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Towards Decomposable Interactive Systems: Design of a Backyard-Degradable Wireless Heating Interface

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Figure 1: From leaf skeletons (left), we create a lightweight packaging that can wirelessly heat its contents (center) and is fully backyard-degradable (right).

ABSTRACT

Sustainability is critical to our planet and thus our designs. Within HCI, there is a tension between the desire to create interactive electronic systems and sustainability. In this paper, we present the design of an interactive system comprising components that are entirely decomposable. We leverage the inherent material properties of natural materials, such as paper, leaf skeletons, and chitosan, along with silver nanowires to create a new system capable of being electrically controlled as a portable heater. This new decomposable system, capable of wirelessly heating to >70°C, is flexible, lightweight, low-cost, and reusable, and it maintains its functionality over long periods of heating and multiple power cycles. We detail its design and present a series of use cases, from enabling a novel resealable packaging system to acting as a catalyst for shape-changing designs and beyond. Finally, we highlight the important decomposable property of the interactive system when it meets end-of-life.

CCS CONCEPTS

• **Human-centered computing → Interactive systems and tools**.

KEYWORDS

sustainability, heating, biodegradation, biodesign, decomposable materials

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1 INTRODUCTION

Sustainability is currently a top priority across industries and research disciplines. Within the Human-Computer Interaction (HCI) community, designers and design researchers have become increasingly conscious of the environmental impact of the materials and processes involved in their physical prototyping. Nonetheless, Lazaro et al.'s 2020 review of the environmental impact of physical prototyping reported that over one-third of physical prototyping published in the last 5 years of CHI proceedings was still done with plastics [71]. Sustainability often remains a secondary consideration brought about late in a design process — an unspoken assumption is arguably that a sustainable material must approximate the material properties of its conventional counterpart to be a competitive choice. As a result, many of the materials labeled as "bio-based," "biodegradable," and "compostable" that are available on the market today have been specially developed and heavily processed from their natural constituents to match the durability and other material properties of conventional, non-sustainable materials. Several commercially-available prototyping materials, such as polylactic acid (PLA), are marketed as eco-friendly, yet many such materials developed for reusable goods are so durable that they are not in fact easily broken down at the end of their life. In practice, the conditions for degradation are often very particular and unavailable in most locales, and as such, items made with these supposedly eco-friendly materials still become landfill in most cases. To avoid confusion with the industrial standards of biodegradability and compostability, in this paper, we use the terms "decomposable" and "backyard-degradable" to describe materials that can readily break down without the need for specialized conditions.

The problem of resorting to non-decomposable materials, or even materials not industrially biodegradable altogether, is especially exacerbated in the design of interfaces with electronic components. To date, biodegradable electronics — both those that are backyard-degradable and those that are industrially biodegradable — cannot compete performance-wise with their conventional counterparts. As a result, a second issue emerges: although designers are progressively experimenting with eco-friendly materials, "smart" and responsive systems still largely rely on embedding discrete, non-renewable electronics like integrated circuits and passive electronic components. Such electronics are generally undesirable from a sustainability point of view because they contain highly toxic components and require hazardous chemicals and gases to process. Unfortunately, because currently available dissolvable or biodegradable materials do not usually meet the original electronic performance specs, they cannot simply be swapped into an existing electronics design. Consequently, most demonstrations of sustainable smart systems prototyping to-date have focused on the components surrounding the electronics, such as the housing. Creating hybrid systems with biodegradable housings that can be removed and disposed of separately from the reusable internal electronics is certainly progress. However, in this paper, we demonstrate that when we more fundamentally rethink the design of physical interactive systems, we can create interactive systems made entirely out of biodegradable — even decomposable — materials.

Of course, with what is currently available, it is not possible to make certain high-speed or precise electronic systems with degradable materials, nor is it necessarily desirable to have every electronic system degrade quickly. Nonetheless, we believe that there exists a space of "semi-permanent" technological design that biological, decomposable materials are well-suited for. For example, packaging for food, cosmetics, and other goods is one application area that demands both reusability and responsible disposability. Increasingly eco-conscious consumers wish to be able to reuse packaging when possible, but packaging inevitably becomes soiled or worn beyond recovery, or it simply becomes overly burdensome to carry in certain on-the-go situations. At the same time, there is a growing demand for smart and interactive packaging that can monitor or regulate temperature for food safety, detect and alert a user of unsafe microbial growth, or indicate prior tampering that might have compromised the packaging's contents [55]. While decomposable packaging made from paper, chitosan, silk, and other renewable materials currently exists, this demand for smart packaging poses an added challenge. The non-degradable electronics that are conventionally considered necessary leave consumers with limited choices that are undesirable. People may throw away the smart packaging when it becomes inconvenient or unusable and bear the ethical weight of creating electronic waste; they may deconstruct the packaging to separate any biodegradable or compostable parts from the electronics, which then need to find a second use; or they may keep the packaging for as long as possible, even after it becomes unsanitary or nonfunctional.

