

# EcoThreads: Prototyping Biodegradable E-textiles Through Thread-based Fabrication

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**Figure 1: We present EcoThreads, a sustainable e-textile prototyping approach for fabricating biodegradable functional threads. We demonstrated five sample applications: (a) Braided capacitive touch sensing hair accessory. (b) Woven pH-sensing underwear. (c) Woven heat sensing bento box band. (d) Knitted cooling gel for fever. (e) Woven sweat rate sensing patch.**

## ABSTRACT

We present EcoThreads, a sustainable e-textile prototyping approach for fabricating biodegradable functional threads. We synthesized two thread-based fabrication methods, wet spinning and thread coating, to fabricate functional threads from biomaterials or modify natural fiber to achieve conductive or interactive functionality. We built a wet spinning tool from a modified DIY syringe pump to spin biodegradable conductive threads. The conductive and interactive threads can be further integrated into textiles through weaving, knitting, embroidery, and braiding. We conducted a workshop study inviting e-textile practitioners to use the materials to fabricate e-textile swatches for transient use cases. The EcoThreads approach presents a path for individual creators to incorporate biodegradable material choices toward sustainable e-textile practices.

## CCS CONCEPTS

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

## KEYWORDS

e-textiles, sustainability, bio-design

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## 1 INTRODUCTION

E-textiles are projected to reach a market size of US \$1.3 Billion by 2032 [29]. As an emerging field, there have been mass prototyping efforts to explore the potential of e-textile products. In the field of Human-Computer Interaction (HCI), this often involves extensive swatch-making by individual creators or workshops in STEM learning, maker spaces, or research labs. Regardless of the final application, the material choice is similar: conductive threads spun at industrial mills. These fiber materials are developed for excellent electrical and mechanical performance and are often blended with synthetic materials to achieve such properties. However, as a result, these rapidly prototyped e-textile projects become a mixture of textile and electronic waste that presents challenges to recycling. The permanency of the material can become an added environmental burden.

In the HCI field, researchers have started looking into the potential solutions to tackle the challenge of environmental impact originating from rapid prototyping. *Unmaking* [85] and *unfabricating* [93] presents an approach using computational design to support the disassembly of mixed-material prototypes. Although this approach can effectively yield reusable materials, it also requires a thorough and careful pre-planned design process to strategically integrate the material at a certain fabrication stage. This can potentially eliminate the spontaneous creation during the making and exploration of e-textiles. On the other hand, biodegradable electronics have been explored [23, 84, 86] to apply biodegradable

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electronic materials to rapid prototyping. These explorations address the unique short lifespan of transient electronics, resulting in biodegradable electronic devices. Among these explorations, biodegradable materials can decay under biological actions (often facilitated by microorganisms), some of which can decompose in the backyard without the need for specialized conditions [84]. However, this approach has been mainly explored in rigid materials and their corresponding digital fabrication methods, and less attention has been paid to e-textiles and textile-based crafts.

Considering the wide range of application scenarios in e-textile fabrication, in this work, we aim to tackle the scenarios of transient e-textile practices often adopted in rapid prototyping through a sustainable life cycle approach. The transient e-textile practices address use cases where e-textile samples are for short-term usage and can be disposable, from STEM education workshops to rapid swatch sampling. In these scenarios, biodegradability may take priority over robustness due to the transient nature of usage. Inspired by textile crafters who spin and dye their own fiber to achieve the variance of color or yarn weight, we propose an accessible and customizable approach of creating biodegradable threads with tunable conductive and interactive properties. The conductive threads can be further integrated into textiles to function as sensors (such as capacitive and resistive sensing) and actuators (such as heating and deformation). The interactive threads, such as thermochromic and colorimetric threads, can be used as temperature and chemical sensors, as well as color-changing displays. These properties of these threads are tunable based on the user's prototyping needs while remaining biodegradable.

We present EcoThreads, a sustainable e-textile prototyping approach that considers the entire life cycle of the e-textile product. We synthesized two thread-based fabrication methods, wet spinning and thread coating, to fabricate functional threads from biomass or to modify natural fiber to achieve functionality. We built a wet spinning tool from a modified DIY syringe pump to spin biodegradable conductive or interactive threads in the desired thickness. We identified a low-volume thread coating approach to coat conductive dispersion onto natural fibers. The conductive and interactive threads can be further integrated into textiles through weaving, knitting, and embroidery. In this paper, our main contributions are:

- (1) We introduce a material exploration on biodegradable conductive and interactive threads using thread-based fabrication and modification methods: wet-spinning and coating. It aims to serve a role in a sustainable e-textile prototyping life cycle for creating biodegradable transient e-textiles.
- (2) We demonstrate how biodegradable conductive or interactive threads can be integrated into e-textile circuits through embroidery, knitting, weaving, and braiding for transient daily applications.
- (3) Through a workshop study with e-textile practitioners, we examine the compatibility of integrating EcoThreads into their e-textile prototyping processes.

## 2 RELATED WORK

### 2.1 E-Textiles in HCI

E-textiles, also known as Smart Textiles, integrate conductive, interactive, or functional soft materials into textiles to enable sensing

[32, 42], actuating [51] and communication [42] capabilities. E-textile practices often utilize common textile crafting techniques, such as weaving [25, 42, 55, 80, 87], knitting [51], embroidery [37, 77], printing [52, 79], and braiding [27, 70] to achieve seamless integration. This variety of compatible crafting techniques and accessible fabrication approaches enable e-textile practices to be widely used for STEM education and rapid prototyping [13, 47, 97]. Projects such as Lilypad [14–16] have provided accessible hardware tools to lower the barrier for beginners, and programs such as E-Textile Summer Camp explored the swatchbook-based community sharing approaches in e-textile education [39]. As a vibrant community, Do it yourself (DIY) tools [75, 76] and rapid prototyping methods [40] are widely explored by individual creators.

Among these e-textile practices, transiency is a common theme: from educational workshops to rapid swatch prototypes, e-textiles are often adopted by individual creators for rudimentary circuitry functions: lighting up LEDs, or crafting resistive soft switches. However, a majority of e-textile techniques originated from electronic prototyping or textile fabrication did not address the transiency in material choices. For instance, metallic spun fiber intertwined with fiber materials [78] is the prevalent choice for crafting low-resistance conductive threads, and low-temperature soldering [9] is the dominant method for affixing hardware components to these soft traces. These materials are often sourced from manufacturers, while the environmental impact is often unstated. Practices to address environmental concerns in the prototyping process often come as an afterthought. At the commercial scale, e-textiles integrate practices in the hardware industry with the fashion industry. Example such as Project Jacquard [78] have managed to mass produce e-textile consumer products<sup>1</sup>. These advancements in the e-textile field can result in a more considerable environmental impact.

Through EcoThreads, we aim to address this lack of attention to the transiency aspect of these e-textile practices, providing a biodegradable, material-based, and sustainable approach to e-textile prototyping.

### 2.2 Sustainable Wearable Prototyping

Sustainable prototyping has become a major practice shift among HCI researchers. Each sector has employed various strategies to address this concern, such as repurposing and recycling products or components. Recently, processes such as sustainable interaction design [10], reuse [43], repair [63], and "unmaking" [85] have received attention as sustainable practices in the design process. These methodologies encourage a shift from the traditional emphasis on durability in favor of more sustainable and environmentally conscious practices. More specifically, the "unmaking" procedures, including "uncrafting" [68], "functional destruction" [23], and "designing to decay" [26] takes the end-of-life condition of the products into design consideration. Researchers have explored sustainable life cycle prototyping thinking to reconsider the entire life cycle of physical prototyping outcomes holistically [23, 59].

<sup>1</sup><https://atap.google.com/jacquard/>

In the fashion and textile field, to address sustainability challenges, practices such as recycling, upcycling, reusing, and renewing have been adapted to consumer fashion lifecycles [38]. At an individual level, zero-waste design [64] and circular design [67] practices have been adopted by designers and researchers. Researchers have also explored bacteria dyeing [8] and staining [6] textiles to reduce chemical waste. However, e-textiles or smart textiles integrating both hardware and soft textile materials, present sustainability challenges faced by both fields [28, 54]. Due to the fact that e-textile products are commonly a mixture of fiber, electronics, and hardware materials, recycling and reusing have been a challenge.

