Desktop Biofibers Spinning: An Open-Source Machine for Exploring Biobased Fibers and Their Application Towards Sustainable Smart Textile Design

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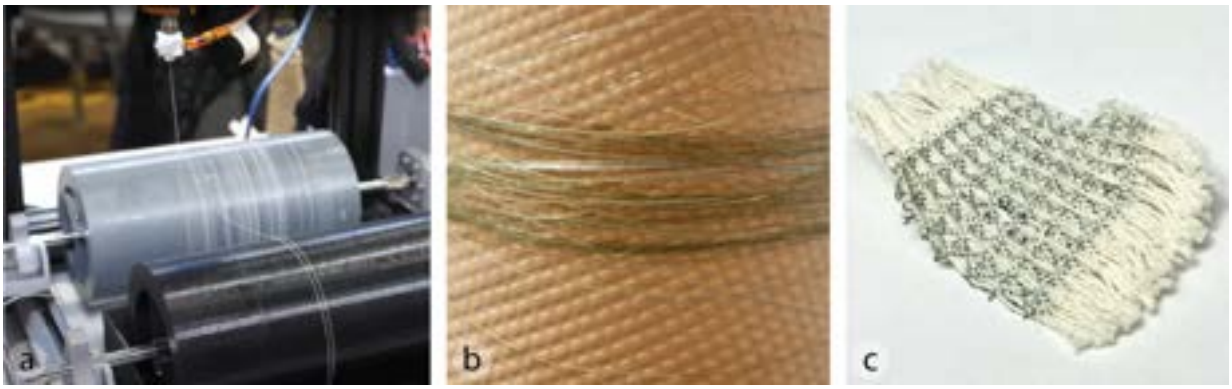

Figure 1: An overview of Desktop Biofibers Spinning: (a) gelatin biofibers spinning process using our machine; (b) a spool with green gelatin biofibers, (c) gelatin biofibers woven into cloth.

ABSTRACT

Smart textiles combine electronics with traditional textile forms, showing great promise in creating soft and flexible interactive systems for human-computer interaction and robotics. However, they also present significant sustainability challenges as they merge two substantial waste streams: textiles and electronics. This paper contributes to sustainability efforts by focusing on the integration of biobased materials that are biodegradable, compostable, and recyclable in the design of smart textiles. We introduce a Desktop Biofibers Spinning Machine to enable smart textile innovators to explore biobased fibers (i.e., biofibers) and envision applications in sustainable smart textiles. We describe the machine's design, a usage walkthrough, considerations for fiber spinning, and an exploration of various formulations to make gelatin biofibers. We provide several examples of biofibers integrated into smart textile applications. Finally, we discuss lessons learned from working with biofibers and the unique opportunities our machine brings to the fiber design space in HCI.

CHI '24, May 11–16, 2024, Honolulu, HI, USA

ACM ISBN 979-8-4007-0330-0/24/05
https://doi.org/10.1145/3613904.3642387

CCS CONCEPTS

• **Human-centered computing** → **Human computer interaction (HCI)**; • **Social and professional topics** → **Sustainability**; • **Hardware** → *Electromechanical systems*; • **Applied computing** → *Computer-aided manufacturing*.

KEYWORDS

sustainable smart textiles, biobased materials, fibers, sustainability, digital fabrication

ACM Reference Format:
Eldy S. Lazaro Vasquez, Mirela Alistar, Laura Devendorf, and Michael L. Rivera. 2024. Desktop Biofibers Spinning: An Open-Source Machine for Exploring Biobased Fibers and Their Application Towards Sustainable Smart Textile Design. In *Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI '24), May 11–16, 2024, Honolulu, HI, USA.* ACM, New York, NY, USA, 18 pages. https://doi.org/10.1145/3613904.3642387

1 INTRODUCTION

Smart, or electronic (e-), textiles integrate electronic materials (e.g., metals or reactive filaments) into textile structures like yarn and fabric extensively used in fashion, robotics, and medicine. The smart textile industry is expected to be worth USD 15.36 billion by 2030 [57], however, it poses significant environmental risks by combining two highly toxic waste streams: textiles and e-waste [15]. In 2018, textiles accounted for 11.3 million tons of landfilled waste in the United States [18]. As smart textiles continue to evolve, this textile waste will compound with the 50 million metric tons of global e-waste generated annually [20, 47].