If we prioritize the decomposability of materials in our design, can we design interfaces that are durable and have enhanced functionality without sacrificing the convenience of responsible disposability? This is a question that is core to the design exploration we present in this paper. We impose the limitation early on that all materials in our design be decomposable and present packaging augmented with basic heating functionality as an example application. We detail the design of a lightweight, reusable packaging for heating food or cosmetic items using natural and off-the-shelf materials. Our packaging design, which is decomposable in its entirety, integrates thin heating elements made from leaf skeletons that can be activated wirelessly without the need for embedded discrete electronic components. We propose an extensible design approach usable beyond packaging that forefronts the use of easily degradable materials from the beginning instead of finding biological analogues for non-renewable components in already existing system designs. We present our main contributions as follows:

- Design and evaluation of a fully backyard-compostable heating packaging that is wirelessly powered, resealable, and capable of indicating product readiness with thermochromic inks
- Proposal of a materials-first product design process that prioritizes the use of biological structures and natural materials to create a wide range of interfaces that are "semi-permanent" but decomposable at home

2 RELATED WORK

HCI researchers have called for more sustainable prototyping and design practices for over a decade [4, 5, 10, 34, 44, 47]. Laudable efforts have been made to propose and integrate practices such as upcycling [7], "salvage fabrication," [9] and "unmaking" [59] into fabrication workflows to prolong the life of physical artifacts through reuse and thus reduce waste. Wu and Devendorf similarly presented explorations for designing smart textiles that were woven to enable unraveling and reconfiguration [80].

When it comes to selecting materials for their designs in the first place, Lazaro et al. highlighted the importance for makers to minimize the "embodied energy" and associated carbon dioxide emissions over their selected materials' entire lifecycle [34].

In the last few years, there have been several commendable and provocative demonstrations of "bio-design" resonating with this call, highlighting and utilizing the aesthetic and functional capabilities of natural, easily-degradable materials [6, 29]. In some cases, interactive interfaces have been designed with living organisms powering shape or color changes [29, 81]. One particularly popular material capable of being grown by an amateur maker is mycelium, the vegetative root structure of fungi. It is easy and quick to grow, has desirable mechanical properties, and is readily compostable. Designers have grown mycelium into various functional objects and proposed it as a viable replacement to plastic in many applications [30, 69, 70, 75]. Mycelium has been explored as a valuable material for integration with electronics. For example, Lazaro et al. have demonstrated that grown mycelium forms may be milled and shaped to incorporate electronics such as batteries and LEDs [69, 70], and Weiler et al. have shown how mycelium may even be made to grow conformally around electronic components embedded during the mycelium growth process [75].

These mycelium-based hybrid electronics systems are certainly a big step towards the sustainable prototyping and manufacturing of electronic and interactive systems. However, while mycelium is backyard-degradable, the embedded electronics are not. They may be reused, but they must first be manually separated from the mycelium. Additionally, once they have reached the end of their life, their disposal is still problematic.

Researchers across multiple disciplines have actively been searching for new materials to make these electronics "green" [39]. In addition to the efforts within the HCI community mentioned already, several papers in materials science have investigated materials such as paper [65], chitin [24], and silk [61] for substrates and encapsulation materials. Additionally, researchers have reported the use of thin films of silver nanowires (Ag NWs) [22], carbon nanotubes [22], iron [82], magnesium [82], or conductive polymers such as PEDOT [38] to make electrodes that readily biodegrade into non-toxic particles. Under arguably the most intense investigation is the search for biodegradable semiconducting materials to replace silicon-based integrated circuits. However, meeting performance standards set by non-degradable electronics, which is an implicit goal of most research in green electronics, is immensely difficult and has led to the development of new materials requiring highly specialized processes conducted under specific laboratory conditions and with specially designed equipment. These efforts are important for the future of biodegradable systems. However, in this paper, we prioritize natural and commercially-available materials that do not rely on such specialized processes or equipment to make our approach more accessible.

There have been a few reports of functionalizing natural materials to make basic interactive systems. Most relevant to our work is the research of Sharma et al., who demonstrated a process for coating leaf skeletons with silver nitrate and, subsequently, Ag NWs to make small, biodegradable heating patches capable of boiling a vial of water [57]. Leaf skeletons coated with Ag NWs have subsequently also been found to be viable options for pressure sensors [31] and fog harvesters [56]. As we will describe in our Fabrication section, we were unable to use Sharma et al.'s exact method of making leaf heaters to reliably build components robust enough to withstand repeated and prolonged use, but this work was foundational to the demonstration we present here.

3 MATERIALS-DRIVEN HEATING DESIGN CONSIDERATIONS

While there are many valid applications to choose from to demonstrate decomposable, semi-permanent electronics, in this paper, we choose to focus primarily on heating systems. Heaters are fundamental elements of many products that people rely on and interact with daily. In addition to being essential to maintaining a comfortable indoor temperature, cooking, and fulfilling other fundamental needs in the home, heaters are common elements built into portable systems, such as drink warmers and on-body therapy pads. Heat has also been explored as a design resource for affective feedback [62, 68, 76–79], navigational cues [63], new aesthetic experiences [25], the communication of social presence [17, 18, 35, 36], and the augmentation of other sensory cues to assist individuals with certain impairments [11, 23].

There are several ways to induce heating. One method commonly used in portable products today is based on an irreversible exothermic reaction, such as the oxidation of a metal. Constituents, such as magnesium or iron filings, are packed into a sealed subcompartment within a larger package, and an individual may activate an exothermic chemical reaction by adding water or exposing the compartment to air. Products relying on this include hand warmers and *Meal, Ready-to-Eat*s (MREs). Downsides of systems like these include bulkiness (from the extra chemical components and packaging to initially isolate them) and non-reusability. A second popular method for integrated heating is through Joule (resistive) heating. In this modality, electrical potential is applied across a resistive element, and the resulting current causes energy to be dissipated as heat. Clothing irons and conventional electric stovetops are examples of commercial products based on Joule heating. Such systems, even when they are portable, also tend to be bulky, relying on portable batteries and hefty metal wiring. There are also biological processes that produce heat as a byproduct, such as fermentation and composting. These have been demonstrated as potential solutions for building-scale heating [14] but have not been utilized for smaller-scale or portable applications.