Recently, HCI exploration in biodegradable functional soft materials has examined soft interfaces [4, 5, 7, 17, 45, 53, 58, 74, 84, 86] and rigid enclosures for wearable purposes [65, 81, 88]. However, these material explorations focus on digital fabrication compatibility to achieve rigid or sheet-form wearable interfaces yet lack the capability to be adopted in a textile form factor. More recent research has been exploring biodegradable fiber materials with light refraction or dissolvable properties [36, 57]. Meanwhile, e-textile researchers have looked into the nuanced nature of e-textile practice and have explored various fabrication approaches to address these challenges, such as designing e-textiles for unfabricating [48, 93] and mending [46]. However, these explorations still rely on using off-the-shelf conductive fiber materials to achieve circuitry functions, with limited biodegradable material options.

In EcoThreads, we explore material-based prototyping by fabricating biodegradable conductive and interactive threads for e-textile prototyping. We see our work situated in the big cycle of sustainable design practice and it is not a stand-alone nor exclusive approach. Biodegradable material choice can be coherently integrated into any existing e-textile practice yet ease the design challenge of required careful planning and strategic designing for approaches such as unfabricating [93] to be successful.

### 2.3 Thread-Based Fabrication and Modification

Aesthetic customization-oriented thread-based textile crafting has been widely adopted by craftspeople across different cultures. For example, it has been a common practice for weavers and knitters to use hand-held spindles or spinning wheels to spin their own yarn to achieve desired color variance and yarn weight using wool roving (wool) or flax fiber (linen). Single-strand spun yarn can be further twisted or braided to achieve improved durability. Beyond fabrication, various modification treatments are used to attain colors and patterns, such as tie-dyeing and resist dyeing. In weaving practice, warp painting and warp dyeing have been used to sectionally color warp yarn to create color blending with weft yarn. We adopt these common thread-based textile crafts into our biodegradable interactive thread fabrication approach.

In the HCI community, fiber-based and thread-based research has achieved sensing [41, 71, 73, 101] and actuating [33, 50] functionalities. The thread-based form factor is extensible. They can be seamlessly integrated into different textile structures compatible with common textile crafts such as weaving, knitting and embroidery.

Recent fiber science research has looked into fabricating biodegradable conductive and interactive threads using corresponding materials through various fiber formation and modification techniques, such as wet spinning and coating. Wet spinning is the process of dissolving polymers in a solvent and then extruding the filament into a nonsolvent to form the fiber [72, 91]. Compared to other spinning techniques, such as melt spinning or electrospinning, wet spinning requires minimum equipment (can be as simple as hand-holding a syringe) and is suitable for producing fiber in low quantities. Among options of wet spinning-compatible biomass, Alginate (biopolymer obtained from brown seaweed) [98] and Carboxymethyl Cellulose (CMC, cellulose biopolymer obtained from wood pulp) [44] can be easily wet spun using water as the solvent and food-safe nonsolvent materials: calcium chloride (nonsolvent for alginate) and aluminum sulfate (nonsolvent for CMC). Especially in DIY community, wet spinning alginate yarn recipes have been explored [11, 19, 21, 24, 49, 61]. This choice of materials enables an accessible fabrication approach and is also compatible with scalable production using DIY syringe pumps [2, 12, 30, 31, 56, 92].

To achieve conductivity, several conductive particles and polymers have received more attention, including silver nanowire (AgNWs) [3, 60, 62, 89], carbon nanotubes (CNTs) [83, 100], PEDOT:PSS [1], etc. Among these materials, AgNWs can be easily decomposed due to the low quantities and small nanowire dimensions and have excellent electrical performance. On the other hand, CNT is a completely carbon-based renewable material with outstanding thermal performance and biocompatibility that have already been used in wearable applications.

However, these approaches often take place in material science research lab settings. The technical barrier inevitably sets the challenge for individual creators to integrate these materials into their practice. In EcoThreads, We present accessible approaches for HCI lab settings, which can be done with common, low-cost kitchen appliances. In this way, researchers and designers can fabricate their own biodegradable conductive and interactive yarns as needed.

## 3 SUSTAINABLE E-TEXTILE LIFE CYCLE

### 3.1 Biodegradable E-Textile Design Space

We synthesized the biodegradable interactive textile design space (Figure 2) from our extensive prototyping interactions and literature review of available materials and accessible fabrication approaches [7, 17, 53, 58, 81, 84, 86, 88]. We identified biodegradable conductive and interactive materials suitable for thread-like form factors, and determined their compatible binder materials to maximize strength and functionality. Within this design space, our emphasis lies on biodegradable threads with conductive and interactive properties, possessing the potential for sustainable seamless integration into textiles.

**Fabrication Methods:** In EcoThreads, we identified two accessible thread-based fabrication methods: wet spinning and thread coating. The wet spinning process involves dissolving polymers in a solvent and extruding the filament into a cross-linking agent to form the fiber. We adapted an open-source syringe pump and altered it to be compatible with wet spinning. The wet-spun monofilaments are single-stranded and can be spun at the desired thread weight and length. The monofilaments can be further twisted or plied to form























Fabrication Method	Conductive Material	Interactive Material	Binder Material	Textile Integration	Application	
					Sensing	Actuating
 Wet Spinning	 Carbon Nanotubes	 Colorimetric Assay	 Alginate (Seaweed)	 Embroidery	 Capacitive Sensing	 Heating
	 Silver Nanowires	 Thermochromic Pigments	 Carboxymethyl Cellulose CMC (Wood Pulp)	 Weaving	 Resistive Sensing	 Display
 Coating	 Activated Charcoal		 Chitosan (Shrimp Shell)	 Knitting	 Conductivity Sensing	 Deformation
	 PEDOT:PSS			 Braiding & Plying	 pH Sensing	

Figure 2: EcoThreads Design Space.

multi-stranded threads. In this paper, we refer to the monofilaments and their processed resultants as threads. Thread coating, on the other hand, leverages an existing natural fiber yarn as a base. Both of the two fabrication methods can result in conductive or interactive threads for e-textile applications.

**Conductive Materials:** We summarized sustainable conductive materials in three categories: metal-based nanowires, conductive polymer-based conductors and carbon-based conductors [28]. Metal-based nanowires present high conductivity. Among these, silver nanowires (AgNWs) have been widely explored as dissolvable conductive material for sustainable applications [23, 84]. Conductive polymer-based conductors have excellent flexibility and biodegradability, such as poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS). Carbon-based materials such as carbon nanotubes (CNT) and activated charcoal are renewable materials yet present higher resistance than the aforementioned options. Recent research has been studying the biodegradability and degradable conditions for these conductive particles and polymers [90, 94]. This variance in biodegradability and their trade-off for electrical performance are critical design considerations. We see these conductive materials' variance in biodegradability and conductivity as a tunable design element in the EcoThreads design space.

**Interactive Materials:** To extend the sensing and actuation functions, we synthesized color-changing materials that function as sensors and displays at the same time. The interactive threads, such as thermochromic and colorimetric threads, do not require circuitry yet offer interactions while being biodegradable. Colorimetric assays sourced from food such as red cabbage and blueberry provide pH-sensing functions [82], and thermochromic pigments (which can be biodegradable [84]) change color in reaction to temperature change. In EcoThreads, we synthesized the formulation of integrating colorimetric assays and thermochromic pigments into the alginate mixture for wet spinning.

**Binder Materials:** To turn conductive and interactive materials into yarn form for textile integration, binder materials are required to formulate the fiber (as the spinning solution) or modify the yarns (as coating binder). We examined three materials derived from biomass and identified their corresponding fabrication methods. Alginates are extracted from brown seaweed and can be wet spun into biodegradable threads. Carboxymethyl cellulose (CMC) is cellulose-based material sourced from wood pulp, while chitosan is sourced from shrimp shells. Both CMC and chitosan can be used as coating binders or added to the alginate spinning solution to tune the durability of the wet-spun yarn. To achieve e-textile functions, the aforementioned conductive and interactive materials can be added to the spinning solution to wet-spin conductive or interactive fiber or added to the coating binder for coating conductive threads.

**Textile Integration:** The wet spun and coated threads can be integrated into textiles through embroidery, weaving, knitting, braiding, and plying. As wet spun alginate thread has lower tensile strength, it is compatible with hand knitting, while coated threads are compatible with both hand and manual machine knitting.