Currently, the integration of smart functionality and electronic components into textiles primarily occurs at high-level structures such as yarn and woven fabric. Within this space, smart textile innovators—including textile craftspeople and engineers with backgrounds across many fields (e.g., human-computer interaction, materials science)—choose from off-the-shelf materials that are generally unsustainable (e.g., derived from fossil fuels); come with specific properties or blends; and are hard to separate making them difficult to recycle [1, 23].

The Human-Computer Interaction (HCI) community has explored several sustainable design approaches in the context of electronics, traditional textiles, and prototyping. These approaches include biodesign [4, 5, 62] and designing for disassembly [65]; repair [53]; and decay [30, 35, 40, 55, 56]. Works that examine biodesign practices within smart textiles emphasize the use of biobased materials [41], particularly as scaffolds for electronics [5, 30, 33, 62]. Bridging these efforts with an awareness of the complex nature of sustainability in smart textiles, we see a unique opportunity to explore biobased materials in the most fundamental unit of all textiles—fibers.

Enabling the design of fibers with biobased materials, or *biofibers*, has the potential to open new avenues for functionality, customization, biodegradability, recyclability, and disassembly in smart textiles. Currently, the fiber production stage is inaccessible to many smart textile innovators due to a lack of tools that support exploration and prototyping, particularly with biobased materials. In this work, we introduce an open-source, low-cost, desktop machine that enables the prototyping, production, and customization of biofibers.

Our Desktop Biofibers Spinning Machine converts sustainable biobased material solutions (e.g., liquid gelatin, which is an industrial by-product [26]) into customizable biofibers. The machine is modeled off of fiber wet spinning [60]—a process commonly used to produce synthetic fibers with highly customized properties from liquid solutions. However, our machine has been adapted to work specifically with biobased materials instead of traditional petroleum or synthetic polymer-based solutions. We intend for our process (Figure 1) and the insights derived from its design to advance the use of biobased materials in HCI and enable smart textile innovators to examine new opportunities for sustainable smart textiles. To this end, this work contributes:

- An open-source desktop biofibers spinning machine.
- A series of gelatin biofiber material formulations.
- Example applications showcasing practical use of the machine in producing biofibers towards sustainable smart textile design.
- Insights derived from fiber production, wet spinning processes, and interdisciplinary fiber design.

2 RELATED WORK

2.1 Sustainability Challenges in Smart Textiles

Smart textiles are at the intersection of textiles, materials science, electronics, and design. They offer innovative ways to interact with technology and the environment. In the field of HCI, smart textiles have been used in a variety of applications such as interactive fashion [19, 66], wearable technology [11, 45, 63], gesture-based interfaces [43, 63, 64], and assistive technology [9, 34]. Smart textiles are often created with conductive threads, fibers, yarns, and fabrics that are suitable for use with different textile fabrication techniques (e.g., sewing, weaving, crocheting, and knitting). These conductive materials are typically produced by blending conductive metals with other fibers that may be natural (e.g., animal-based) or synthetic (e.g., chemically synthesized). These fibers are chosen for their functional qualities (e.g., flexibility and strength) to ensure that the produced smart textile has both electrical conductivity and mechanical functionality.

While blending enables the creation of smart textiles, this approach also introduces sustainability challenges. Electronic and textile components are difficult to separate for proper recycling or disposal, often requiring specialized facilities that are not readily available. Another environmental challenge of smart textiles is that they are typically made from synthetic materials that do not easily biodegrade, if at all. This in turn leads to long-lasting waste in landfills and contributes to plastic pollution. Addressing these sustainability challenges requires a holistic approach that considers the entire life-cycle of smart textiles, from design and production to use and disposal [15, 17]. This includes making smart textiles readily disposable with biodegradable and compostable materials; optimizing manufacturing processes; designing for longevity, reusability, and recyclability; promoting responsible consumption; and investing in research and development for more sustainable smart textile technologies [23].

Existing HCI efforts have focused on repairing [27], reusing [28], and disassembling [65] smart textiles. At the same time, material design communities [31, 36, 37] have explored creating sustainable materials and DIY biomaterials [46, 50] through open-source material archives [39, 51]. These material archives focus primarily on recipes for materials that can be made into sheets or molded. In contrast, we believe that focusing on fibers—the backbone of all textiles—can open a new design space to address sustainability challenges in smart textiles. In this work, we seek to enable the HCI and digital fabrication communities to engage in the fiber design space and explore these materials, their affordances, and their applications.