Among these choices, we chose Joule heating as the basis for our system. In addition to allowing our system to be reheated multiple times, Joule heating requires very few components, simplifying the number of components to be developed. A basic Joule heater comprises 2 parts: a power source, conventionally provided by portable battery or via a power cord to a wall outlet, and a conductive large-area heating element, conventionally made from copper or Nichrome (nickel-chromium alloy) wires arranged in a mesh or serpentine pattern.

Batteries and contact-based interconnects are not easily made with decomposable materials, so we eliminated these as possibilities for our design. We identified the most promising alternative to be wireless power transfer. Wireless chargers are commercially available and quickly becoming ubiquitous in homes, vehicles, offices, restaurants, and other locations for charging electronics on-the-go. There are even some mobile phones available on the market today that can be transformed into a wireless charger, allowing wirelessly-powered interfaces like ours to be truly portable and usable virtually anywhere. In a typical wireless charging system, a transmitter circuit creates an alternating magnetic field by generating alternating current (AC) through a conductive coil. This magnetic field in turn induces an alternating current in a receiver coil that is aligned with and placed near the transmitter coil. Typically, the receiver end contains a circuit of discrete electronic components such as rectifiers and capacitors to filter and convert the AC signal into direct current (DC) for charging applications. However, because our primary design goal was to create a fully decomposable system, we eliminated the use of such components as an option, requiring that our system be able to operate on AC power. This allowed the circuit to be integrated into our packaging to be very simple.

Finally, for the heating element, conventional Joule heaters are made with metal traces that are patterned to evenly distribute heat over a given area. The pattern is usually created either by a mechanical shaping process (if using bulk wires) or a subtractive wet or vapor-based chemical etching process (if starting with a planar metal foil or thin film). As we describe in the upcoming section, to replace these materials and processes, we looked to nature — specifically tree leaves — to find an appropriate area-covering structure.

With these considerations and design decisions in mind, we next detail the design of our system.

4 DESIGN OF ELECTRONICS-FREE HEATER

4.1 System Overview

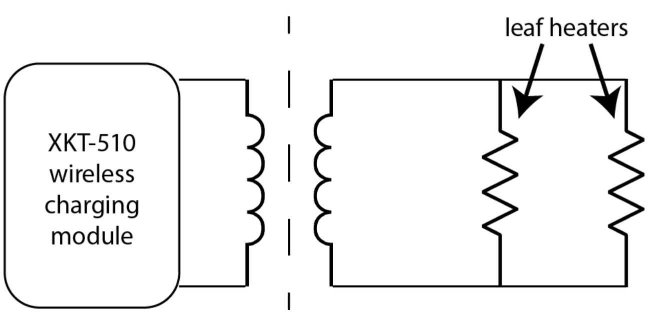

Figure 2: Schematic of heating packaging.

The electrical schematic of our system is shown in Figure 2. As previously mentioned, by powering our system wirelessly with AC power, we simplify the circuit to allow us to successfully create it with decomposable materials. The circuit on our packaging design contains only resistive elements in the form of leaf heaters, whose fabrication is detailed in the next section; non-toxic, compostable conductive ink; and a receiving coil, which may be patterned with the same ink.

We used an off-the-shelf XKT-510 IC-based wireless charging module to power and test our heating packaging. The amount of power delivered, and thus the amount of heat generated, may intentionally be varied by adjusting the position of the receiving coil on the packaging relative to the transmitting coil of the wireless charging module. When the coils are aligned on top of each other with virtually no spacing between them, the system can achieve maximum heating. To achieve lower temperatures, the package may be moved side to side or elevated above the charging module.

Next, we discuss the selection of our materials and the fabrication of our system.

4.2 Material Choices

There are several options for decomposable conductive inks to connect heating elements and pattern a wireless receiving coil. Here, we use a commercially-available, highly conductive, and water-based silver ink certified to be non-toxic (Circuit Scribe) [52]. Other decomposable conductive inks, such as Copprint's Nano Copper [58], metal oxides, and conductive carbon inks may also be used [39].

Crafting the heating element itself is more challenging. For this, we take advantage of one of nature's branching structures: tree leaves. As leaves grow on trees, their veins branch out in a fractal pattern to cover relatively large areas, naturally accomplishing patterns similar to those in conventional Joule heaters. Leaf skeletons comprise the network of veins and structural components of natural leaves that are left behind after the soft, fleshy parts have decomposed or have been eaten away. They may also be prepared at home by soaking leaves in a washing soda and water solution for roughly 2 hours [53]. Different trees produce skeletons with differing fractal patterns that could be strategically selected depending on the desired application. We initially experimented with un-dyed *Ficus religiosa* (bodhi) leaf skeletons as well as *Ficus elastica* (rubber tree) leaf skeletons from the Nava Chiangmai shop on Amazon.com. We did not find a notable difference in performance or reliability between heaters made with these two species so decided to continue solely with *Ficus religiosa* leaf skeletons, which were easier to cut into regular squares of a desired size due to their larger size and less obtrusive central stem compared to the *Ficus elastica* leaf skeletons.

As our conductor, we used off-the-shelf Ag NWs from Sigma-Aldrich to form a thin coating over the substrate. Ag NWs in low concentrations are considered to be non-toxic and biodegradable and have gained attention for a variety of electronic, opto-electronic, and biomedical applications [12, 41, 66]. Ag NWs may be synthesized in a variety of ways, including via "green" methods that do not require toxic solvents or reagents [12, 42].