**Applications:** Based on the selected combinations of conductive, interactive, and binder materials, the resulting variance in thread resistance can be tailored for diverse applications. Threads with conductive or resistive properties can serve in resistive, capacitive, and conductivity sensing, as well as in heating. Threads embedded with colorimetric pH indicators cater to pH-sensing applications. Threads infused with thermochromic pigments can change color in response to temperature variations, making them suitable for temperature-sensitive visual indicators. Moreover, the wet-spun alginate thread, which exhibits shrinking when dried and swelling when wet, offers potential in deformation-based applications.



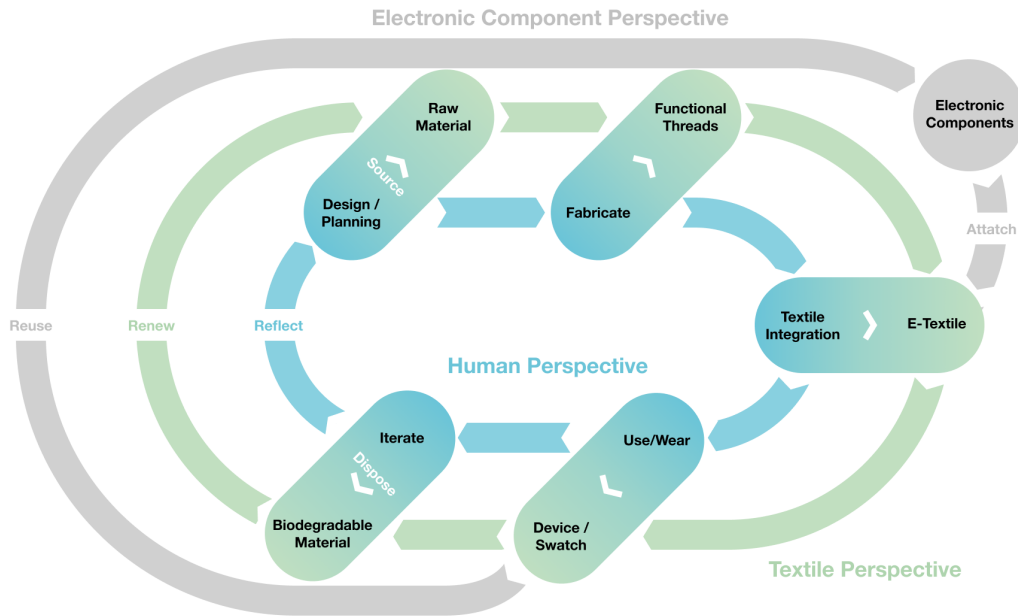


Figure 3: EcoThreads Sustainable E-Textile Life Cycle Prototyping Workflow.

### 3.2 EcoThreads Sustainable Life Cycle Prototyping Workflow

Here, we present a sustainable e-textile life cycle prototyping workflow for individual creators using EcoThreads (Figure 3). Through literature review, expert feedback and prototyping with a variety of sustainable materials, we summarized this workflow to address how EcoThreads can be used in a circular design process [23, 28, 58, 59, 88, 96]. We illustrate how EcoThreads can be used to address the environmental impact in a complete e-textile process. We highlighted three cycles that intertwine with each other: the human perspective, the textile materials perspective, and the electronic component perspective. Although the hardware aspect is not the main focus of this work, we synthesized the workflow that includes the integration of electronic components. We understand that biodegradability is not a one-off solution towards sustainability. However, this offers opportunities that prior work cannot address, especially when reuse/recycle is not an option with the particular material choice or function to achieve.

**Design/Planning:** In the design and planning phase of the project, designers/researchers can responsibly source suitable materials as part of the design process. Material choice will no longer be an afterthought after the design decision. Instead, material choice and material property manipulation become part of the design. For e-textile purposes, the raw material includes natural fiber, biodegradable conductive coating, and biomass binder materials. We summarized recent studies of the biodegradability of the materials in our recipe, including their degrading time and conditions in Table 1. For materials such as CNT that require specific decomposition conditions, further design processes can be incorporated to post-process the materials after usage. By adjusting the proportion of materials, the fine-tuned material properties can be tailored for different designs.

Table 1: Material Biodegrade Time and Conditions

Material	Biodegrade Time and Conditions
Alginate	14 days in compost [66]
CMC	7-10 days in soil [95]
Chitosan	14 days in soil [69]
AgNW	<1 day in water [99]
CNT	<10 days by microorganisms [94]

**Fabricate:** The fabrication step includes directly spinning functional yarns and modifying non-functional materials like cotton yarns. We identified accessible tools such as household kitchen appliances and DIY syringe pumps for fabrication. This step can occur in home kitchens, textile studios, or maker spaces.

**Textile Integration:** In this life cycle, we focus on the creation of e-textiles by individual creators rather than mass manufacturing, as the mass production of e-textiles remains a challenge in many different ways [102]. EcoThreads materials are compatible with common e-textile crafts, which can open up new opportunities for material-derived crafts.

**Use/Wear:** The crafted devices or swatches will be used or worn in this step. As the materials are biodegradable, the use cases can be transient: disposable designs can be integrated in this step.

**Iterate:** We see the sustainable e-textile life cycle as an iterative process: the end of product life can inform new designs. In this step, designers and researchers reflect on the learning from the design and materials, and the knowledge gained through this process can be applied for new iterations. Materials, on the other side, get reused, recycled, or renewed thanks to their biodegradability.

## 4 FABRICATING ECOTHEADS

Here, we detail our two fabrication methods for generating EcoThreads: (1) wet spinning (Figure 4) and (2) thread coating (Figure 6). We also present a characterization of the mechanical and electrical behavior of the generated threads.

### 4.1 Wet Spinning Biodegradable Interactive Threads

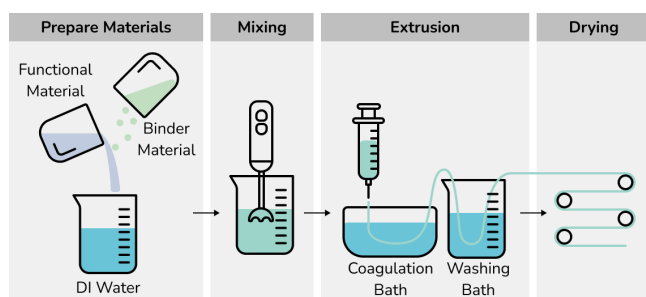


Figure 4: Wet Spinning Process.

**DIY Wet Spinning Tools:** Wet spinning is the process of dissolving polymers in a solvent and then extruding the filament into a cross-linking agent to form the fiber [72]. Compared to other fiber spinning techniques, such as melt spinning or electrospinning, wet spinning requires minimum equipment as simple as hand-holding a syringe to extrude the fiber. However, from our iterative prototyping process, fiber extruded from hand-held syringes cannot achieve an even diameter due to the inconsistent extruding speed. To tackle this, we modified an open-source syringe pump [31] for wet spinning (Figure 5).

In this setup, we leveled up the syringe pump and extended the dispensing needle through silicone tubing (McMaster Carr 51135K617) with tube coupling sockets and plugs. This way, the dispensing needle functions as the spinneret and can be submerged in the coagulation bath. We placed a stir plate underneath the coagulation bath to avoid accumulated fiber around the dispensing needle. The stirring speed also provides an initial drawing for fiber formation. As our wet spinning mixture presents higher viscosity, we used a high torque stepper motor NEMA 17 Bipolar 59Ncm with high current motor driver A4988 at 2A current limit to prevent jamming.

**Material Formulation** From our iterative sampling of wet spinning biodegradable polymers, including Alginate, CMC, and Chitosan, we identified alginate as the most desirable binder material for wet spinning biodegradable threads due to its high compatibility with functional materials as well as its low failure rate in wet spinning. The formulation is adopted from alginate string recipes [11, 24] with alternation to maximize syringe pump extrudability and tensile strength. In this recipe, sodium alginate (Cape Crystal Brands), Glycerin (Ward’s Science), Sunflower Seed Oil (365 by Whole Foods Market), and deionized (DI) water are all food-safe and can be processed in a kitchen. Based on this formulation, conductive, resistive, and interactive materials can be added with corresponding formula adjustments to achieve desired thread properties.

