane tape increased resistance by roughly 30%. In addition to providing water-repellent protection, we explored transferring LIG using the tape to other surfaces.

	conductivity	water repellent	compliant
Beeswax	+20%	yes	no
BioLIG Fabric as coating	-5%	no	yes
Cellophane Tape	-10%	yes	yes

Table 5: Beeswax[74], Cellophane Tape[76], Any coating can effect the conductivity of LIG and forms a compromise between robustness and efficiency.

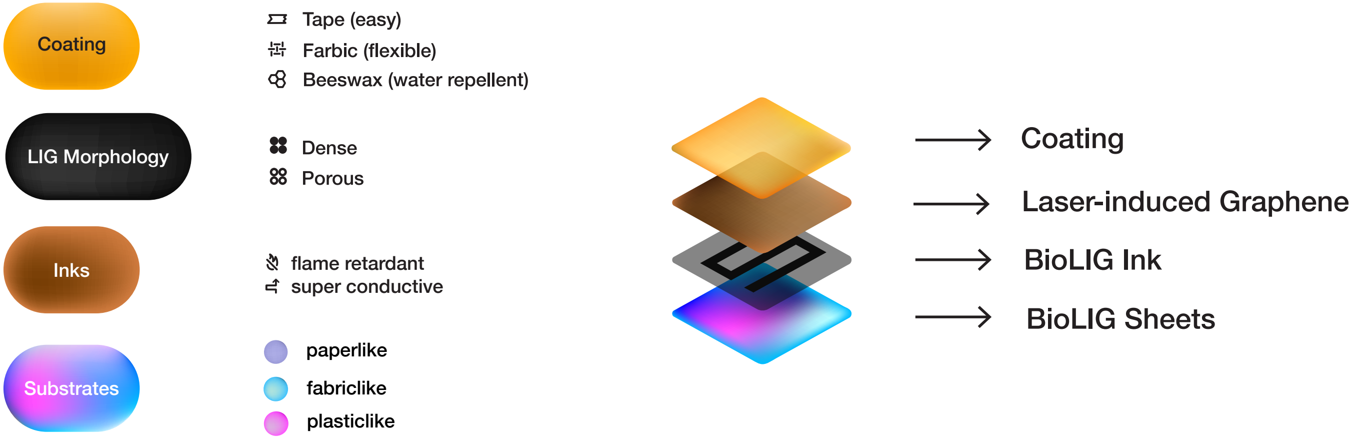


Figure 10: Combination of different *BioLIG* materials to form multifunctional biocomposites.

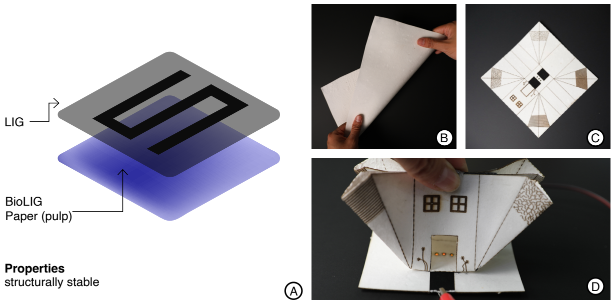
8 Conductive Biocomposites

BioLIG sheets, paints, and coatings can be combined to complement each other and create new biocomposites with unique characteristics and properties such as hydrophobic/hydrophilic, mechanical compliance, or electrical resistivity. For example, *BioLIG Fabric* can be coated with the *BioLIG Ink* to increase conductivity while remaining flexible for wearables or on-skin applications.

9 Applications

In the following, we show six applications using our framework. The combinations are not meant to be exhaustive but demonstrate how flexible makers can combine our materials to make multifunctional biocomposites. The presented selection is chosen based on the most common sensors and prototyping practices for HCI. All figures follow: (A) shows the biocomposite, (B) the material, (C) the fabrication, and (D) the application.

9.1 Interactive Paper Circuits



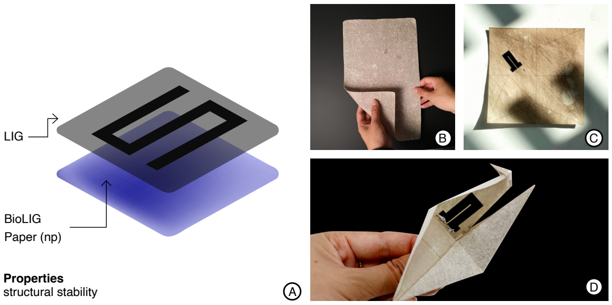


Figure 11: Top to bottom: Tent Circuit makes paper model with electrical capabilities in a single-step process. Origami Crane Circuit is an origami crane that lights up with the flap of its wings.

5.1a) shows an Open-Fire Tent Model Circuit that could be the response of an architecture student to the assignment "Design a foldable Tent Structure". *BioLIG Paper* with high cellulose content, e.g., 20%, is the ideal material because it is foldable but structurally stiff. Then, the student prepares the digital file for laser cutting with lines to cut, textures and patterns to engrave, and perforation creases for folding, similar to their usual workflow. To capture the coziness of a campfire, they add LIG traces that can be connected to orange LEDs to symbolize the warmth of the fire. 5.1b) Origami is a practice with a long tradition, and in the HCI community, it has served as an inspiration for haptic feedback [16] and foldable interactive robotic mechanisms [45]. Using *BioLIG Paper* (newsprint), we made an Origami Crane Circuit consisting of a bend sensor and an LED. The LED lights up with the wing's motion. It took several prototypes to find the ideal length and position for the bend sensor. We reused all the iterations as a base material for the final *BioLIG Paper* sheets.

9.2 Humidity Sensor

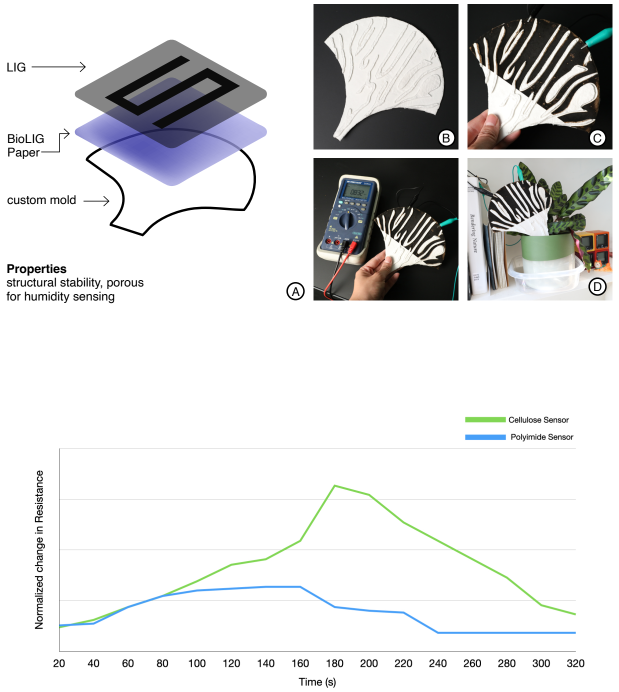


Figure 12: Top: A humidity sensor made using the hydrophilic nature of cellulose. Bottom: comparing humidity sensor on polyimide to that on *BioLIG Paper*.