2.2 Challenges in Fiber and Biofiber Production Techniques

Research into fiber and filament-based production techniques highlights innovative approaches to textile design, revealing challenges

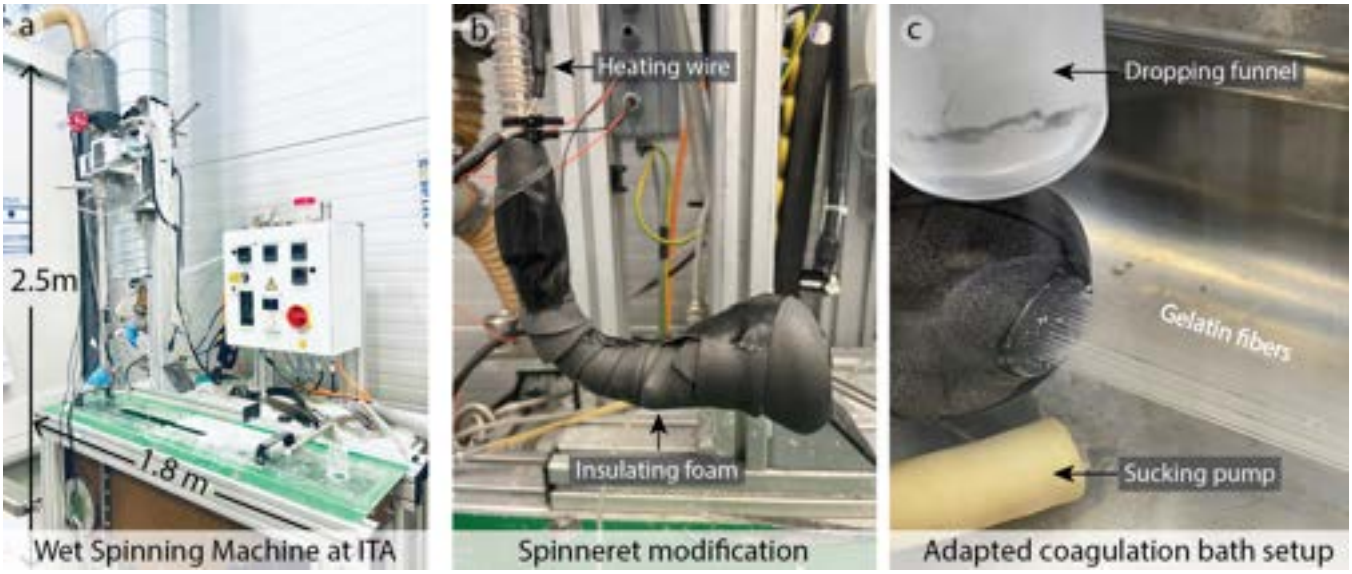

Figure 2: Gelatin fibers spinning challenges: a. DIENES LabLine machine for fiber spinning, b. Spinneret modification consists of a heating wire around the area of the spinneret that goes inside the coagulation bath, wrapped with insulating foam to maintain the desired temperate at spinning time, and c. Coagulation bath setup adapted to handle two different liquid concentrations in the same bath. One comes from the dropping funnel and the other one is already filled in the bath. The pump sucks the liquid coming from the dropping funnel to maintain the desired concentration levels in the bath. This enabled the spinning of gelatin fibers using a nozzle of 120 holes with 100-micron resolution.

and constraints that influence the trajectory of sustainable smart textile innovation. In many cases, innovators in the textile design domain must construct custom systems to facilitate their work. For instance, Egusa et al. [16] developed a desktop filament production system capable of depositing "smart" materials in cylindrical layers. Similarly, Behabtu et al. [3] demonstrated the production of thin, strong, and highly conductive carbon nanotube filaments using a specialized wet spinning machine. While showcasing the potential of fiber design, these custom systems pose challenges as they are often designed for specific materials, lack tunability, and are challenging for others to replicate.

In the HCI community, researchers have explored various techniques to create fibers in the context of 3D printing. For example, Rivera and Hudson [52] developed an open-source 3D printer that produces PLA fibers from PLA via melt electrospinning. Others have investigated using 3D printing to create hair-like structures [32, 44]. While these efforts demonstrate creative approaches to fiber design, it's crucial to recognize that these techniques rely on unsustainable materials such as thermoplastic filaments and photopolymer resins.

To achieve sustainability in smart textiles, a thorough consideration of material choice, fabrication techniques, and the overall life-cycle is necessary [23]. Without accessible tools and workflows for fiber design, exploration of new and more sustainable material choices is unlikely, if not impossible. Moreover, it's worth noting that the materials with perhaps the greatest potential for sustainability benefits—namely, biobased materials—often lack adequate support or remain under-explored within the textile design pipeline, particularly in the context of yarn production. These challenges extend to the production of fibers made from biobased materials.