For conductive threads, we explored mixing AgNWs dispersion (ACS Materials NWAG04E1, 40 nm average diameter) CNT dispersion (Tuball Batt H2O 0.8%), and activated charcoal powder (Nature’s Way) into the alginate mixture. Although food-grade activated charcoal is food-safe, the extruded thread presents a coarse surface texture and flakes charcoal powder during usage. AgNWs require higher concentration to achieve conductivity, which is not a cost-efficient choice compared to CNT dispersion. Unlike multi-wall carbon nanotubes (MWCNTs), which have evidence to be carcinogenic in specific respirable form, recent studies do not provide evidence of carcinogenicity for single-walled carbon nanotubes (SWCNTs) [34]. The 0.8%(w/w) SWCNTs dispersed in water with 0.8%(w/w) CMC as a dispersing agent mixed in alginate thread presents excellent mechanical properties and consistent conductivity. In Table 2, we summarized the material formulations with adjustable ranges to tailor specific project requirements. These recipes are from our experiments with changes in sodium alginate, sunflower seed oil, glycerin, bath time, and extrusion diameters to achieve syringe pump extrudability and higher tensile strength. The desired viscosity is based on the maximum torque afforded by the syringe pump. With this recipe, a 2-minute coagulation bath is sufficient for alginate to cross-link.

For interactive threads, compatible color-changing assays and pigments can be added to the base alginate formulation. Because colorimetric assays are diluted in water, the corresponding weight of DI water needs to be deducted from the base formulation to maintain consistent viscosity. pH sensing colorimetric assays such as Anthocyanins can be extracted from food such as red cabbage and blueberry<sup>2</sup>, while litmus can be harvested from general purpose pH test strips [101]. As wet spun alginate threads will shrink after drying, the color density of the mixture needs to be adjusted accordingly.

Table 2: Wet Spinning Sample Formulation.

Basic Alginate Thread				
Sodium Alginate	Glycerin	Sunflower Seed Oil	DI Water	Food Coloring
4g	5g	2.5g	150g	0~6 drops
CNT Resistive Thread				
Sodium Alginate	Glycerin	Sunflower Seed Oil	DI Water	CNT Dispersion
4g	9g	2.5g	100g	120g
pH Sensing Thread				
Sodium Alginate	Glycerin	Sunflower Seed Oil	DI Water	Colorimetric Assay
4g	5g	2.5g	125g	25g

**Material Preparation:** We first mixed 4g sodium alginate powder in 2.5g sunflower seed oil and blended until combined before adding 150g DI water in sections. 5g glycerin was added last for best results. Functional ingredients including CNT dispersion, pH sensing solution, thermochromic pigment, etc., were added directly to the mixture as the last step. The solution needs to be thoroughly

<sup>2</sup><https://www.wikihow.com/Make-Homemade-pH-Paper-Test-Strips>

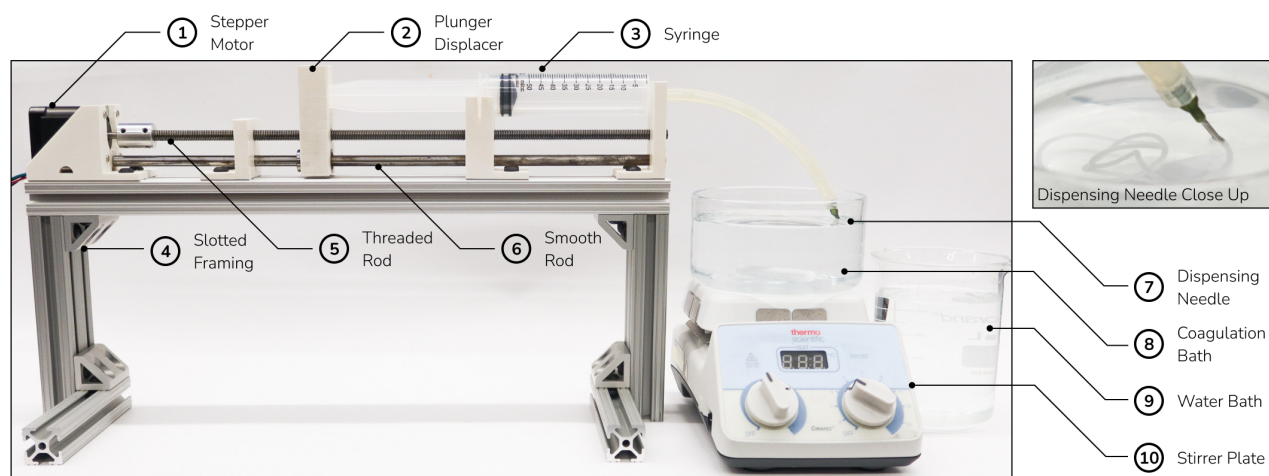


Figure 5: Wet Spinning Setup.

mixed using either a lab overhead stirrer or a kitchen immersion blender. The solution was refrigerated overnight or vacuumed to remove air bubbles, and may be refrigerated and stored for up to one week. The coagulation bath is prepared by creating a 10% w/w solution of calcium chloride in DI water.

**Wet Spinning:** The volume of the syringe and the size of the needle dispenser tip define the diameter and maximum continuous length of the wet spun thread. We used 50 mL syringes with needle dispensers ranging from 14 gauge (ID: 0.061") to 16 gauge (ID: 0.047"). To wet spin the mixture, we slowly poured the mixture into the syringe and used a stainless steel laboratory spatula to remove large bubbles. The solution may be stored in a syringe and refrigerated to remove bubbles before wet spinning. The syringe pump must be fully in the open position so the full syringe can fit in between the displacer and the front of the syringe pump. After the syringe was placed on the syringe pump, the stepper motor was switched on and the speed was adjusted to achieve a consistent solution flow. After the solution was extruded, wait 2 minutes before thoroughly removing the thread and washing it in the distilled water bath. After removing any excess water with a paper towel, the threads were gently wrapped between the pegs of a warping board for drying. The string was wrapped multiple times and then strung between opposing pegs to straighten the thread and allow it to dry on all sides.

## 4.2 Biodegradable Coatings for Functional Threads

**Coating Preparation:** We identified two dispersions that can function as biodegradable conductive coating material to turn natural fiber yarn into functional materials: AgNWs (ACS Materials NWAG04E1, 40 nm average diameter) and CNT (Tuball Batt H2O 0.8%). To increase the binding performance of the coating, we tested options of biodegradable binders, among which CMC presents the best mechanical performance that prevents the coating from flaking.

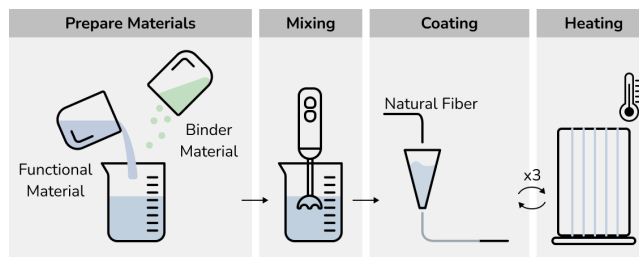


Figure 6: Coating Process.

For AgNWs, mixing the dispersion with 0.4% w/w CMC in a 4:1 ratio for optimal conductivity while decreasing the ratio to 2:1 results in lower yet consistent resistance. The 0.4% w/w CMC is prepared by magnetic stirring 0.4g CMC powder (La Tienda Confectionery Essentials) in 100g DI water for 2 hours at 60 degrees Celsius.

**Thread Preparation:** The fibrous structure of natural fibers presents an advantage in absorbing coating materials in the coating process. Among natural fibers, cotton fiber has a high absorption rate compared to silk. In contrast to sewing threads that are often waxed, weaving threads tend to have minimum treatment, which requires a minimum cleaning process before coating. Hence, we chose mercerized perle cotton weaving thread 10/2 (4,200 yd/lb, two strands) and 20/2 (8,400 yd/lb, two strands) for the coating application. For cleaning purposes, we immersed the yarn in isopropanol alcohol for a period of 5 minutes and then air-dried.

**Coating Application** Cleaned cotton threads were coated by using a pipette tip and filling it with the 0.4% AgNW mixture (about 1 mL). A needle threader was used to thread the cotton thread through the end of the pipette tip, right side up. The cotton thread was slowly pulled through, careful to coat the thread in the mixture completely. Then, the coated thread was set in the oven for 5 minutes at 60 degrees Celsius. This process was repeated twice more for a total of three coatings. The same coating process was repeated with the CNT dispersion for CNT-coated threads.

### 4.3 Understanding EcoThreads: Characterization

To further understand EcoThreads, we characterized the material in terms of electrical and mechanical behavior. This characterization can guide users in customizing EcoThreads with desired properties.