Before the application of Ag NWs, however, our leaf skeletons must be coated in chitosan to form an all-natural substrate for the Ag NWs. Chitosan is a natural material from shellfish waste that is an attractive candidate for a myriad of applications due to its low cost, bioavailability, biodegradability, and biocompatibility [2]. This combination of leaf skeletons and chitosan is necessary to make stable heaters, as each one individually has failure modes that prevent them from acting as a reliable heater substrate. Sharma et al. demonstrated small leaf heater patches without a stabilizing overcoating like chitosan. However, we found that when attempting to make larger-area heaters needed for packaging and other functional applications with the reported method, electrical current usually concentrated at a small point on the leaf, eventually burning through the structure and rendering the leaf heater unusable, as seen in Figure 3. The leaf skeleton itself is still critical, however.

As Figure 3 shows, a smooth, untreated chitosan film dipped in Ag NW solution results in a non-uniform Ag NW layer that is not continuously conductive across the sample and thus not functional as as heater. In summary, chitosan acts to stabilize the leaf skeletons while they are heated, and the leaf skeletons provide an underlying texture and pattern for the Ag NWs to adhere to.

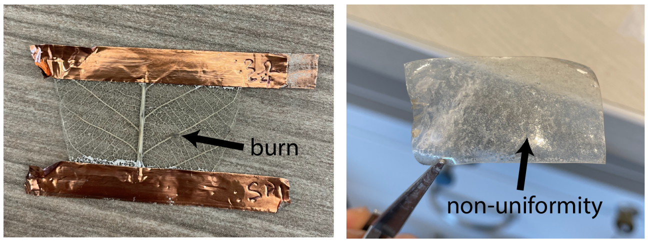

Figure 3: Left: An Ag NW-coated leaf skeleton without chitosan burns and becomes non-operational very easily upon heating. Right: An Ag NW-coated chitosan film without a leaf skeleton or other texture for the nanowires to adhere to is not uniformly conductive.

Leaf skeletons and chitosan are extremely cheap, with the quantity used for a 7.6cm x 7.6cm leaf heater amounting to a few US cents. We purchased Ag NWs from Sigma-Aldrich for $235 for 25mL. As Ag NWs become more popularly used, we expect their cost to drop, but even as-is, the amount of Ag NWs loaded on each leaf heater amounts to a mere 50 US cents.

4.3 Fabrication of Leaf Heaters

The fabrication process for making our core leaf heater elements is straightforward and does not require specialized equipment. First, a chitosan jelly is prepared by mixing dried chitosan powder (medium molecular weight) into a 2% acetic acid solution (v/v) for 1 hour. Glycerol is then added as a plasticizer in a 0.4:1 glycerol:chitosan weight ratio and mixed for an additional 30 minutes. All materials are purchased and used as-is from Sigma-Aldrich. Next, *Ficus religiosa* leaf skeletons are dipped in the chitosan solution and hung to dry for 4 hours. The resulting substrates largely retain the texture and aesthetic of the underlying leaf skeletons (Figure 4).

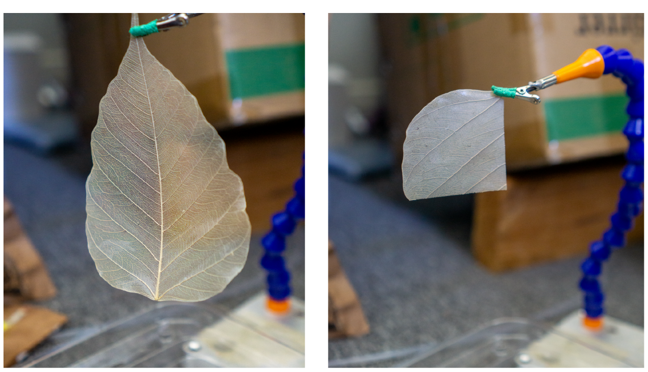

Figure 4: Left: *Ficus religiosa* leaf coated in chitosan. Right: section of prepared leaf dipped in silver nanowires.

Figure 5: Left: Open-faced view of the leaves, silver traces, and paper packaging. Right: Reverse side of packaging showing charging coil (off-the-shelf copper coil used as stand-in for printed silver coil).

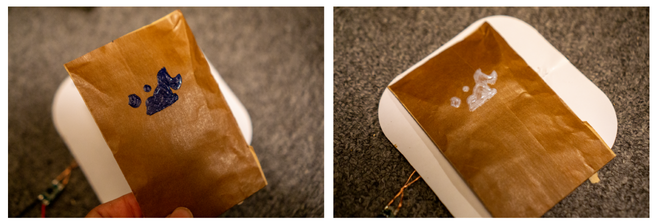

Figure 6: Thermochromic inks are used to indicate when the packaging is hot. Left: thermochromic ink design is purple before the packaging is heated. Right: Thermochromic ink design turns clear when the packaging is placed on a wireless charger.

Once dried, the leaves are cut into 7.6cm x 7.6cm pieces and dipped into an Ag NW solution (0.5mg/mL in ethanol) for 20 seconds. They are then once again hung to dry for 10 minutes at room temperature (Figure 4). At this point, they are ready to be integrated into a system. As our main example, we describe the next steps to create interactive packaging that wirelessly heats its contents.

4.4 Assembly of Packaging

The prepared leaf heaters are mounted onto the adhesive side of paper tape that has a natural rubber adhesive. For greater area coverage, we connect leaf heating elements in parallel. They are connected via water-based, non-toxic silver ink by using a stencil and brushing the ink onto the substrate by hand. The assembly is then simply adhered onto a kraft paper bag, as seen in Figure 5.