On an industrial scale, synthetic fibers are typically made from stable liquid solutions using specialized machines for wet or dry spinning. However, these machines are less suitable for biobased liquid solutions, which tend to be less stable during the fiber spinning process. The complexities of fiber spinning prototyping pose considerable challenges, particularly when contemplating the engagement of designers and researchers in HCI seeking to explore this fiber design space.

Our first-hand experience at the Institute of Advanced Textiles (ITA) at RWTH Aachen [54] in Germany during the summer of 2022 revealed challenges tied to the production of biofibers from a gelatin liquid solution using standard wet spinning equipment. The room-sized equipment (4m long) required substantial spinning solution quantities—a minimum of 500 mL—to perform a single test. Moreover, opportunities for fine-tuning the machine parameters to facilitate the spinning process were limited.

Challenges that we faced attempting to use heat-sensitive biobased liquid solutions further emphasized the need for accessible tools and workflows for fiber design and exploration, especially in the context of sustainable smart textiles. Within biodesign and HCI, it is common practice to use modest quantities of material (i.e., 10 mL) to investigate how changes in composition and process parameters can influence material outcomes. Our attempts to modify the standard equipment encountered a series of setbacks, including issues like clogs. Despite implementing ad-hoc modifications to the machine (Figure 2b, c), achieving consistent and predictable properties in the gelatin fibers through parameter manipulation remained a challenge. The insights gained from this experience contributed to an understanding of the essential preparation needed for a wet

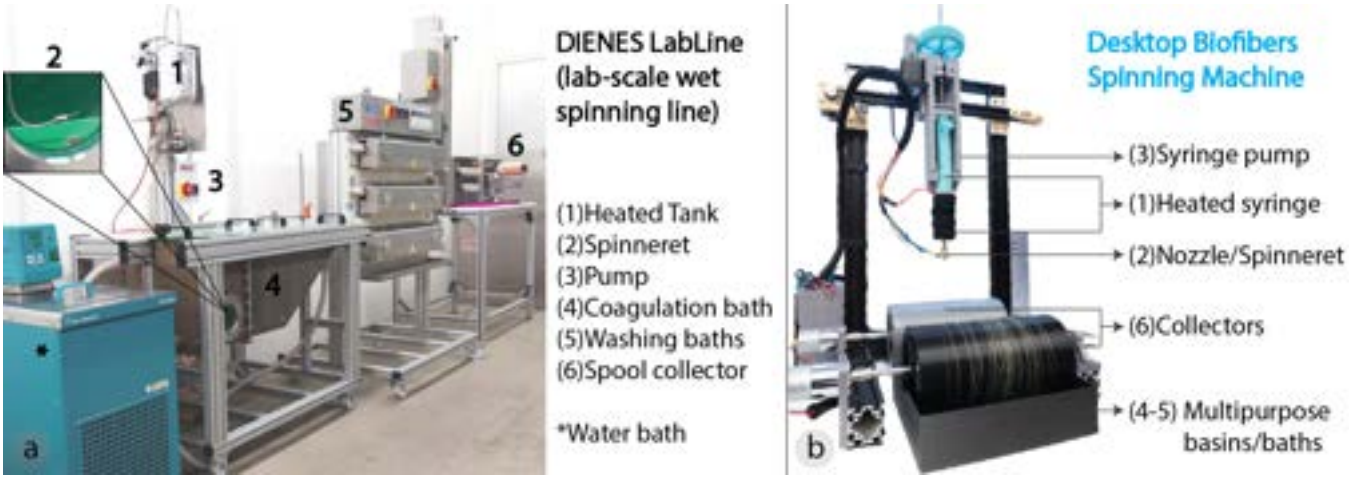

Figure 3: Comparison between DIENES LabLine, a lab-scale wet spinning machine, and the Desktop Biofibers Spinning Machine. In both setups, an off-the-shelf (*)water bath can be used.

spinning process and motivated the need for the Desktop Biofibers Spinning Machine (Figure 3b) as we describe in the next section.

3 A DESKTOP BIOFIBERS SPINNING MACHINE

Our Desktop Biofibers Spinning Machine is designed to mimic a dry-jet wet spinning process (Figure 4), considered a variation of wet spinning. A comparison of our machine and a lab-scale wet spinning machine is shown in Figure 3. Crucially, our machine enables biofibers with customizable properties to be produced from liquid biobased solutions. In this section, we describe the design of the machine and provide a walkthrough of its fiber-spinning process.