**Resistance Characterization: Coating Layers.** For coated conductive threads, we prepared 20/2 cotton in 1 yard for each test. We measured the resistance of 4" from three segments in a single thread after each coating layer. The average resistance in ohms/inch of each layer indicated that 2 layers of coating can provide sufficient conductivity while 3 layers present optimized resistance as shown in Table 3.

**Binder Proportion.** To understand how binder affects the resistance, we compared both AgNWs and CNT coating with different binder ratios. The ratio is calculated by binder powder to conductor dispersion ratio w/w. Additional glycerin, sunflower seed oil and DI water are added based on the aforementioned recipe. For AgNWs coating, we compared the resistance of different CMC:AgNWs ratios as shown in Table 3. For the lowest resistance, 0.1% CMC ratio is optimal. In practice, we premixed 0.4% w/w CMC mixture in DI water, then added it to the AgNWs dispersion at 25% w/w and achieved an easy-to-coat cocktail. For wet spun CNT alginate threads, we compared the resistance of different Alginate:CNT ratios as shown in Table 4. The 3.3% alginate ratio presents the lowest resistance but maintains extrudability. This recipe is presented in detail in Table 2.

**Table 3: Resistance characterization: cotton-coated conductive threads' resistance measured after each layer of coating.**

Cotton-Coated Conductive Threads					
Material Formulation			Resistance ( $\Omega/in$ )		
Conductor	Binder	Ratio	1st Layer	2nd Layer	3rd Layer
AgNWs	CMC	0.1%	2.10	0.96	0.85
AgNWs	CMC	0.13%	9.81	5.90	4.03
AgNWs	CMC	0.2%	39.17	13.51	9.53
CNT	CMC	0.8%	75.83	36.25	20.83

**Table 4: Resistance characterization: wet-spun conductive threads in different CNT alginate ratios.**

Wet Spun Conductive Threads				
Material Formulation			Resistance ( $k\Omega/in$ )	
Conductor	Binder	Ratio		
CNT	Alginate	3.3%	1.38	
CNT	Alginate	4.0%	3.57	
CNT	Alginate	5%	6.69	

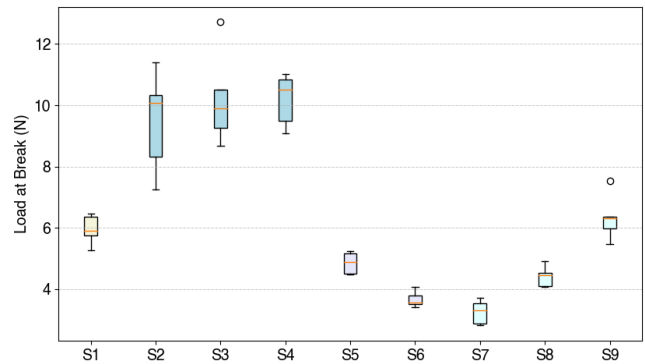
**Tensile Strength Characterization:** To characterize the tensile strength of wet spun threads, we used the Instron Universal Testing System (Instron 5566) to measure the breaking strength and elongation following the ASTM D5034 procedure. The Instron was set to a gauge length of 5 cm and clamps with a small surface area were used for best results as shown in Figure 7 with their corresponding specifications in Figure 5. The load is balanced before placing the

sample in the clamps and testing the sample. The breakpoint is selected after the stress vs. strain graph is obtained. We prepared N=5 samples of each wet spun recipe and repeated the abovementioned procedure.

**CMC Alginate Ratio.** CMC as an adhesive binder material, when added to the alginate mixture, improves the durability of the thread. However, an exceeded amount of CMC may result in brittle filaments. We compared different CMC alginate ratio and identified that an additional 0.4% CMC enhances the mechanical performance significantly yet increases the stiffness of the threads.

**Needle Dispenser Diameters.** We compared the tensile strength of alginate threads extruded with different needle dispenser diameters. As shown in the figure, a smaller dispenser size results in easier breaks.

**CNT Alginate Ratio.** As CNT was added to alginate to achieve conductivity, it also reduced the amount of alginate in the mixture. We compared different CNT alginate ratios to understand the trade-off between electrical and mechanical performance. Although CNT increases the conductivity of the threads as shown in Table 4, it eliminates the mechanical strength of the threads as shown in Fig 5.



**Figure 7: Load at Break (N) of Alginiate Thread Samples.**

**Table 5: Alginiate Thread Sample Specifications**

Sample ID	Formulation	Dispenser Size
S1	Alginate	14G
S2	Alginate + 1% CMC	14G
S3	Alginate + 0.7% CMC	14G
S4	Alginate + 0.4% CMC	14G
S5	Alginate + 1% CMC	16G
S6	Alginate + 0.7% CMC	16G
S7	CNT + 3.3% Alginate	14G
S8	CNT + 4% Alginate	14G
S9	CNT + 5% Alginate	14G

**Design Recommendations:** Based on the characterization, we concluded our recommended recipe as shown in Table 2. Fine-tuning the composition of ingredients in the recipe can further tune the material properties as needed. Increasing the ratio of conductive materials enhances the conductivity, yet decreases the tensile strength of the material. For textile integration that requires



**Table 6: Participants' IDs, profession, expertise in e-textiles.**

ID	Profession	E-Textile Practice	Related E-Textile Projects
P1	Interdisciplinary designer, artist, educator	12 years	Sewing & quilting soft circuitry
P2	Interaction designer, wearable consultant	4 years	Weaving with optical fiber
P3	Textile artist, educator	5 years	Weaving fluidic display
P4	Creative technologist, artist	10 years	E-textile educational toolkits
P5	Textile artist, textile engineer	3 years	Biomedical textile engineering

high tension, such as knitting and braiding, it is recommended to increase the ratio of alginate in CNT to improve tensile strength.

The modified syringe pump for wet spinning (Figure 5) provides an accessible tool to fabricate EcoThreads with consistent tensile strength and resistance properties. By adjusting the dispenser size, the tensile strength of the outcome changes as shown in Table 5 and Figure 7. The choice of wet spinner settings further affords design opportunities to adjust the wet spun monofilament.

The characterization of EcoThreads mainly focuses on the single-stranded coated or wet spun threads, yet the wide range of textile integration, as shown in the EcoThreads Design Space (Figure 2), enables more opportunities to combine thread properties with textile fabrication techniques to expand their functional behavior. We further explored this affordance in the workshop study and sample applications.

## 5 WORKSHOP STUDY: UNDERSTANDING PRACTITIONER USAGE OF ECOTHEADS

To understand how EcoThreads could be adapted to existing e-textile practices, we conducted a workshop study with five practitioners with e-textile experience ranging from 3 to 12 years. Participants were shipped the needed EcoThreads supplies and conducted the study in their homes or studios. We chose to do so (instead of having participants come to our lab) to observe how people might integrate EcoThreads materials into their existing prototyping processes, using tools and compatible supplies they were already familiar with.

### Participants:

We invited participants with various expertise in e-textiles in the broader field of art, design, and engineering with the following criteria: (1) Participants are familiar with e-textile techniques, including soft circuitry and/or functional textiles; (2) Participants have their tools and supplies to complete an e-textile swatch in their own choice of space, including their home or studio space. We conducted the study with five participants (all female) with an age range of 28-35 as shown in Table 6. We provided a \$ 40 USD gift card as gratuity.

### Workshop Procedure:

- (1) Session 1: Briefing and brainstorming session (1 hour on Zoom). We introduced the motivation of the EcoThreads approach and provided an overview of the EcoThreads Sustainable Life Cycle Prototyping Workflow (Figure 3). Then, we presented the choices of biodegradable conductive/resistive/interactive threads and compatible textile integration options afforded by the EcoThreads design space (Figure 2). After that, we asked participants to brainstorm a project idea situated in the prompt

of a *transient use case* and confirm with us the EcoThreads materials needed. After this session, we tailored the fabrication of the EcoThreads materials as requested by participants and shipped the materials to them.

- (2) Session 2: Sample creation session (2.5 hours on Zoom). Session 2 took place after participants received their supplies. Participants used their own tools and additional materials to craft a sample of their desired design in their choice of location. During this session, researchers are available on Zoom to introduce the provided materials and offer material-specific technical support. Participants were asked to take photos of the process and outcome for documentation purposes, and the crafted artifacts were shipped to the researchers after the creation session.
- (3) Session 3: Post-study semi-structured interview (30 min on Zoom). We conducted a post-study semi-structured interview. The questions we asked included their overall experience using the EcoThreads, the challenges and differences they faced during the crafting process, their feedback on the material property, and their understanding of using biodegradable materials for e-textile purposes.