On the reverse side of the kraft paper bag, traces are patterned for wireless power receiving. Wireless receiving antenna designs are well established and typically consists of concentric rings or antenna lines for the reception of wireless power. This can readily be done with silver ink or Ag NWs themselves using techniques such as ink-jet printing [13, 40, 50] and transfer-printing [84]. Here, as a proxy and for prototyping simplicity, we use an off-the-shelf copper coil that we connect to our heating elements with our non-toxic silver ink.

At this point, the packaging is functional, but there is no visual feedback or other interactive feature to suggest to a user when the packaging is hot. For this, thermochromic elements can be added to the outside of the packaging as an indicator of "readiness," as seen in Figure 6. We mix thermochromic pigment with a non-toxic,

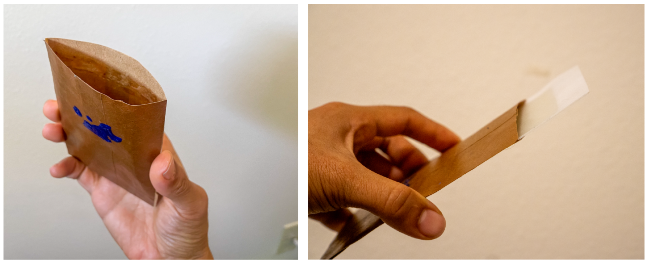

Figure 7: Assembled packaging

water-based glue and brush it onto one face of the packaging in a decorative pattern. The thermochromic design may alternatively be applied via screen-printing.

To create a heat-activated resealing mechanism, beeswax is melted and stirred with damar resin and jojoba oil (beeswax:resin:oil volume ratio of 4:1:1) in a double boiler for 15 minutes. Once all components are combined, the mixture is brushed as a strip onto 2 sides of the inside of the packaging and air-dried for 1 minute. This allows the packaging's contents to stay fresh and helps prevent any small pieces from falling out.

Our assembled packaging is shown in Figure 7. The fabrication process described is done by hand, but several steps can easily be adapted to computer-aided or automated manufacturing processes. For example, conductive ink may be selectively deposited via well-established ink-jet or screen printing processes for higher throughput and higher precision assembly.

5 EVALUATION

5.1 Electrical and Heating Characteristics

The wireless charger used in this study has a DC input voltage range of 5-12V that we varied with a DC power supply to better characterize the electrical and heating characteristics of our packaging. A plot of the current consumed by the charger (with the packaging placed directly on the charging mat) vs. input voltage is shown in Figure 8. As seen, the relationship is linear, indicating a constant resistance across the range of operation. By taking the inverse of the slope of the least squares regression line, we calculate the effective resistance to be 15.5Ω. This was also confirmed via direct measurement with a standard multimeter.

Figure 8 also shows the relationship between packaging temperature and charger power consumption. We used an FLIR C2 Compact Thermal Imager to monitor the heating of our packaging. Ambient temperature was 23°C for the duration of the test. At each voltage step, the temperature was monitored for and recorded after 20 seconds. The temperature stabilized within a few seconds and remained constant during the 20 second period. Even at a low power of 1.25W (corresponding to 5V and 250mA), the packaging was able to heat to 44°C, or 21°C greater than ambient temperature. As expected, temperature increased roughly linearly with power, up to 74°C at a power of 8.46W (corresponding to 12V and 705mA). As a point of comparison, a standard incandescent light bulb consumes 60W, and an equivalent-lumens LED light bulb consumes 12W [54].

An example IR image of our package taken seconds after being placed on the charging mat (input voltage = 12V) is shown in Figure

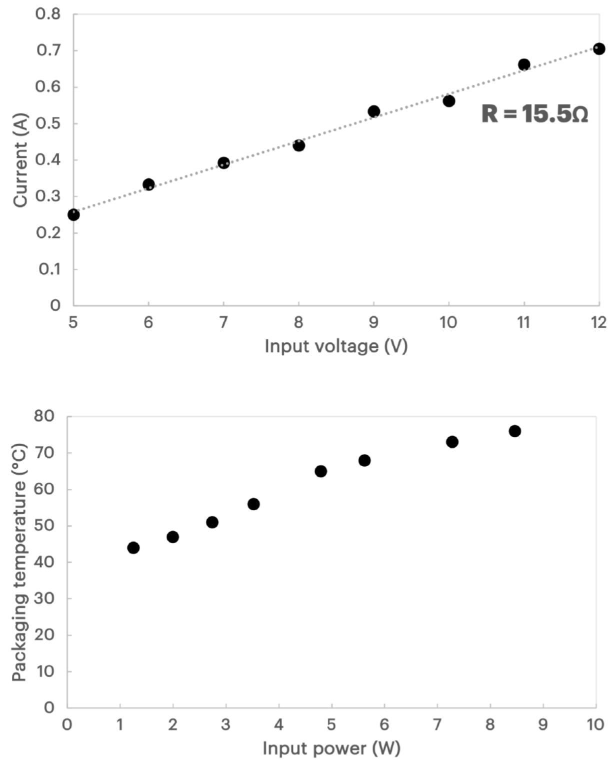

Figure 8: Top: Measured charger current vs. input voltage with the packaging placed directly on the charging mat. Bottom: Packaging temperature vs. charger power consumption.