Through its material porosity, bio-based materials can be suitable for exploring more-than-human design [50, 81]. Most off-the-shelf humidity sensors use metal oxides [63], which are often anti-bacterial and possibly disturb the very microbiome more-than-human design wants to sense. In Nicolae et al.'s paper, the antimicrobial properties of silver-coated fibers embedded into Scoby killed the culture after approximately 3 days [55]. Cellulose, as a humidity sensor, on the other hand, is plant- and soil-compatible. To evaluate the humidity sensor, we compared one fabricated using *BioLIG Paper* as substrate and a second using polyimide as substrate. In a simple humidity testing environment (sealable box + humidifier), characterization data were taken. While the polyimide reacts much quicker to sudden humidity changes, cellulose offers finer granularity in readings. The *BioLIG Paper* humidity sensor reached a high resistance of 850Ω and low of 250Ω at different levels. However, the cellulose material would saturate with moisture and require more 'cool down time' in between readings, and is therefore more suitable for measuring gradual humidity changes e.g. air moisture over a day.

Working with these strengths and weaknesses, we designed a humidity sensor prototype to detect plant leaf transpiration rather than soil moisture. A custom mold is made for this application to create an interesting 2.5D shape and increase surface area for sensing. Prototyping not only visualizes ideas but also helps makers think. Especially when exploring ideas that question the norm, not relying on off-the-shelf components with predetermined shapes and behaviors allows people to explore ideas that push the boundaries more in-depth.

9.3 Capactive Proximity Sensor

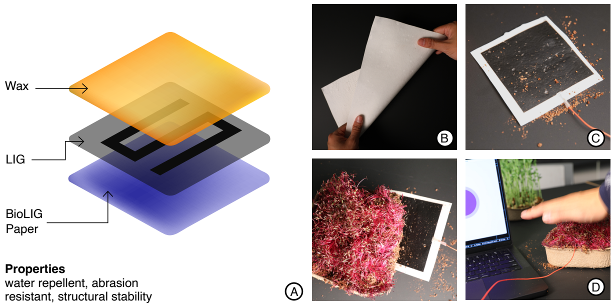


Figure 13: Capacitive Proximity Sensor for non-toxic in soil application.

This application demonstrates a water-repellent biocomposite fabricated using the *BioLIG* framework. Beyond design research, Human-plant interaction is also interesting in the context of human well-being, sustainable product design, and agricultural or interspecies design [15, 64]. In this application, we demonstrate a coated BioLIG capacitive sensor that is entirely biodegradable and agreeable to plants. We used *BioLIG Paper* and protected it from watering, dirt, and moisture with beeswax as a coating. The capacitive sensor pattern was a 10cm x 10cm LIG square. Xiao SAMD21 electronic board reads out the signal with a QT pin.

9.4 Heat Display

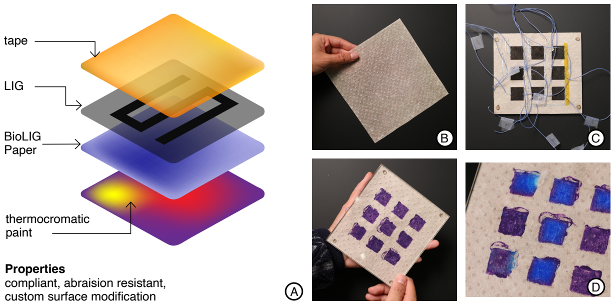
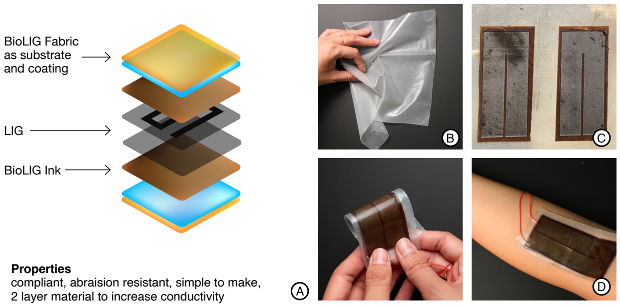


Figure 14: Heat Display. Each heater is created by the laser and then combined with thermochromic paint.

Beyond simple circuits and resistive sensors as input devices, LIG has excellent electrothermal properties that can be used as an output device. Heat is an interesting element to use for interface design. Researchers use them to give thermal feedback, defrost surfaces to reveal messages, or combine them with thermochromic paint to create creative expressions [67, 82]. Controlling these interfaces electrically is preferred because users can manage them remotely and with greater precision. We used *BioLIG Paper* as the precursor and created a heat grid. We used non-toxic thermo-chromatic pigments to visualize the heat. The 3x3 heat grid is 10cm x 10cm and took 20 min to pattern. A single heating pad requires 6 volts to heat up to 40~ C, the temperature needed to activate the thermochromic paint. The maximum temperature achieved was 180 °C at 15 volts before the substrate started to smoke—furthermore, the rapid response time of 5 sec to reach equilibrium and cool down in 2 sec.

9.5 On Body Bend Sensor



Properties
compliant, abraision resistant, simple to make,
2 layer material to increase conductivity

Figure 15: On body stretch sensor uses *BioLIG Fabric*. In addition to mechanical compliance, it is compatible with human skin.

In the skin, wearable sensors are one of the primary areas of use of soft sensors in HCI. These applications are challenging because they require a substrate and conductor that is flexible, conforming, and durable. We demonstrate a soft bend sensor using *BioLIG Fabric* coated with *BioLIG Ink* for increased conductivity. First, the digital sensor pattern is designed. To increase the surface area and reduce resistance, we mirrored the sensor design so that it can then be folded on top of each other. Before conductive-making, we brushed *BioLIG Ink* evenly onto the fabric-like material. The biocomposite is then graphitized and folded. The non-inked or graphitized area remains self-adhesive and sealed off the sensor to create the final multifunctional biocomposite. The force-resistive bend sensor exhibits a resistance range of 140 to 1k Ohms when bent 90 degrees. While the material is soft and flexible, its solubility in moisture might limit the application. It is best suited for temporary or short-term on-body sensing and is unsuitable for high-moisture environments.