3.1 Machine Design

The Desktop Biofibers Spinning Machine is inspired by desktop 3D printers and is constructed from readily available components (e.g., aluminum extrusions). It is designed to be modular—different components of the machine can be swapped or extended to enable different material explorations and further customization in produced fibers. The full bill of materials, part files, and associated firmware are open-source and available at: https://github.com/utilityresearchlab/desktop-biofibers-spinning/.

Mechanical Components. The machine has several major components: the frame; the X-axis carriage; the syringe pump; the heated syringe; the nozzle/spinneret; the expandable Y-axis; and the collectors and basins. The basis of the machine is a frame made of various aluminum extrusions, similar to many open-source 3D printer designs. These frames enable various parts to be mounted and easily adjusted. The X-axis carriage is similar to one on a typical 3D printer. The X-axis carriage moves across from left to right based on user-specified commands. It is mounted on the vertical portion of the frame and its height determines the air-gap distance for the spinning process. In our setup, a motor-driven syringe pump is mounted onto the carriage. However, the carriage has mounting holes that enable other types of extrusion mechanisms (e.g., pneumatic) to be used instead. We use the open-source Large Volume Extruder (LVE) syringe pump [48] with a 60 mL luer lock syringe[1] on our machine to facilitate extruding potentially viscous material solutions. The syringe is heated with a 12V/25W silicone heater wrap secured to the syringe using hook-and-loop straps. The nozzle/spinneret attached to the tip of the syringe can either consist of a luer lock syringe tip (any size) or a standard 3D printer hot-end nozzle attached using a luer lock-to-M6 adapter[2]. The latter setup enables material solutions to be heated to a specific temperature at extrusion time. In addition, any size standard V6/M6-threaded 3D printer nozzle can be used.

The Y-axis of the machine—along the base of the frame—enables collector assemblies to be placed and the distance between them to

[1] 60 mL Syringe: https://www.amazon.com/dp/B007RYA22I/
[2] Luer Lock to M6 Adapter: https://www.amazon.com/gp/product/B087SXKX6S/

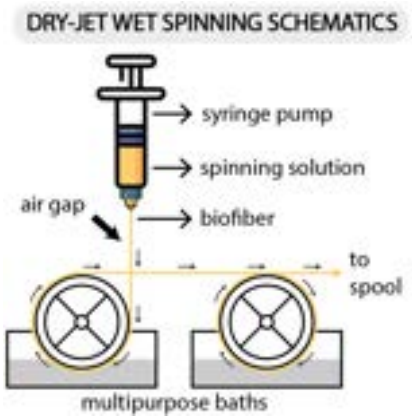

Figure 4: Dry-jet wet spinning schematic of our machine. The multipurpose baths can be used for any post-production process such as coagulation, finishing, drying, or treatment.

be easily adjusted. Each collector assembly consists of a DC motor fixed to an 8 mm linear rod using a M5-to-M8 motor coupler, a 3D-printed roller (the collector), a latch mechanism, and printed brackets. The roller is fixed to the linear rod such that it rotates based on a user-specified speed in revolutions-per-minute (RPM). The latch mechanism allows the roller and rod assembly to be supported while rotating, but easily removable when the fiber spinning process is completed. Each collector is accompanied by a 3D-printed basin (multipurpose bath) that is placed underneath the collector. The basin serves as a container for various fiber production (e.g. coagulation bath) and post-production processes (e.g., finishing, drying, treatment, etc.). As a fiber is wound around a collector, it is coated by the solution in the basin. While the current machine setup features two collectors, the Y-axis of the frame can be extended with an adapter to support additional collector assemblies for further fiber post-production processing.

Electronics. The machine is controlled using an Arduino Mega 2560 Rev3 microcontroller[3] coupled with a RAMPS 1.4 control board[4]. This combination is commonly used in open-source 3D printers. It provides the necessary functionality to run multiple heaters, temperature sensors, and motor drivers. We use NEMA 17 stepper motors to drive the X-axis and the syringe pump. We use auxiliary pins on the RAMPS board to run additional Adafruit TB6612 1.2A DC Motor Drivers[5], which control the 10 RPM DC motors of the collectors. A standard 3D printer hot-end assembly consisting of an NTC 3950-100K thermistor and a 12V/30W cartridge heater is used to heat the nozzle. Lastly, we use an additional NTC 3950-100K thermistor secured to the syringe heater wrapped with Kapton tape for temperature feedback.