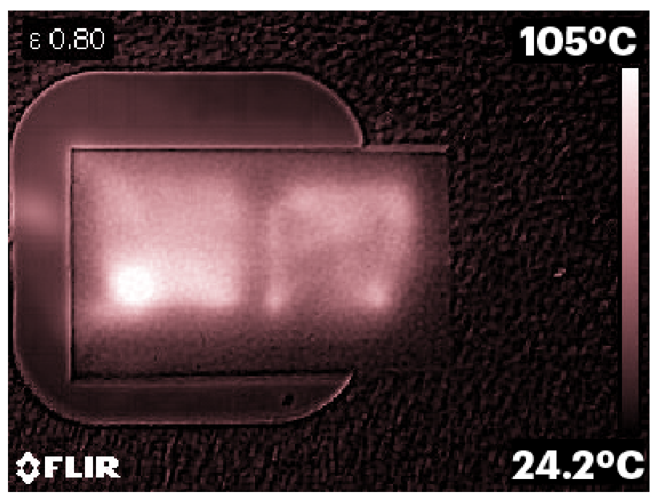

Figure 9: Infrared image of package placed onto charging mat.

9. Uniformity across the sample is analyzed with ImageJ[1]. The

[1] https://imagej.nih.gov/ij/

Figure 10: Left: packaging before being buried in soil on day 1. Middle: packaging dug up after 15 days. Right: packaging dug up after 30 days.

Table 1: Component Decomposition Times in Soil

Component	Decomposition Time
Leaves	21-365+ days [21]
Chitosan	30-60 days [46]
Paper	~28 days [49]
Beeswax	14-28 days [20]
Thermochromic ink	50-180 days [72]
Ag NWs	<1 day in water [83]

average temperature across the two heating patches in the image in Figure 9 is 73.6°C +/- 11.3°C.

The temperature and power consumption of the packaging is stable over long periods time as well. We left the package on the charging mat for 8 hours and observed no change in average temperature or power, as measured by the power supply to the wireless charging mat. We also conducted a cycling test in which we moved the package on and off the charging mat in 5 minute on/5 minute off cycles and similarly observed that the temperature and power remained the same for 20+ cycles.

5.2 Degradation

We created a swatch containing all components of our packaging — paper tape, NW-coated chitosan-leaves, silver ink, beeswax sealing, and thermochromic ink — and buried it under 20 cm of soil in a community garden in Berkeley, California for 60 days. The soil was alluvial soil with a moisture content of 30% as measured by a handheld moisture meter. The packaging was dug up and photographed on day 15 and on day 30 as intermediate checkpoints. The test was conducted during the summer of 2021. The swatch very visibly decomposed over the course of this test, as seen in Figure 10. After 60 days, the swatch was again checked on, and it was visually indistinguishable from the surrounding soil. This is unsurprising, since we intentionally selected components that are known to be decomposable. Known decomposition times of each components are reported in Table 1. Decomposition times do vary across different environments, but one can readily see that the time scale for decomposition is orders of magnitude smaller than the hundreds of years that even plastics marketed as "eco-friendly," such as PLA, take to naturally degrade.

6 APPLICATIONS FOR LEAF HEATERS

We next discuss several applications for our leaf heater system, both as packaging and as a platform for other designs.

6.1 Food

Food is a basic necessity for all as well as a subject of delight for many. Access to health-safe food is limited by the regional availability of processing, packaging, and storage technology. Pasteurization is one important but simple technique relied on worldwide that uses mild heat to destroy harmful microbes in liquid foods without changing the nutritional content or taste. This process is critical for treating products such as milk and juices. The pasteurization of milk requires a sustained temperature of 63°C for 15 minutes or 72°C for 15 seconds to sufficient to destroy all yeasts, molds, and gram-negative bacteria [26]. These parameters are easily achievable by our leaf heaters, positioning them as an attractive solution for food safety in environments and locales where specialized equipment is unavailable.

Our packaging may also be used as a reusable receptacle for heating food for more optimal enjoyment. To demonstrate this, we took a store-bought chocolate chip cookie, placed it in our packaging, and placed the packaging on our wireless charger (input voltage = 12V) for 2 minutes. After removing it from the packaging, the cookie was soft, and the chocolate chunks had been melted (Figure 11). Similar scenarios could be useful for other snacks or beverages in various settings, such as outdoors on a hike or in an airport, where microwaves and other kitchen appliances are not readily available, or in situations in which it might not be desirable to share such equipment. With a few basic modifications, instead of taking the shape of a rectangular bag, our packaging could be a sheet with pre-creased origami folds (or pre-scored kirigami cuts) so that it may be transported and stored flat but be easily assembled into aesthetically interesting and/or functional 3D shapes, such as bowls for soup.

Figure 11: Cookie before (left) and after (right) being heated in our packaging for 2 minutes.

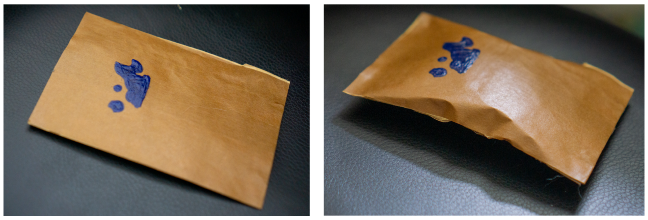

Figure 12: Thermally expanding microspheres placed inside the packaging can be activated to provide padding or achieve a desired shape.

Figure 13: A waxing strip becomes pliable and is able to stick to skin after being heated in our packaging for a few seconds.

6.2 Activating Shape Changes

4D printing and shape-morphing materials are active research areas that promise to revolutionize many fields, such as manufacturing, shipping, implantable devices, and tangible user interfaces [37, 64]. Many of the popular approaches rely on heat to activate a programmed-in shape change [1, 16, 19, 73, 74]. As proof-of-concept demonstrations, in research papers, the changes are usually activated with a radiative heating lamp, hot water, or a commercial Joule heater wired to a power source. Small, lightweight, and eco-friendly heaters such as ours could be used to make such demonstrations portable, perhaps opening the door for more applications.