10 Biodegradability and Circular Making

Biodegradability of raw materials

Cellulose - present in most of our materials - is biodegradable via microbial pathways. Composting studies show that within 25 days in water, newsprint decomposes 25% and bleached hardwood pulp decomposes 90% [36]. Cellulose nanofibers (CNF) and Hydroxyethylcellulose (HEC) share these traits [24, 39]. Sodium alginate, present in *BioLIG Paper* and *BioLIG Fabric*, exhibits rapid biodegradation in soil, with full decomposition within approximately 28–30 days[70]. Glycerol, our plasticizer derived from plant oils, is rapidly biodegradable—achieving a rate of biodegradation of 85.9mg COD/g/h in water [30]. Chitosan, used in the *BioLIG Stain*, fully degrades within 6–8 weeks in soil or composting environments [91]. Acetic Acid, undergoes rapid degradation with studies indicating that it degrades by over 99% under anaerobic conditions within 7 days [35]. Lignin, while naturally more resistant in the environment, biodegrades through microbial/fungal pathways and has been integrated into compostable systems [83] Beeswax and Coconut oil, used in the Coatings, readily break down within 28 days in anaerobic conditions [21, 33]. For the Cellophane tape we refer to manufacturer characterizations [34]. Boric acid though not biodegradable, it is water-soluble and non-persistent and approved for organic agricultural use under regulation [85]. In *BioLIG Plastic*, PVA refers to Polyvinyl Alcohol, not Polyvinyl Acetate. Among industrial vinyl polymers, PVA is uniquely biodegradable by microorganisms. It is water-soluble and biodegradable under specific industrial conditions. However, its biodegradability is highly dependent on environmental factors and does not reliably occur in soil or marine contexts [18].

Although LIG derived from biocompatible substrates minimizes toxic byproducts, key factors such as particle size and exposure routes remain critical to consider. Preliminary studies have shown that LIG shows low toxicity even at high concentrations. For example, a recent study demonstrated that LIG shows low toxicity in models of zebrafish [28]. This biocompatibility is further supported by studies in human cells, including breast [89] and epithelial cells [28], where LIG exhibited lower cytotoxicity effects than graphene-based nanomaterials. Moreover, the SEM images confirm that the generated LIG is at the micrometer scale, minimizing health risks, as it is less likely to be inhaled or cause cytotoxic effects than nanoscale particles. Bioderived LIG, produced from eco-friendly substrates such as lignin and paper, demonstrates low environmental toxicity, aligns with the principles of the circular economy by minimizing hazardous by-products and supporting the sustainable upcycling of waste materials [26, 54].

Biodegradability of Biocomposites

Building on the biodegradability of the raw materials, we rationalize biodegradability on a biocomposite level as likely in environmental or industrial conditions. Biocomposite films combining alginate, chitosan, and cellulose nanocrystals (CNCs) - comparable to our sheets - biodegrade over 90% in water within 5 days [88]. A 2024 investigation of alginate–chitosan coatings - similar to our stain - for food packaging confirmed to fully degrade in soil within 2–3 weeks [3].

Circular Making

Beyond making, the un-making is a key component of BioLIG. BioLIG allows what otherwise would be prototyping waste to be repurposed, contributing to an on-site circular fabrication process. *In water* Our water dissolution tests on test pieces 25mm x 25mm and using a magnetic stirrer reports:

Figure 16: BioLIG sensors and circuits can be recycled and disposed of in different ways. (A) leverages the water-soluble properties to separate conventional electronics from the substrate. (B) sensors can also be composted with no harm to the soil. (C) material cut-offs and scraps created during the subtractive manufacturing process can be blended to make new substrates.

BioLIG	initial mass	final mass	submerge time	mass loss
Paper	0.213g	0g	21 min	100 %
Fabric	0.131g	0g	11 min	100 %
Plastic	0.291g	0.174g	30 min	40.2 %
Paper coated in Beeswax	0.738g	0.630g	30 min	14.6 %

Table 6: Water dissolution test results for four material specimens. The water is agitated at 600 RPM using a magnetic stirrer plate for 30 minutes.

After dissovling, we collected wires and electronic components to reuse for other projects. We also reused wastewater for the production of new materials. LIG is not water-soluble; therefore, LIG particles float in water. However, after repeated testing, we did not observe any negative effects on the new substrate made from wastewater.

Blending: Scrap materials from the subtractive laser process can be collected and directly reintegrated into production. We developed several new materials by blending scrap materials from different recipes. Although the final substrate may exhibit variability in conductivity, we achieved consistent results by incorporating additional cellulose to ensure the desired conductivity.

Compost BioLIG Plastic and coated biocomposites are compostable in a short period without specialized industrial conditions. We buried a piece of *BioLIG Paper* with LIG traces on it in the soil and our initial testing reports a mass-loss of over 99% within 3 days (from 5g to completely decomposed). While it demonstrates the inherent biodegradability of the material, the exact time can heavily depend on the weather conditions.

11 Discussion

11.1 Differences between off-the-shelf rapid prototyping and bio-rapid prototyping

While working on BioLIG, we noticed key challenges and opportunities for bio-rapid prototyping compared to prototyping with off-the-shelf components. Surprisingly, one of the biggest advantages of bio-rapid prototyping might be time, a crucial factor for the iterative process of prototyping. In the following, we compare the prototyping process of an off-the-shelf HiLetgo DHT11 humidity sensor and that of a *BioLIG Paper* humidity sensor. While it is important to consider learning processes, we compare the time to execute the protocol after learning it. We chose this estimation since learning speed varies across user groups and is not the focus of this paper.

Ordering or sourcing the appropriate off-the-shelf sensor took about 1 hour, and the shipping took 48 hours, resulting in a total of 49 hours for the DHT11 to be ready to use. Fabricating the *BioLIG Paper* humidity sensor substrate took 1 hour, and drying took 12 hours. Following the optimized recipe and workflow minimizes the time commitment, making bio-rapid prototyping an attractive option for makers. Finally, designing/fabricating the sensor took 1 more hour, resulting in a total of 14 hours for the BioLIG humidity sensor to be ready to use. Bio-rapid prototyping is, in this case, 3.5 times faster than working with off-the-shelf components. Further, bio-rapid prototyping in general offers greater freedom in customizing electronics, reducing the labor involved in adapting existing sensors to fit custom housings. Lastly, bio-based materials reduce the burden of making mistakes and support iterative development. This is especially true for the BioLIG framework, as it provides a computational workflow that allows for easy error correction, and

	HiLetgo DHT11 humidity sensor	*BioLIG Paper humidity sensor*
preparation time	1h, research and order sensor online 24hrs - 48hrs, delivery time, longer on weekends **= 25hrs - 49hrs**	1h, fabricate material 12hr, drying 1hr, designing and fabbricating sensor **= 14hrs**
implementation	based on data sheet	characterize to evaluate max. and min. values, could be enhanced with design tool
system integration	Design the enclosure around the given dimensions of the sensor;	custom and creative sensor shapes case by case
mistakes and number of iteration	Ordered more sensors from the beginning	made 3 iterations of sensors to finetune property
cost	$2.99	$0.01

Table 7: Comparison of off-the-shelf prototyping and bio-rapid prototyping process.

its materials can be readily recycled. In contrast, with store-bought sensors, makers often have to anticipate and account for errors at the ordering stage - right at the beginning of an unpredictable prototyping process.