### Data Collection & Analysis:

During each of the workshop procedures, we collected data in various formats: (1) pre-study survey collecting participants' prior relevant e-textile and sustainable design experience in Session 1; (2) photos and videos of fabrication processes during Session 2; (3) post-study survey collecting participant's rating for the EcoThreads material property and crafting experience in Session 3; (4) audio recording of the semi-structured interview, which was later on transcribed; (5) the artifacts participants created were collected for functional testing and documentation.

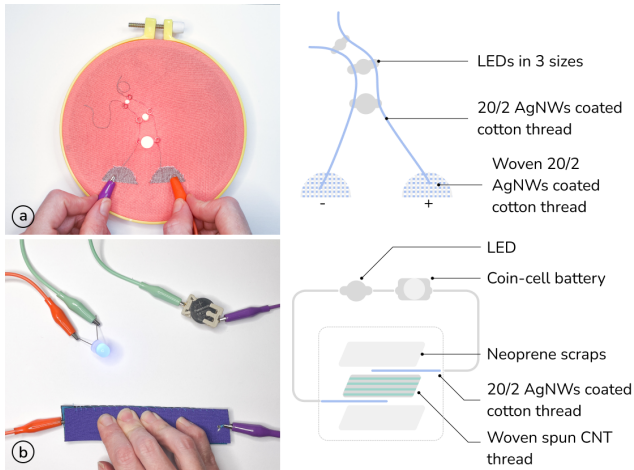
Based on the participants' background and experience collected from the pre-study and post-study survey, in the semi-structured interview, participants elaborated on their experience using the materials in their design process and their comprehension of biodegradable e-textiles. The transcription of the interview was analyzed using the grounded theory approach [20]. The transcripts were coded by the first and last authors, who then discussed themes based on the coding. Finally, researchers collected artifacts produced during the workshop to examine their functionality.

### P1's project: Biodegradable e-textile swatches for teaching.

P1 has years of experience teaching e-textile-related courses to graduate students in a design and technology program and has developed her own set of swatches for her teaching practice. In response to the prompt, she is interested in recreating the same sample swatches from her teaching sample book using the EcoThreads conductive threads, as in her classes, students would fabricate the



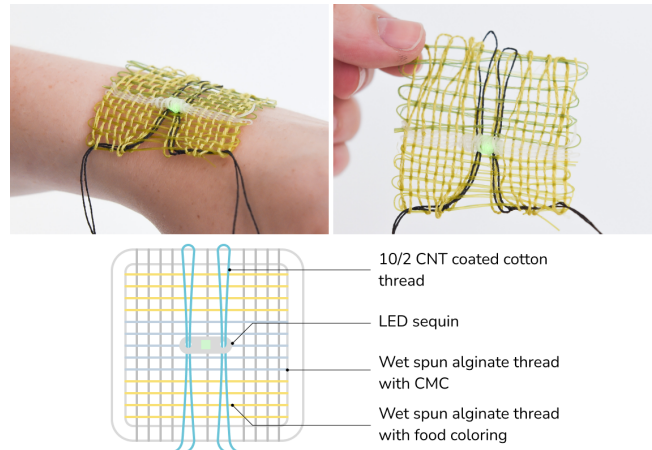
sample swatches for practice and no longer use them afterward. She used couching stitches to complete an LED circuit that contains three LEDs in different sizes in a parallel circuit and used a sandwich structure to construct the bend & pressure sensor that changes resistance when bent or pressed (Figure 8). She was surprised to see herself complete the exact same swatch design with the EcoThreads material without any design changes needed. She has also found that the CNT alginate threads provide suitable resistance to function as a changeable voltage dividing resistance in the circuit, unlike store-bought Velostat with fixed sheet resistance that can sometimes be too resistive.



**Figure 8: P1's project: Biodegradable e-textile swatches for teaching. (a) LED swatch; (b) Bend & pressure sensor.**

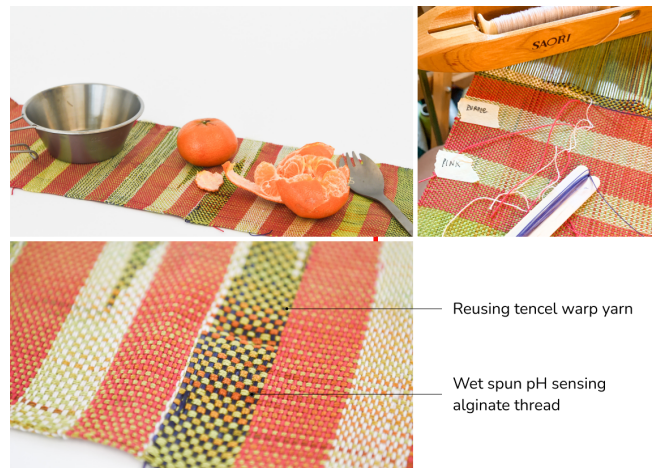
**P2's project: Disposable woven LED patch for concerts.** P2 has been using tapestry weaving to teach adults how to DIY their own sensors in maker space settings. After learning about the EcoThreads materials, she is interested in using tapestry weaving techniques to create an LED patch for concerts and festival events. Users can use the lights at the venues and choose to keep or dispose of them afterward. She chose CNT-coated cotton threads as a conductor and used semi-transparent wet-spun threads as light diffusers. To achieve semi-transparency, we mixed CMC into an alginate mixture for wet spinning at the ratio of 1:1. She integrated the LED into the woven patch as she wove on a small tapestry loom by feeding the conductive threads through the LED sequin pads. Then she used wet spun thread to weave the top layer of the circuitry and wrapped it around the LED to reinforce the attachment (Figure 9). She was excited to see the different wet spun threads present different mechanical properties that enable a variety of tapestry stitches.

**P3's project: Decomposable pH sensing picnic blanket.** P3's prior textile artwork involves food as a component. For example, one of her prior works explores how serving food directly on a tablecloth can dye the tablecloth as an art performance. In this study, she chose to use pH-sensing alginate threads to weave a sample of a picnic blanket that can change color when food is directly placed on it and can be left in nature to decompose after usage (Figure 10). We prepared alginate threads with pH-sensing extraction from red



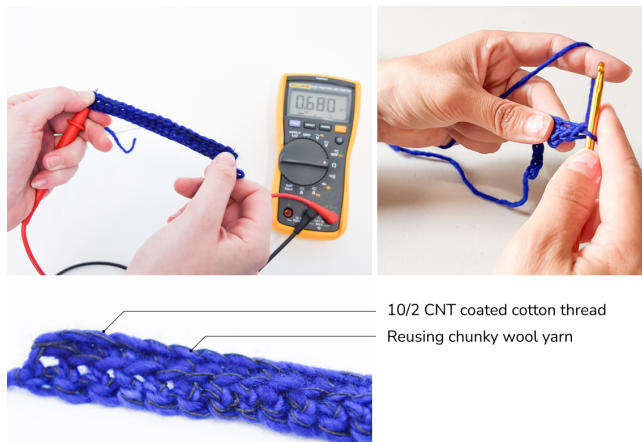
**Figure 9: P2's project: Disposable Woven LED patch for concerts.**

cabbage. She wove them on a two-shaft loom with remaining warp from her prior projects. She tested the color change using food liquids such as vinegar. She expressed that there were no tension or weaving technique adjustments needed, and she was able to weave the sample using her standard weaving technique.



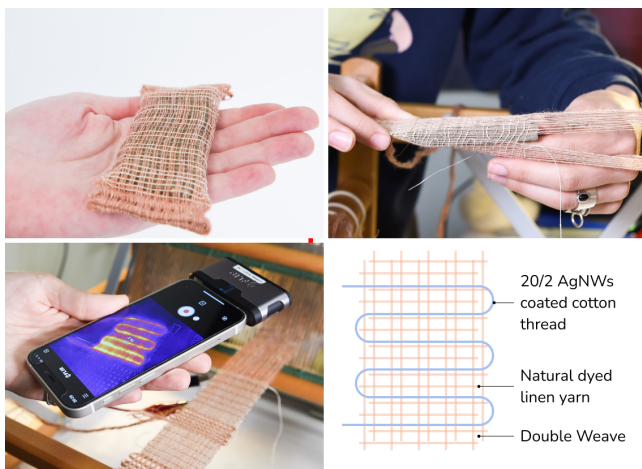
**Figure 10: P3's project: Decomposable pH sensing picnic blanket.**

**P4's project: Disposable crochet stretch sensor for posture sensing.** P4 is interested in using the crochet technique to create a series of stretch sensors for posture sensing. She envisioned that the sensor swatches could be attached to multiple body locations on the clothing and removed after usage. She chose CNT-coated cotton threads as the resistive material for this purpose and explored a variety of crochet stitches that enable variant stretchiness. 10/2 CNT coated cotton thread was thinner than the yarn she usually crochets with, so she crocheted it with chunky wool yarn to achieve maximum stretchability (Figure 11).