Shape-changing elements could be also integrated into a packaging form factor to indicate prior usage, perhaps as a safety feature or perhaps as a decoration. For instance, Gu et al. demonstrated that by varying print speed and direction, a 3D printer may be used to print objects that lie flat when printed but morph into 3D forms as specified by the designer when later heated [19]. These objects could be adhered to the outside of packaging, with a shape changing indicating if the package has been heated before. This could help a user determine if the packaging's inner contents are safe or valid. Depending on aesthetic preferences, these features could be designed to be spartan and purely functional, or they may be intentionally designed to be playful and whimsical.

Heat-activated shape-changing materials such as expanding foams, made from silicone and thermally-expanding microspheres [27], can also be incorporated into our packaging to protect arbitrarily-shaped contents. The unexpanded foam can be packed flat into the walls of the packaging to allow for easy transport when the packaging is empty. Once the packaging is filled, the expanding foam can be easily activated to inflate and conform to the contents by placing the packaging on a charging mat. An example of packaging filled with thermally-expanding microspheres before and after heating is shown in Figure 12.

6.3 Enhancing On-Body Experiences

There are several cosmetic and personal health products that our packaging can also enable and improve the experience of using. For instance, waxing strips must be warmed before they are able to adhere to skin. We placed such a strip inside our packaging, and after just a few seconds, the product was ready for use (Figure 13). Other items that need to be heated for an optimal user experience include lotions and essential oils.

Beyond being integrated into packaging for such on-body products, our leaf heater system could be applied as semi-permanent on-body wearables. One straightforward implementation is as a stand-alone heat therapy patch. The system may also be used to activate thermoresponsive designs on clothing. Additionally, there are several reports of interactive wearable designs that require heat to activate, but like the shape-changing interfaces previously discussed, demonstrations are conventionally done with a non-portable or otherwise bulky power scheme. They are either wired directly to an external power supply or battery, which drives current through the wearable, or heated with conventional Joule heaters that are in turn wired to an external power supply or battery. Kao et al.'s *SkinMorph* is a hydrogel-based wearable that can programmably change texture based on temperature [28]. In Kao's presentation, Nichrome wires are sewn into SkinMorph patches and wired to a battery-powered circuit board. Our leaf heater system could potentially simplify the use and eventual disposal of such a wearable.

7 DISCUSSION AND FUTURE WORK

7.1 Leveraging Wireless Charging

Our design takes advantage of the growing ubiquity of wireless charging systems. Such inductive charging hardware is increasingly available and used to charge mobile phones, smartwatches, headphones, speakers, and more [45, 48]. This enables us to exploit a growing ecosystem of power to drive our novel heater design. By decoupling the power from electronics and our heater design, we are able to create a truly decomposable, interactive system. We are also seeing a rise in the number of mobile phones and other IoT devices that are capable of bi-directional charging — that is, mobile phones that can receive charge wirelessly as well as deliver wireless charge from their internal battery. For example, Samsung's Galaxy S10 is able to provide 4W of power wirelessly [67] to other devices. This level of power would allow our decomposable heating design to easily operate on the inductive coupling from a mobile phone alone and heat to 60°C, which is more than sufficient for most applications. This also significantly increases the ease of operation, variety of interaction, and range of functional places, since the heater can simply be triggered by placing it adjacent to a mobile phone, which is easily and commonly carried and thus readily on hand. Looking into the future, there is also budding research on fully biodegradable batteries [8, 32] that could eventually enable even more applications of decomposable interfaces in environments where wireless power might not be a feasible option.

7.2 Beyond Heaters

We envision how a focus of constraining designs to use only decomposable materials can also be extended beyond the heater example discussed in this paper. For instance, as mentioned in the related work section, the branching fractal structure of our leaf skeletons is also promising for pressure sensing. We could apply a very similar design approach to what we present here to create a fully decomposable wirelessly-powered system for this application.

Even more possibilities for decomposable designs may be imagined when we broaden out from the exact materials we use in this paper. Beyond smart packaging, many other applications are also well suited for decomposable, semi-permanent electronic design. As an example, in spite of a growing counter-movement to fast fashion, consumers generally do not keep an item of clothing or accessory until its end of life, instead often letting go of pieces that no longer suit their ever-changing style. While there is an argument to be made for making durable, smart garments that can change color, texture, and style electronically to keep up with trends, research suggests that smart, especially wearable, devices are often abandoned after a short period of use [15, 33]. Instead of building entire electronic systems into clothing that complicate end-of-life handling, we can employ the same power decoupling strategy of our design — for example, a non-decomposable mobile phone with bi-directional charging could be leveraged to wirelessly power and illuminate fully decomposable, electroluminescent patches sewn into or adhered to the clothing fabric. Similarly, sensor networks or other equipment deployed to a remote or dangerous environment could have limited operating lifetimes that allow useful data to be collected without the need to retrieve or remove the sensors, since they would degrade into non-toxic components soon after use. Of course, while significant scientific advances are still needed to realize all of these systems, we have clearly demonstrated a first step. Our argument is only that through the novel usage of selected decomposable materials, limited but useful electronic technologies can be designed and put into operation. Such systems will have limitations, such as intermittent power, slow operation, short duty cycles, and limited storage. Indeed, as more explorations are done in this area, we inevitably will find that certain applications do require long-lasting, speedy electronics that are difficult to achieve with decomposable materials. However, we believe that there is still a range of other applications for which these trade-offs are more than worth it for the tremendous benefits that come with a decomposable system.