11.2 Technical limitations

We demonstrated five applications for BioLIG sensors and simple circuits. However, the current process is unsuitable for producing intricate or multilayered PCB boards. The inherent resistive nature of carbon-based conductors makes LIG orders of magnitude less conductive than metal-based materials such as copper or silver. While this may present challenges for specific designs like high-power or high-frequency circuits, most sensors do not necessitate high conductivity. For example, an off-the-shelf humidity sensor typically exhibits high internal resistance in the megaohm range, allowing for more precise stepped readings. Another limitation is that it is not feasible to directly solder onto LIG, complicating the assembly of circuits with numerous small components. We employed silver epoxy as a connector to establish a stable connection between LIG and electronic components. Although silver epoxy can be easily dissolved and disposed of properly, discovering a more affordable and straightforward method for establishing these connections is crucial to enabling more intricate BioLIG circuits. We briefly tested lignin-based ink as an adhesive, followed by a wax seal to press on the contacts, as well as a conductive glue doped with LIG particles; however, the bond strength was inconsistent, and the conductivity was too low for reliable use. Bio-based interconnects that reliably establish a connection and are non-toxic are a key area for future work. An entirely different approach we explored uses copper-plated laser-induced graphene traces. Copper plating provides excellent conductivity and solderability but necessitates additional production steps. Given the urgency to promote the adoption of bio-based materials for prototyping, we believe that utilizing off-the-shelf microcontrollers combined with various BioLIG sensors can facilitate a wide range of interactions and address many rapid prototyping needs.

12 Future Work

12.1 Expanding the Library of BioLIG

While current BioLIG research focuses on materials like newsprint and kitchen towels, there is significant potential for expanding the library of bio-based substrates. Exploring new materials such as bamboo, wool, sugarcane bagasse, or agricultural waste could unlock properties like improved conductivity, flexibility, and biodegradability. Testing and fine-tuning new formulations that combine cellulose or lignin with other biodegradable polymers or natural additives could further expand the scope of BioLIG, allowing for more specialized applications. These developments would provide a broader range of options for users, enhancing the versatility of BioLIG for sustainable electronics. Developing rigid and thicker sheets is another area of future work. While current substrates are thin and robust, creating stiff BioLIG materials could open up new avenues for structural electronics. Materials like wood pulp, mycelium, or bamboo fiber could be pressed into thicker sheets that are better suited to applications requiring greater mechanical strength. Thicker substrates would also help mitigate issues like warping and shrinking during drying, allowing for more consistent LIG traces. Achieving scalability and consistency in producing these thicker materials would significantly enhance the versatility of BioLIG for diverse applications.

13 Conclusion

In this paper, we introduced BioLIG, a fabrication framework for functionalizing biocomposites with laser-induced graphene for biodegradable electronics prototyping. (1) We contributed and characterized five optimized material formulations and laser settings to enable computational and iterative rapid prototyping of biodegradable circuits and sensors with conductivity comparable to synthetic alternatives. (2) We demonstrated three protective coatings that allow bio-based prototypes to be much more versatile in everyday use while remaining biodegradable. (3) We implemented five applications and showed in detail how to combine different substrates, paints, and coatings for multifunctional biocomposites. These encouraging results highlight the versatility of bio-based materials and represent a timely and necessary step toward sustainable and circular digital fabrication.

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References

[1] [n. d.]. Jiva Materials Ltd | The World's First Fully Recyclable PCB Substrate. https://www.jivamaterials.com/

[2] Fabricademy Academy, Textile. 2021. Fabricademy 2021-22 Week 06 Biofabricating Materials by Cecilia Raspanti. https://vimeo.com/639230954/58e599f00d

[3] Faheem Ahmad, Ali Hassan, Bushra Mushtaq, Farooq Azam, Sheraz Ahmad, Abher Rasheed, and Yasir Nawab. 2024. A biodegradable alginate/chitosan hydrogel based nonwoven from pre-consumer cotton waste and virgin wool for food packaging. *Industrial Crops and Products* 216 (Sept. 2024), 118795. doi:10.1016/j.indcrop.2024.118795

[4] Valerio Francesco Annese, Pietro Cataldi, Valerio Galli, Giulia Coco, João Paulo Vita Damasceno, Alex Keller, Yogeenth Kumaresan, Pietro Rossi, Ivan K. Ilic, Bokeon Kwak, Lauro Tatsuo Kubota, Athanassia Athanassiou, Jonathan Rossiter, Dario Floreano, and Mario Caironi. 2024. A Sprayable Electrically Conductive Edible Coating for Piezoresistive Strain Sensing. *Advanced Sensor Research* 3, 5 (2024), 2300150. doi:10.1002/adsr.202300150 _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/adsr.202300150.

[5] Arnold Grummer's. 2025. Hardwood Pulp Supply. https://arnoldgrummer.com/pulp-sampler-1943.html. Accessed: 2025-07-17.

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

[7] Fiona Bell, Derrek Chow, Hyelin Choi, and Mirela Alistar. 2023. SCOBY BREASTPLATE: SLOWLY GROWING A MICROBIAL INTERFACE. In *Proceedings of the Seventeenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '23)*. Association for Computing Machinery, New York, NY, USA, 1–15. doi:10.1145/3569009.3572805

[8] Fiona Bell, Derrek Chow, Eldy S. Lazaro Vasquez, Laura Devendorf, and Mirela Alistar. 2023. Designing Interactions with Kombucha SCOBY. In *Proceedings of the Seventeenth International Conference on Tangible, Embedded, and Embodied Interaction*. ACM, Warsaw Poland, 1–5. doi:10.1145/3569009.3571841

[9] Fiona Bell, Camila Friedman-Gerlicz, and Leah Buechley. 2025. Biomaterial Recipes for 3D Printing: A Cookbook of Sustainable and Extrudable Bio-Pastes. In *Proceedings of the Nineteenth International Conference on Tangible, Embedded, and Embodied Interaction*. ACM, Bordeaux/Talence France, 1–15. doi:10.1145/3689050.3704427