**Figure 11: P4's project: Disposable crochet stretch sensor for motion tracking.**

**P5's project: Heated pocket for stones.** P5's biomedical textile engineering work focuses on how functional textiles can be integrated into the body to replace metal inserts. For this study, she was also interested in exploring the connection between personal health and textiles. She was interested in fabricating a woven pocket that can heat up a stone for hot stone massage or as a pocket heater. She dressed a 4-shaft table loom using her madder root hand-dyed linen as warp and chose AgNWs-coated cotton thread with desired resistance as the heating thread. She designed a double weave pattern and wove the heating thread as weft on the top layer. After weaving the pocket, she inserted a stone she picked up during a recent hike into the pocket and powered the circuit to test the heating function. She is interested in returning the stone back to the trail to explore the notion of components that come from nature and also return to nature.



**Figure 12: P5's project: Heated pocket for stones.**

**Observations** We summarized our observations from the crafting session and post-study interview into the following themes.

*Compatibility with existing personal e-textile practices.* All five participants successfully incorporated EcoThreads with their specialized e-textile crafting techniques, ranging from embroidery, weaving to knitting, demonstrating EcoThreads' compatibility with existing e-textile practices. For example, P3 did not need to change the warp tension on her loom to accommodate alginate threads. Furthermore, all the participants reused yarn and fabric supplies from their prior work to complete the swatches, highlighting EcoThreads' compatibility with existing sustainable textile practices such as reusing. P1, who teaches with an e-textile swatch book in which students replicate, was surprised by the ease of EcoThreads in replacing conductive threads. P1 described using EcoThreads in their teaching curriculum to eliminate waste from student-replicated swatches and increase student awareness of material usage in planning and design. P2, P3 and P5 perceive the proposed sustainable e-textile life cycle (Figure 3) as congruent with their current textile practices, introducing no additional complications. P3 and P5 have been dyeing their own yarns for their textile art practice, and they are interested in exploring wet spinning as a personal fabrication approach to fabricate interactive materials.

*Knowledge and ownership over the source of materials.* All five participants emphasized the challenge of sourcing proper materials for their projects. When it comes to functional textiles with special properties, they do not have control over whether the thread materials are environmentally friendly. P3 and P5 elaborated that in the textile community, it's possible to source yarns and rovings from local suppliers, but it's much harder to do so with functional materials. The EcoThreads workflow enables them to fabricate their own functional threads using biodegradable materials and knowing the source of materials. This awareness also benefits the understanding of their environmental impact: "If you're making your material, you automatically have a better understanding and awareness of how you're using it and what goes into making it." as stated by P1.

More specific to e-textile practices, P1, P2 and P3 have all mentioned their preference for particular conductive threads, usually from a vendor abroad, with electrical and mechanical properties that were suitable for their project needs. However, these materials are challenging to access due to limited sources and international shipping regulations. Furthermore, store-bought functional threads and fabrics usually have fixed properties, requiring users to overcome these limits through specific stitches and cutting patterns. P1 and P2 are excited to see how they could customize the material property in the EcoThreads workflow to achieve the desired material performance.

*Sustainability awareness and access.* P1 reflected on how, by working with off-the-shelf conductive materials for so long, she became "desensitized" towards the environmental impact of prototyping and how EcoThreads brought forth "mindfulness" and "awareness" during her prototyping process. She also reflected on how EcoThreads Sustainable Life Cycle could contribute to building "intentional routines that perpetuate more sustainably minded behaviors." P2, P3 and P4 pointed out that the accessible DIY fabrication approach can potentially include a wider community in sustainable conversations. P3 stated that being aware of the sustainable material options opens new opportunities for her future work, and P2 expressed her appreciation of having hands-on experience using a biodegradable conductive material, which motivated her to explore sustainability



in e-textiles further. P4, who is an independent creative technologist and artist, stated how *"having more access to these materials"* could open up opportunities for sustainability conversations in the e-textile community that often only take place in more *"privileged"* academic or industrial spheres. P1 reflected on her choice of using neoprene scraps to fabricate the pressure sensor that she had *"moral tension"* in her head whether she should use the neoprene material even if it is a scrap piece, and she saw this thinking as a way to approach the learning of sustainable design.

*Design for decay.* All the participants expressed transiency as the design prompt initiated the ideation of transient use cases that they rarely considered. While their textile practices typically strive for a degree of permanence, all participants noted that they had witnessed elements of degradation throughout the lifespan of previous projects. P5 stated that one of her prior works used synthetic monofilament yarns as weft for weaving, and the filaments became yellowed over time. By taking time as an element in the design for the change and decay of a project, P5 has expressed her interest in exploring textile work with a desired lifespan. This mirrors the slowness in textiles described by Bell et al., which fosters a longer-term relationship between the user and the textile [6]. P1 has also expressed the appreciation of slowness in this spinning, drying, and crafting process: *"I think that reducing the speed and the pace with which we build things is not always a bad thing. It forces us to step back and think more deeply about how we're constructing those pieces."*

## 6 APPLICATIONS

To further explore the affordances of the EcoThreads approach, we ideated five transient e-textile use cases and prototyped them using EcoThreads biodegradable functional materials.

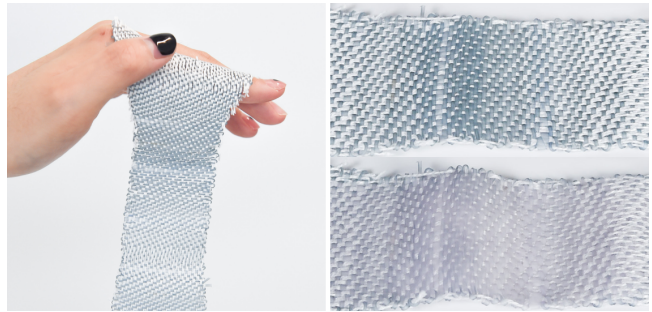


**Figure 13: Braided Capacitive Touch Sensing Hair Accessory.**

**Braided Capacitive Touch Sensing Hair Extensions (Figure 13).** Hair extensions afford temporary transition of one's style. As hair can often be cut or styled in different looks, we created a biodegradable conductive hair extension that can be trimmed if too long or replaced if too short with less environmental impact. To explore braiding as the integration technique, we braided four strands of CNT alginate thread around a connecting pad on a Gemma M0 microcontroller and then braided the device into the hair. The alginate conductive threads replaced synthetic blended metallic threads to reduce non-biodegradable waste in the trimming process. This

example application demonstrated the opportunity of using the EcoThreads material as transient hair-based interfaces [27].

**Woven pH Sensing Underwear (Figure 14).** As pH-sensing alginate threads can absorb liquid and react to pH level changes, we wove red cabbage-extracted pH-sensing alginate threads into the form of a panty liner. When in contact with vaginal discharge (typically around pH 4), the alginate threads will absorb the discharge and the color will change from light blue to purple depending on the pH level detected. We envision the biocompatibility of the materials can enable a broader range of body fluid sensing and awareness [18, 101].



**Figure 14: Woven pH Sensing Underwear.**

**Woven Heat sensing Bento Box Band (Figure 15).** In this application, we explored the integration of e-textiles into daily objects. We wove thermochromic pigment-infused alginate threads with cotton yarn on a TC2 jacquard loom to create a bento box band that indicates the warmth of the food. Elastic bands tend to lose their elasticity after a certain usage period, and we are interested in exploring using alginate-based threads as an alternative option.



**Figure 15: Woven Heat sensing Bento Box Band.**

**Knitted Cooling Gel for Fever (Figure 16).** This application explores the gel-like properties of alginate threads when wet. We directly knit freshly spun alginate threads without a drying process using chunky gauge knitting needles and stored the gel in the fridge. This patch can function as a cooling patch for fever and can be easily decomposed after usage.