7.3 Aesthetics of Decomposable Interactive Systems

Here, we chose to sandwich leaf heaters between two paper layers to create packaging that takes on the appearance of a standard paper envelope. This approach of prioritizing aesthetic *typicality* might be advantageous for promoting the adoption of leaf-based heating systems among people who are wary of the unknown or unfamiliar [30]. Alternatively, the leaves could intentionally be exposed by encapsulating them with clear, degradable cellophane tape instead of paper tape, or they could be left un-encapsulated entirely to fully showcase their appearance and texture. Leaf-based heating systems could thus become a vehicle to express personal style, perhaps as a pairing with gold or silver-dipped leaf jewelry. Furthermore, since no two leaves are identical, each system would have a unique, one-of-a-kind appearance that could increase one's emotional attachment to the system and also consequently promote more sustainable reuse practices [6].

Even after end-of-life is inevitably reached at some point, there are more opportunities to take advantage of the unique aesthetics of decomposable systems. Because decomposable systems are degradable in one's own backyard, they may give rise to new enriching experiences even after they are no longer able or wanted to be used for their original purpose. By selecting materials that degrade at different rates — for instance, in Figure 10, the beeswax strip appears to degrade slower than the paper, silver, and leaf components — a designer may intentionally exploit those differing decay rates directly into their design. This incorporation of *unmaking* [59] into objects is a critical new formulation in how designers design. That is, designers design not only for form and function but also for the range of intermediary forms and sub-functions of a digital artifact as it progresses towards its eventual decay. This fluid design could also celebrate and capture a broad range of ephemeral [60] transitory designs. Similarly, Liu et al. describe the degradation of natural materials as an opportunity for "natureculture co-creation" — a collaborative design process between nature and humans that de-centers the role of the human designer, encouraging humans to connect with nature [43]. As a decomposable interface changes form or texture, it could hence inspire a more intimate connection to the material object and decay experience [3] in addition to provoking reflections around the environment, consumerism, craftmanship, and materialism [43].

7.4 Challenges and Future Work

The design we have presented is Do-It-Yourself (DIY)-friendly in that it relies entirely on off-the-shelf, non-toxic materials and household-safe equipment and processes to make. As mentioned, we use a proxy copper coil in our demonstration in place of a printed Ag NW coil, for which the capability and process of printing such a coil is well documented [13, 40, 50, 84]. However, printing an Ag NW coil does require a conductive ink-jet printer and electromagnetic simulation software to optimize the coil geometry for efficient power transfer. Next steps will be geared towards replacing the proxy coil with a printed one to eliminate the need for coil detachment before composting. With further material exploration, it may be possible to build even more sustainable systems than what we demonstrate here. One future avenue of research lies in exploring the possibility of harvesting the heat released from fermentation or other organic processes. This could pave the way for completely stand-alone heating systems that are self-powered without relying on any non-natural power sources — wired or wireless — at all.

Even though we believe that a person without specialized design, materials science, or engineering experience can successfully acquire the materials and follow the fabrication process presented in this paper, we acknowledge that using unfamiliar materials can be intimidating. As such, we offer a single-page manual with links to purchase materials and step-by-step instructions in our Supplemental Materials section. We envision that such instructions could be distributed in a self-contained kit with pre-portioned quantities of all materials needed to make a desired number of heaters, further facilitating DIY fabrication and exploration and allowing our design to be more widely adopted. More broadly speaking, when it comes to exploring new materials and other designs, we acknowledge the difficulty of weeding through years of research in biology and materials science to find natural, degradable materials that might be suitable. Sometimes, even understanding what materials are "safe" and/or biodegradable can be a challenge. To facilitate this, building an open-source library of natural materials, such those compiled in the online recipe database *materiom*[51], could help facilitate the selection and subsequent design of more degradable smart systems than what we can imagine here. Suggestions for what materials to use could even be directly integrated into conventional design tools, such as CAD modeling software, to further assist designers form more sustainable creations.

We believe that DIY-friendly materials and designs are critical to inspiring new uses of sustainable materials and are also useful in enabling unique aesthetics even among different artifacts that arise from the same set of instructions. Still, we understand the value of enabling the eventual large-scale production of sustainable designs, which perhaps start as DIY approaches, to maximize awareness and use beyond what might be enabled even by the aforementioned self-contained kits. For the design presented in this paper, more experimentation is needed to understand if larger designs could be created by using larger leaves or by layering multiple leaves together with chitosan or another backyard-degradable binder. In general, one challenge of using natural materials is that they are often inherently non-uniform. For example, leaves may have natural holes or areas of sparse venation that could affect their efficacy as heaters on large scales. To address this, one possible approach is to simply take inspiration from the branching structure of leaf veins to design large-area networks of artificial skeleton leaves made from an alternative backyard-degradable material that can be 3D-printed, milled, or otherwise digitally fabricated into the desired form.

8 CONCLUSION

We have presented the design of a fully decomposable, wirelessly-powered, and portable heating system that is integrated into packaging. We argue that by prioritizing the use of natural and decomposable materials early in the design process, we can create functional, interactive interfaces with materials that are already commercially available. We have detailed a space of applications for "semi-permanent" interactive systems, such as the packaging we presented, for which we believe decomposable materials are particularly well suited. We further encourage designers to leverage a materials-first product design process that prioritizes the use of biological structures and natural materials to create additional novel applications and designs that are backyard-degradable.

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