[10] Fiona Bell, Camila Friedman-Gerlicz, Lauren Urenda, and Laura Buechley. 2025. 3D Printing Eggshells: Exploring Eco-Socio-Technical Relations through Biomaterial Design. In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems*. ACM, Yokohama Japan. doi:10.1145/3706598.3714290

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

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

[13] Anna Chiara Bressi, Alexander Dallinger, Yulia Steksova, and Francesco Greco. 2023. Bioderived Laser-Induced Graphene for Sensors and Supercapacitors. *ACS Applied Materials & Interfaces* 15, 30 (Aug. 2023), 35788–35814. doi:10.1021/acsami.3c07687

[14] Leah Buechley, Sue Hendrix, and Mike Eisenberg. 2009. Paints, paper, and programs: first steps toward the computational sketchbook. In *Proceedings of the 3rd International Conference on Tangible and Embedded Interaction (TEI '09)*. Association for Computing Machinery, New York, NY, USA, 9–12. doi:10.1145/1517664.1517670

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

[16] Zekun Chang, Tung D. Ta, Koya Narumi, Heeju Kim, Fuminori Okuya, Dongchi Li, Kunihiro Kato, Jie Qi, Yoshinobu Miyamoto, Kazuya Saito, and Yoshihiro Kawahara. 2020. Kirigami Haptic Swatches: Design Methods for Cut-and-Fold Haptic Feedback Mechanisms. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–12. doi:10.1145/3313831.3376655

[17] Tingyu Cheng, Taylor Tabb, Jung Wook Park, Eric M Gallo, Aditi Maheshwari, Gregory D. Abowd, Hyunjoo Oh, and Andreea Danielescu. 2023. Functional Destruction: Utilizing Sustainable Materials' Physical Transiency for Electronics Applications. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23)*. Association for Computing Machinery, New York, NY, USA, 1–16. doi:10.1145/3544548.3580811

[18] Emo Chiellini, Andrea Corti, Salvatore D'Antone, and Roberto Solaro. 2003. Biodegradation of poly (vinyl alcohol) based materials. *Progress in Polymer Science* 28, 6 (June 2003), 963–1014. doi:10.1016/S0079-6700(02)00149-1

[19] Yieu Chyan, Ruquan Ye, Yilun Li, Swatantra Pratap Singh, Christopher J. Arnusch, and James M. Tour. 2018. Laser-Induced Graphene by Multiple Lasing: Toward Electronics on Cloth, Paper, and Food. *ACS Nano* 12, 3 (March 2018), 2176–2183. doi:10.1021/acsnano.7b08539 Publisher: American Chemical Society.

[20] CVS Pharmacy. 2025. CVS Beauty USP Pure Glycerin, 6 OZ. https://www.cvs.com/shop/cvs-beauty-usp-pure-glycerin-6-oz-prodid-1015638. Accessed: 2025-07-17.

[21] Anu Kumar Das, Dayal Ch Shill, and Saibal Chatterjee. 2022. Coconut oil for utility transformers – Environmental safety and sustainability perspectives. *Renewable and Sustainable Energy Reviews* 164 (Aug. 2022), 112572. doi:10.1016/j.rser.2022.112572

[22] Karijn Den Teuling, Amy Winters, and Miguel Bruns. 2024. Chitosan Biofilm Actuators: Humidity Responsive Materials for Sustainable Interaction Design. In *Proceedings of the Eighteenth International Conference on Tangible, Embedded, and Embodied Interaction*. ACM, Cork Ireland, 1–7. doi:10.1145/3623509.3635262

[23] Laura Devendorf, Joanne Lo, Noura Howell, Jung Lin Lee, Nan-Wei Gong, M. Emre Karagozler, Shiho Fukuhara, Ivan Poupyrev, Eric Paulos, and Kimiko Ryokai. 2016. "I don't Want to Wear a Screen": Probing Perceptions of and Possibilities for Dynamic Displays on Clothing. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. Association for Computing Machinery, New York, NY, USA, 6028–6039. doi:10.1145/2858036.2858192

[24] Yongfu Diao, Mingwei Song, Yulin Zhang, Lin-ying Shi, Yusan Lv, and Rong Ran. 2017. Enzymic degradation of hydroxyethyl cellulose and analysis of the substitution pattern along the polysaccharide chain. *Carbohydrate Polymers* 169 (Aug. 2017), 92–100. doi:10.1016/j.carbpol.2017.02.089

[25] Carl DiSalvo, Phoebe Sengers, and Hrönn Brynjarsdóttir. 2010. Mapping the landscape of sustainable HCI. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '10)*. Association for Computing Machinery, New York, NY, USA, 1975–1984. doi:10.1145/1753326.1753625

[26] Nandini Dixit and Swatantra P. Singh. 2022. Laser-Induced Graphene (LIG) as a Smart and Sustainable Material to Restrain Pandemics and Endemics: A Perspective. *ACS Omega* 7, 6 (Feb. 2022), 5112–5130. doi:10.1021/acsomega.1c06093 Publisher: American Chemical Society.

[27] Fernanda Dobal and Vali Lalioti. 2021. Circular Species: Designing critical thinking into children's science education through biomaterials and augmented reality. In *Proceedings of the 20th Annual ACM Interaction Design and Children Conference (IDC '21)*. Association for Computing Machinery, New York, NY, USA, 8–17. doi:10.1145/3459990.3460698

[28] Marta d'Amora, Andrea Lamberti, Marco Fontana, and Silvia Giordani. 2020. Toxicity assessment of laser-induced graphene by zebrafish during development. *Journal of Physics: Materials* 3, 3 (June 2020), 034008. doi:10.1088/2515-7639/ab9522 Publisher: IOP Publishing.

[29] Malai Eco. [n. d.]. Malai Eco. https://malai.eco/

[30] European Chemicals Agency (ECHA). 2025. Brief Profile: Substance Information - Ethylene Glycol. https://echa.europa.eu/brief-profile/-/briefprofile/100.000.601. Accessed: 2025-07-17.

[31] FitLane. 2025. Sodium Alginate Specification Sheet. https://tinyurl.com/3sut46rr. Accessed: 2025-07-17.

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

[33] Garima Gupta and Kumari Anjali. 2023. Environmentally Friendly Beeswax: Properties, Composition, Adulteration, and its Therapeutic Benefits. *IOP Conference Series: Earth and Environmental Science* 1110, 1 (Feb. 2023), 012041. doi:10.1088/1755-1315/1110/1/012041 Publisher: IOP Publishing.

[34] https://tinyurl.com/52ctc32v [n. d.].