**Woven Sweat Rate Sensing Patch (Figure 17).** Sweat rate sensing provides non-invasive monitoring of body fluid loss, and textile-based sweat sensors have the unique advantage of wearability and

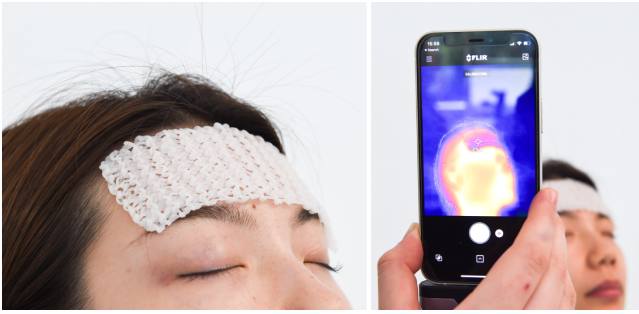


Figure 16: Knitted Cooling Gel for Fever.

conformability. However, used sweat-sensing textile patches require washing and drying before the next usage. We wove AgNWs-coated cotton threads with cotton weft to create an absorbing sweat-sensing patch. This patch can be attached to sportswear and absorb sweat for sweat rate sensing. The disposable conductive threads can replace synthetic blended metallic threads commonly used in such applications [32].



Figure 17: Woven Sweat Rate Sensing Patch.

## 7 DISCUSSION, LIMITATIONS & FUTURE WORK

**Embracing Transiency in the Design Process.** In our workshop study with e-textile practitioners and in developing the sample applications, we observed how the transiency of EcoThreads served unique design affordances. This distinctive approach sets it apart from conventional textile-based designs, particularly considering the prevalent cultural norm of crafting handmade textiles for prolonged use. Transiency can also provide an eco-friendly pathway for single-use and disposable applications that are commonly considered wasteful. Especially with the emerging application areas of personalized biosensing interfaces in which reusability is a challenge due to irreversible sensor properties and hygienic requirements, the introduction of transient e-textiles could potentially be an option for these particular scenarios, such as personalized face masks [35] and sweat sensors [101].

We also observe how the transiency of EcoThreads may render it suitable for particular phases in the prototyping process. Due to its biodegradable properties, EcoThreads can be a suitable material for the early-phase, low-fidelity prototyping processes in

e-textile design, in which many swatches are rapidly fabricated to understand the materiality of specific yarns combinations and textile structures before moving on to a "high-fidelity" final project [39]. Using these materials in this informal yet rapid prototyping stage enables spontaneous design exploration while minimizing environmental impact. Although our workshop study and sample applications focus on demonstrating the capability of transient use cases, the EcoThreads biodegradable materials can also be used in combination with other sustainable prototyping approaches, such as *unfabricating* [93], which maximizes the portion of reusable materials after disassembly for future iterations. One example of such a combination is that while a certain portion of the materials used in the *unfabricating* process can be harvested and reused, the trims can be biodegraded at the end of life. We envision that the EcoThreads approach could enable future opportunities for combined sustainable design practices.

**Intimate and Accessible Functional Textile Fabrication.** In our workshop study, participants expressed their interest in gaining hands-on experience using the wet spinning setup to spin their own functional threads. Especially, the ability to craft their own threads in familiar kitchen or studio environments brought forth opportunities for Intimate Making [7] in the context of functional threads. In our approach, we provided sample formulations (Table 2) paired with step-by-step instructions for HCI researchers and e-textile practitioners to have a low-barrier beginning process to enter this domain. Through characterization and design recommendations, we provide potential directions for researchers to modify the recipe to achieve desired properties. For example, the user could decrease the portion of CNT to fabricate resistance-based sensors at higher resistance. The choice of kitchen appliances in this approach enables textile studios and HCI research labs to adapt this to their workflow easily. We envision that designers, makers, and HCI researchers would only need minimum types of equipment and entry-level knowledge in material science to get started with the fabrication exploration.

The choice of the tools for wet spinning also affects the performance of the outcome. For wet spinning, extruding by hand using a syringe [11, 19, 21, 24, 49, 61] has been a common practice for makers. However, the uneven extrusion rate results in inconsistent tensile strength. We hope that by providing the DIY syringe pump option, users can assess the trade-off between accessibility and performance for fiber-based or thread-based fabrication and choose the tools that best suit their practices. Further iteration on the wet spinner can focus on improving user-friendliness by introducing a foot pedal, waterproof controlling panel, and a take-up winder to offer a plug-and-play experience for users who are less familiar with such mechanical systems. In this way, we can conduct follow-up user studies to invite participants to spin their own choice of materials. Furthermore, although the coating procedure currently requires minimum tools, introducing automated coating mechanisms can also open up opportunities for more advanced coating materials. We see these tools as a critical addition to the existing electric spinning wheels<sup>3</sup> that enable material innovation through open-source tools.

<sup>3</sup><https://www.studiohilo.com/open-tools>

**Formulation Standardization of User-Friendly Material Approaches in HCI.** Recent material-focused HCI research has been exploring a wide range of material innovation with compatible accessible fabrication approaches [22, 53, 86]. We see a common theme of sharing the *recipe* as the technical contribution. In our experience of learning, prototyping, and analyzing prior work in this realm, we observed that recipe-based knowledge transfer has its unique challenges. As many of the ingredients are sourced locally, material performance tends to vary among different sources of supplies. This variability is distinct for material-driven investigations, contrasting with hardware- or software-based knowledge transfer, which adhere to more universal standards. We are interested in the potential ways to standardize material-driven procedures in the HCI field.

Furthermore, interdisciplinary research plays a significant role in material-focused HCI explorations. Initiatives such as Future Materials Bank<sup>4</sup> and the Textile Academy<sup>5</sup> have explored the programming aspects of fostering community-based learning opportunities. These approaches offered open-source learning resources to enable a low-barrier entryway for people with limited material science expertise. EcoThreads aims to bridge the gap between these communities with advanced material exploration in the e-textile-specific domain.

**Towards Fully Integrated Sustainable E-Textile Prototyping.** In the current EcoThreads design space (Fig 2), we mostly focus on the textile substrates, including conductive and interactive thread elements. Hardware electronics are considered as detachable components that can be removed before decomposing. Hardware and soft material integration has always been a challenge to e-textile fabrication at different scales [102]. To improve the connections between hardware and substrate, compatible soft fasteners can be further explored for the easy attaching and detaching process. Furthermore, the recent advancement in biodegradable hardware electronics [22, 86] have revealed a possibility of fully biodegradable e-textile circuitry, including battery and components, which could lead to a fully integrated sustainable e-textile prototyping. Although EcoThreads focus on the fabrication of biodegradable e-textiles at individual creator's scale, the industrial-scale production of wet-spun alginate yarn demonstrates the scalability of the base binder material<sup>6</sup>. Future work will be needed to assess the manufacturing capability of EcoThreads recipes and the environmental impact of wet-spinning biodegradable materials in mass production.

## 8 CONCLUSION

We present EcoThreads, a sustainable e-textile prototyping approach integrating biodegradable conductive and interactive threads into existing e-textile practices. We synthesized two thread-based fabrication methods, wet spinning and thread coating, to fabricate functional threads from bio-mass or to modify natural fiber to achieve interactive functionality. We built a wet spinning tool from a modified DIY syringe pump to spin biodegradable conductive and

interactive threads in the desired thickness. We identified a low-volume thread coating approach to coat conductive threads onto natural fibers. The conductive and resistive threads are compatible with weaving, knitting, embroidery, and braiding techniques for textile integration.

To understand how EcoThreads could be adapted to existing e-textile practices, we conducted a workshop study with five practitioners with e-textile experience ranging from 3 to 12 years. Each of them completed an e-textile swatch with the design prompt of a transient use case. The study reveals the compatibility of the EcoThreads materials and highlights how this approach could evoke sustainability awareness. Through our five sample application designs, we further explore the notion of transient e-textiles and examine the material affordance of the EcoThreads through sewing, knitting, weaving, and braiding.

We see our work situated in the broader cycle of sustainable design practice and it is not a stand-alone nor exclusive approach. Biodegradable material choice can be coherently integrated into any existing e-textile practice to bring sustainability thinking into prototyping processes.

## ACKNOWLEDGMENTS

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