[35] https://www.fda.gov/files/food/published/Environmental-Assessment-for-Food-Contact-Notification-No.-1783.pdf [n. d.]. accessed: 7 July 2025.

[36] Martin A. Hubbe, Jesse S. Daystar, Richard A. Venditti, Joel J. Pawlak, Marielis C. Zambrano, Morton Barlaz, Mary Ankeny, and Steven Pires. 2025. Biodegradability of cellulose fibers, films, and particles: A Review. *BioResources* 20, 1 (Jan. 2025). doi:10.15376/biores.20.1.hubbe

[37] Suk-Won Hwang, Hu Tao, Dae-Hyeong Kim, Huanyu Cheng, Jun-Kyul Song, Elliott Rill, Mark A. Brenckle, Bruce Panilaitis, Sang Min Won, Yun-Soung Kim, Young Min Song, Ki Jun Yu, Abid Ameen, Rui Li, Yewang Su, Miaomiao Yang, David L. Kaplan, Mitchell R. Zakin, Marvin J. Slepian, Yonggang Huang, Fiorenzo G. Omenetto, and John A. Rogers. 2012. A Physically Transient Form of

Silicon Electronics. *Science* 337, 6102 (Sept. 2012), 1640–1644. doi:10.1126/science.1226325 Publisher: American Association for the Advancement of Science.

[38] Ayaka Ishii, Kunihiro Kato, Kaori Ikematsu, Yoshihiro Kawahara, and Itiro Siio. 2022. CircWood: Laser Printed Circuit Boards and Sensors for Affordable DIY Woodworking. In *Proceedings of the Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '22)*. Association for Computing Machinery, New York, NY, USA, 1–11. doi:10.1145/3490149.3501317

[39] Heli Kangas, Marja Pitkänen, Minna Vikman, Jari Vartiainen, and Irina Tsitko. 2015. Biodegradability, compostability and safety of cellulose nanofibrils (CNF) and CNF-based products: International Congress on Safety of Engineered Nanoparticles and Nanotechnologies, SENN2015.

[40] Majeed Kazemitabaar, Jason McPeak, Alexander Jiao, Liang He, Thomas Outing, and Jon E. Froehlich. 2017. MakerWear: A Tangible Approach to Interactive Wearable Creation for Children. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. Association for Computing Machinery, New York, NY, USA, 133–145. doi:10.1145/3025453.3025887

[41] Sunyoung Kim and Eric Paulos. 2011. Practices in the creative reuse of e-waste. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11)*. Association for Computing Machinery, New York, NY, USA, 2395–2404. doi:10.1145/1978942.1979292

[42] Marion Koelle, Madalina Nicolae, Aditya Shekhar Nittala, Marc Teyssier, and Jürgen Steimle. 2022. Prototyping Soft Devices with Interactive Bioplastics. In *Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology*. ACM, Bend OR USA, 1–16. doi:10.1145/3526113.3545623

[43] Naoji Kubota and Yukari Eguchi. 1997. Facile Preparation of Water-Soluble N-Acetylated Chitosan and Molecular Weight Dependence of Its Water-Solubility. *Polymer Journal* 29, 2 (Feb. 1997), 123–127. doi:10.1295/polymj.29.123

[44] Bohdan Kulyk, Beatriz F. R. Silva, Alexandre F. Carvalho, Sara Silvestre, António J. S. Fernandes, Rodrigo Martins, Elvira Fortunato, and Florinda M. Costa. 2021. Laser-Induced Graphene from Paper for Mechanical Sensing. *ACS Applied Materials & Interfaces* 13, 8 (March 2021), 10210–10221. doi:10.1021/acsami.0c20270 Publisher: American Chemical Society.

[45] Mikiya Kusunoki and Haoran Xie. 2023. UX Study for Origami-Inspired Foldable Robotic Mechanisms. In *Proceedings of the Asian HCI Symposium 2023 (Asian CHI '23)*. Association for Computing Machinery, New York, NY, USA, 28–34. doi:10.1145/3604571.3604576

[46] Eldy S. Lazaro Vasquez, Mirela Alistar, Laura Devendorf, and Michael L. Rivera. 2024. Desktop Biofibers Spinning: An Open-Source Machine for Exploring Biobased Fibers and Their Application Towards Sustainable Smart Textile Design. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. ACM, Honolulu HI USA, 1–18. doi:10.1145/3613904.3642387

[47] Eldy S. Lazaro Vasquez, Netta Ofer, Shanel Wu, Mary Etta West, Mirela Alistar, and Laura Devendorf. 2022. Exploring Biofoam as a Material for Tangible Interaction. In *Designing Interactive Systems Conference*. ACM, Virtual Event Australia, 1525–1539. doi:10.1145/3532106.3533494

[48] Eldy S. Lazaro Vasquez, Hao-Chuan Wang, and Katia Vega. 2020. Introducing the Sustainable Prototyping Life Cycle for Digital Fabrication to Designers. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference (DIS '20)*. Association for Computing Machinery, New York, NY, USA, 1301–1312. doi:10.1145/3357236.3395510

[49] Jian Lin, Zhiwei Peng, Yuanyue Liu, Francisco Ruiz-Zepeda, Ruquan Ye, Errol L. G. Samuel, Miguel Jose Yacaman, Boris I. Yakobson, and James M. Tour. 2014. Laser-induced porous graphene films from commercial polymers. *Nature Communications* 5, 1 (Dec. 2014), 5714. doi:10.1038/ncomms6714 Publisher: Nature Publishing Group.

[50] Jen Liu, Daragh Byrne, and Laura Devendorf. 2018. Design for Collaborative Survival: An Inquiry into Human-Fungi Relationships. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, Montreal QC Canada, 1–13. doi:10.1145/3173574.3173614

[51] Jasmine Lu, Beza Desta, K. D. Wu, Romain Nith, Joyce E Passananti, and Pedro Lopes. 2023. ecoEDA: Recycling E-waste During Electronics Design. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology (UIST '23)*. Association for Computing Machinery, New York, NY, USA, 1–14. doi:10.1145/3586183.3606745

[52] Qiuyu Lu, Semina Yi, Mengtian Gan, Jihong Huang, Xiao Zhang, Yue Yang, Chenyi Shen, and Lining Yao. 2024. Degrade to Function: Towards Eco-friendly Morphing Devices that Function Through Programmed Sequential Degradation. In *Proceedings of the 37th Annual ACM Symposium on User Interface Software and Technology (UIST '24)*. Association for Computing Machinery, New York, NY, USA, 1–24. doi:10.1145/3654777.3676464

[53] Jennifer C. Mankoff, Eli Blevis, Alan Borning, Batya Friedman, Susan R. Fussell, Jay Hasbrouck, Allison Woodruff, and Phoebe Sengers. 2007. Environmental sustainability and interaction. In *CHI '07 Extended Abstracts on Human Factors in Computing Systems (CHI EA '07)*. Association for Computing Machinery, New York, NY, USA, 2121–2124. doi:10.1145/1240866.1240963

[54] Hye-ran Moon and Byunghoon Ryu. 2024. Review of Laser-Induced Graphene (LIG) Produced on Eco-Friendly Substrates. *International Journal of Precision Engineering and Manufacturing-Green Technology* 11, 4 (July 2024), 1279–1294. doi:10.1007/s40684-024-00595-y

[55] Madalina Nicolae, Vivien Roussel, Marion Koelle, Samuel Huron, Jürgen Steimle, and Marc Teyssier. 2023. Biohybrid Devices: Prototyping Interactive Devices with Growable Materials. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology*. ACM, San Francisco CA USA, 1–15. doi:10.1145/3586183.3606774

[56] Sai Nandan Panigrahy, Chang Hyeon Lee, Vrahant Nagoria, Mohammad Janghorban, Richa Pandey, and Aditya Shekhar Nittala. 2024. ecSkin: Low-Cost Fabrication of Epidermal Electrochemical Sensors for Detecting Biomarkers in Sweat. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. ACM, Honolulu HI USA, 1–20. doi:10.1145/3613904.3642232

[57] Yuecheng Peng, Danchang Yan, Haotian Chen, Yue Yang, Ye Tao, Weitao Song, Lingyun Sun, and Guanyun Wang. 2024. IntelliTex: Fabricating Low-cost and Washable Functional Textiles using A Double-coating Process. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. ACM, Honolulu HI USA, 1–18. doi:10.1145/3613904.3642759

[58] Ivan Poupyrev, Nan-Wei Gong, Shiho Fukuhara, Mustafa Emre Karagozler, Carsten Schwesig, and Karen E. Robinson. 2016. Project Jacquard: Interactive Digital Textiles at Scale. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. Association for Computing Machinery, New York, NY, USA, 4216–4227. doi:10.1145/2858036.2858176

[59] Jie Qi and Leah Buechley. 2010. Electronic popables: exploring paper-based computing through an interactive pop-up book. In *Proceedings of the fourth international conference on Tangible, embedded, and embodied interaction (TEI '10)*. Association for Computing Machinery, New York, NY, USA, 121–128. doi:10.1145/1709886.1709909

[60] Caiqin Qin, Huirong Li, Qi Xiao, Yi Liu, Juncheng Zhu, and Yumin Du. 2006. Water-solubility of chitosan and its antimicrobial activity. *Carbohydrate Polymers* 63, 3 (March 2006), 367–374. doi:10.1016/j.carbpol.2005.09.023

[61] redhouse. [n. d.]. redhouse. http://www.redhousearchitecture.org

[62] Michael L. Rivera, S. Sandra Bae, and Scott E. Hudson. 2023. Designing a Sustainable Material for 3D Printing with Spent Coffee Grounds. In *Proceedings of the 2023 ACM Designing Interactive Systems Conference*. ACM, Pittsburgh PA USA, 294–311. doi:10.1145/3563657.3595983

[63] M. Sajid, Z. J. Khattak, K. Rahman, G. Hassan, and K. H. Choi. 2022. Progress and future of relative humidity sensors: a review from materials perspective. *Bulletin of Materials Science* 45, 4 (Nov. 2022), 238. doi:10.1007/s12034-022-02799-x

[64] Olivia Seow, Cedric Honnet, Simon Perrault, and Hiroshi Ishii. 2022. Pudica: A Framework For Designing Augmented Human-Flora Interaction. In *Proceedings of the Augmented Humans International Conference 2022 (AHs '22)*. Association for Computing Machinery, New York, NY, USA, 40–45. doi:10.1145/3519391.3519394

[65] Sigma-Aldrich. 2025. Lignin - Product 370959. https://www.sigmaaldrich.com/US/en/product/aldrich/370959. Accessed: 2025-07-17.

[66] Sigma-Aldrich. 2025. Sodium Hydroxide. https://tinyurl.com/e7zewvh2. Accessed: 2025-07-17.

[67] Katherine W Song, Aditi Maheshwari, Eric M Gallo, Andreea Danielescu, and Eric Paulos. 2022. Towards Decomposable Interactive Systems: Design of a Backyard-Degradable Wireless Heating Interface. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems (CHI '22)*. Association for Computing Machinery, New York, NY, USA, 1–12. doi:10.1145/3491102.3502007

[68] Katherine W Song and Eric Paulos. 2021. Unmaking: Enabling and Celebrating the Creative Material of Failure, Destruction, Decay, and Deformation. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. ACM, Yokohama Japan, 1–12. doi:10.1145/3411764.3445529

[69] Katherine Wei Song and Eric Paulos. 2023. Vim: Customizable, Decomposable Electrical Energy Storage. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23)*. Association for Computing Machinery, New York, NY, USA, 1–18. doi:10.1145/3544548.3581110

[70] Natalia Stachowiak, Jolanta Kowalonek, Justyna Kozlowska, and Aleksandra Burkowska-But. 2023. Stability Studies, Biodegradation Tests, and Mechanical Properties of Sodium Alginate and Gellan Gum Beads Containing Surfactant. *Polymers* 15 (June 2023), 2568. doi:10.3390/polym15112568

[71] Meera Stephen, Ali Nawaz, Sang Yeon Lee, Prashant Sonar, and Wei Lin Leong. 2023. Biodegradable Materials for Transient Organic Transistors. *Advanced Functional Materials* 33, 6 (2023), 2208521. doi:10.1002/adfm.202208521 _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/adfm.202208521.

[72] Tanvir Sultana, Shahin Sultana, Husna Parvin Nur, and Md Wahab Khan. 2020. Studies on Mechanical, Thermal and Morphological Properties of Betel Nut Husk Nano Cellulose Reinforced Biodegradable Polymer Composites. *Journal of Composites Science* 4, 3 (Sept. 2020), 83. doi:10.3390/jcs4030083 Number: 3 Publisher: Multidisciplinary Digital Publishing Institute.

[73] Supplier. 2025. Acetic Acid. https://tinyurl.com/hkadcsxz. Accessed: 2025-07-17.

[74] Supplier. 2025. Beeswax. https://tinyurl.com/38bsfwm5. Accessed: 2025-07-17.

[75] Supplier. 2025. Boric Acid. https://tinyurl.com/5yv4452x. Accessed: 2025-07-17.

[76] Supplier. 2025. Cellophane Tape. https://tinyurl.com/32vspn9t. Accessed: 2025-07-17.

[77] Supplier. 2025. Chitosan. https://tinyurl.com/2vzsx3xf. Accessed: 2025-07-17.

[78] Supplier. 2025. Hydroxyethyl Cellulose (HEC). https://tinyurl.com/mry8xmx7. Accessed: 2025-07-17.

[79] Supplier. 2025. Newsprint. https://tinyurl.com/364xhmdt. Accessed: 2025-07-17.

[80] Supplier. 2025. Polyvinyl Alcohol. https://tinyurl.com/yhnbbt92. Accessed: 2025-07-17.

[81] Lauren Thu and Ron Wakkary. 2025. Designing-With and Situating Biomaterials. In *Proceedings of the Extended Abstracts of the CHI Conference on Human Factors in Computing Systems (CHI EA '25)*. Association for Computing Machinery, New York, NY, USA, 1–6. doi:10.1145/3706599.3720039

[82] Yutaka Tokuda and Tatsuya Kobayashi. 2024. Painting Inferno: Novel Heat and Stiffness Control Methods with Carbon Nanomaterial Conductive Heating Paint. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems (CHI '24)*. Association for Computing Machinery, New York, NY, USA, 1–17. doi:10.1145/3613904.3642226

[83] M. Tuomela, M. Vikman, A. Hatakka, and M. Itävaara. 2000. Biodegradation of lignin in a compost environment: a review. *Bioresource Technology* 72, 2 (April 2000), 169–183. doi:10.1016/S0960-8524(99)00104-2

[84] University of Maine. 2025. Order Nanocellulose. https://umaine.edu/pdc/nanocellulose__trashed/order-nanocellulose/. Accessed: 2025-07-17.

[85] U.S. Environmental Protection Agency. 2008. Reregistration Eligibility Decision (RED) Factsheet for Boric Acid. https://www3.epa.gov/pesticides/chem_search/reg_actions/reregistration/fs_PC-011001_1-Sep-93.pdf. Accessed: 2025-07-17.

[86] 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*. ACM, London United Kingdom, 308–311. doi:10.1145/3341162.3343808

[87] Eldy S. Lazaro Vasquez and Katia Vega. 2019. Myco-accessories: sustainable wearables with biodegradable materials. In *Proceedings of the 23rd International Symposium on Wearable Computers*. ACM, London United Kingdom, 306–311. doi:10.1145/3341163.3346938

[88] Beti Vidmar, Ana Oberlintner, Blaž Stres, Blaž Likozar, and Uroš Novak. 2023. Biodegradation of polysaccharide-based biocomposites with acetylated cellulose nanocrystals, alginate and chitosan in aqueous environment. *International Journal of Biological Macromolecules* 252 (Dec. 2023), 126433. doi:10.1016/j.ijbiomac.2023.126433

[89] Wei Wang, Bing Han, Yang Zhang, Qi Li, Yong-Lai Zhang, Dong-Dong Han, and Hong-Bo Sun. 2021. Laser-Induced Graphene Tapes as Origami and Stick-On Labels for Photothermal Manipulation via Marangoni Effect. *Advanced Functional Materials* 31, 1 (2021), 2006179. doi:10.1002/adfm.202006179 _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/adfm.202006179.

[90] Wen Wang, Lining Yao, Teng Zhang, Chin-Yi Cheng, Daniel Levine, and Hiroshi Ishii. 2017. Transformative Appetite: Shape-Changing Food Transforms from 2D to 3D by Water Interaction through Cooking. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, Denver Colorado USA, 6123–6132. doi:10.1145/3025453.3026019

[91] Natalia Wrońska, Nadia Katir, Marta Nowak-Lange, Abdelkrim El Kadib, and Katarzyna Lisowska. 2023. Biodegradable Chitosan-Based Films as an Alternative to Plastic Packaging. *Foods (Basel, Switzerland)* 12, 18 (Sept. 2023), 3519. doi:10.3390/foods12183519

[92] Di Wu, Emily Guan, Yunjia Zhang, Hsuanju Lai, Qiuyu Lu, and Lining Yao. 2024. Waxpaper Actuator: Sequentially and Conditionally Programmable Wax Paper for Morphing Interfaces. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. ACM, Honolulu HI USA, 1–16. doi:10.1145/3613904.3642373

[93] Zeyu Yan, Mrunal Sanjay Dhaygude, and Huaishu Peng. 2025. Make Making Sustainable: Exploring Sustainability Practices, Challenges, and Opportunities in Making Activities. In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems (CHI '25)*. Association for Computing Machinery, New York, NY, USA, 1–14. doi:10.1145/3706598.3713665

[94] Zeyu Yan, Advait Vartak, Jiasheng Li, Zining Zhang, and Huaishu Peng. [n. d.]. PCB Renewal: Iterative Reuse of PCB Substrates for Sustainable Electronic Making. https://arxiv.org/html/2502.13255v1

[95] Lining Yao, Jifei Ou, Chin-Yi Cheng, Helene Steiner, Wen Wang, Guanyun Wang, and Hiroshi Ishii. 2015. bioLogic: Natto Cells as Nanoactuators for Shape Changing Interfaces. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. ACM, Seoul Republic of Korea, 1–10. doi:10.1145/2702123.2702611

[96] Manzhao Yao, Xiaoyun Bi, Zuhao Wang, Peng Yu, Alain Dufresne, and Can Jiang. 2022. Recent advances in lignin-based carbon materials and their applications: A review. *International Journal of Biological Macromolecules* 223 (Dec. 2022), 980–1014. doi:10.1016/j.ijbiomac.2022.11.070

[97] Takashi Yokoyama and Kenji Odamura. 2015. *Tensile stress-strain properties of paper and paperboard and their constitutive equations.* doi:10.13140/RG.2.1.1945.3924

[98] Yang Zhang and Chris Harrison. 2018. Pulp Nonfiction: Low-Cost Touch Tracking for Paper. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–11. doi:10.1145/3173574.3173691

[99] Zhi Zhang, Hao Zhu, Wenjie Zhang, Zhaoyang Zhang, Jinzhong Lu, Kun Xu, Yang Liu, and Viboon Saetang. 2023. A review of laser-induced graphene: From experimental and theoretical fabrication processes to emerging applications. *Carbon* 214 (Oct. 2023), 118356. doi:10.1016/j.carbon.2023.118356

[100] Clement Zheng, HyunJoo Oh, Laura Devendorf, and Ellen Yi-Luen Do. 2019. Sensing Kirigami. In *Proceedings of the 2019 on Designing Interactive Systems Conference (DIS '19)*. Association for Computing Machinery, New York, NY, USA, 921–934. doi:10.1145/3322276.3323689