Firmware. Our machine runs a variation of the Marlin 2.1.1 Firmware[6], commonly used for desktop 3D printers. We modified the firmware to support the control (e.g., speed and direction) of multiple DC motors. These motors are used to independently drive the machine's collectors. We also made adjustments to various machine-related parameters including the steps/mm for the syringe pump motor; the min/max temperature ranges; and the temperature calibration for the syringe heater wrap and the nozzle heater. The temperature calibration was adjusted to accommodate the relatively low processing temperatures of many biobased material solutions (typically <100 °C). We communicate with the machine using G-code[7] commands sent through Repetier-Host[8], a commonly used 3D printer host controller software.

3.2 Biofiber Spinning Walkthrough

To illustrate the practical use of our machine, we provide a walkthrough of the fiber spinning process (Figure 5). We describe each step of the process, producing gelatin biofibers that are flexible and yellow as an example (Figure 9c). More details about fiber wet spinning considerations can be found in Section 4.

[3]Arduino Mega 2560 Rev 3: https://store-usa.arduino.cc/products/arduino-mega-2560-rev3
[4]RAMPS 1.4: http://reprap.org/wiki/RAMPS_1.4)
[5]Adafruit TB6612: https://www.adafruit.com/product/2448
[6]Marlin 2.1.1: https://marlinfw.org/meta/download/
[7]G-code Reference: https://marlinfw.org/meta/gcode/
[8]Repetier-Host: https://www.repetier.com/

3.2.1 Step 1: Pre-Heating the Spinning Solution. We place a capped syringe containing the spinning solution into a water bath set to 60 °C for 15 minutes. As the solution's temperature increases, it should go from a gel-like state to a syrup-like consistency. We gently invert the syringe outside of the water bath and observe consistency. If the desired viscosity is not yet achieved, we return the syringe to the bath for an additional 5-10 minutes before re-evaluating. Once the desired consistency is achieved, we proceed to the next step. For comprehensive instructions on preparing the spinning solution and appropriate storage, see Section 4.

3.2.2 Step 2: Preparing the Multipurpose Baths. This step involves the preparation and pouring of solutions into their respective basins. To create the gelatin biofibers, we designate the first basin (located directly below the syringe pump) as a coagulation bath which will precipitate the biofibers. The second basin (towards the front of the machine) is designated as the finishing bath which will add flexibility and color to the biofibers. In the first basin, we pour an off-the-shelf isopropanol solution (90% concentration) until the liquid reaches the bottom of the collector. For the second bath, we mix isopropanol (90% concentration), glycerine (5% concentration), and 3 drops of yellow food coloring in a separate container. We stir the mixture until the color is uniform and then pour it into to the second basin until it reaches the bottom of the collector.

3.2.3 Step 3: Loading the Material into the Machine. We retract the machine's syringe pump until the pre-heated syringe's plunger can be slotted in. This can either be done by manually turning the pump's drive gear or using the host controller software to send a retraction G-code command (e.g., `G1 E-40 F30` to retract 40 mm at 30 mm/min). We insert the syringe into the pump. We then secure the silicone heater wrap around the body of the syringe, ensuring that its associated thermistor is in direct contact with the lower section of the syringe's wall. Throughout this step, it is important to keep the syringe capped to prevent material loss. In host controller software, we set the heater wrap's temperature to be 40 °C using the G-code command: `M104 T1 S40`. We then wait until the temperature is reached.

3.2.4 Step 4: Setting Up the Nozzle and the Collectors. We remove the cap from the syringe and quickly attach the desired nozzle—either a luer lock syringe tip or the 3D printer hot-end using the luer lock-to-M6 adapter. In this case, we use the 3D printer hot-end with a 0.4 mm diameter nozzle. In the host controller software, we set the temperature of the nozzle to be 31 °C using the G-code command: `M104 T0 S31`. We then wait until the nozzle temperature is reached. Afterward, we prime the nozzle by repeatedly extruding a small amount at a slow speed using the G-code command: `G1 E0.1 F1`. Once the spinning solution emerges from the tip of the nozzle, we set the speed of the collectors by sending the G-code command `M3 S100`, where the speed value is out of 255 and proportional to the max RPM of the collector's DC motor: $RPM_{\texttt{collector}} = (value/255) * RPM_{\texttt{max}}$. A value of 100 with a 10 RPM DC motor results in a collector speed of 3.9 RPM. While this setup maintains the same speed for all collectors, this will be customizable in future iterations of the machine.

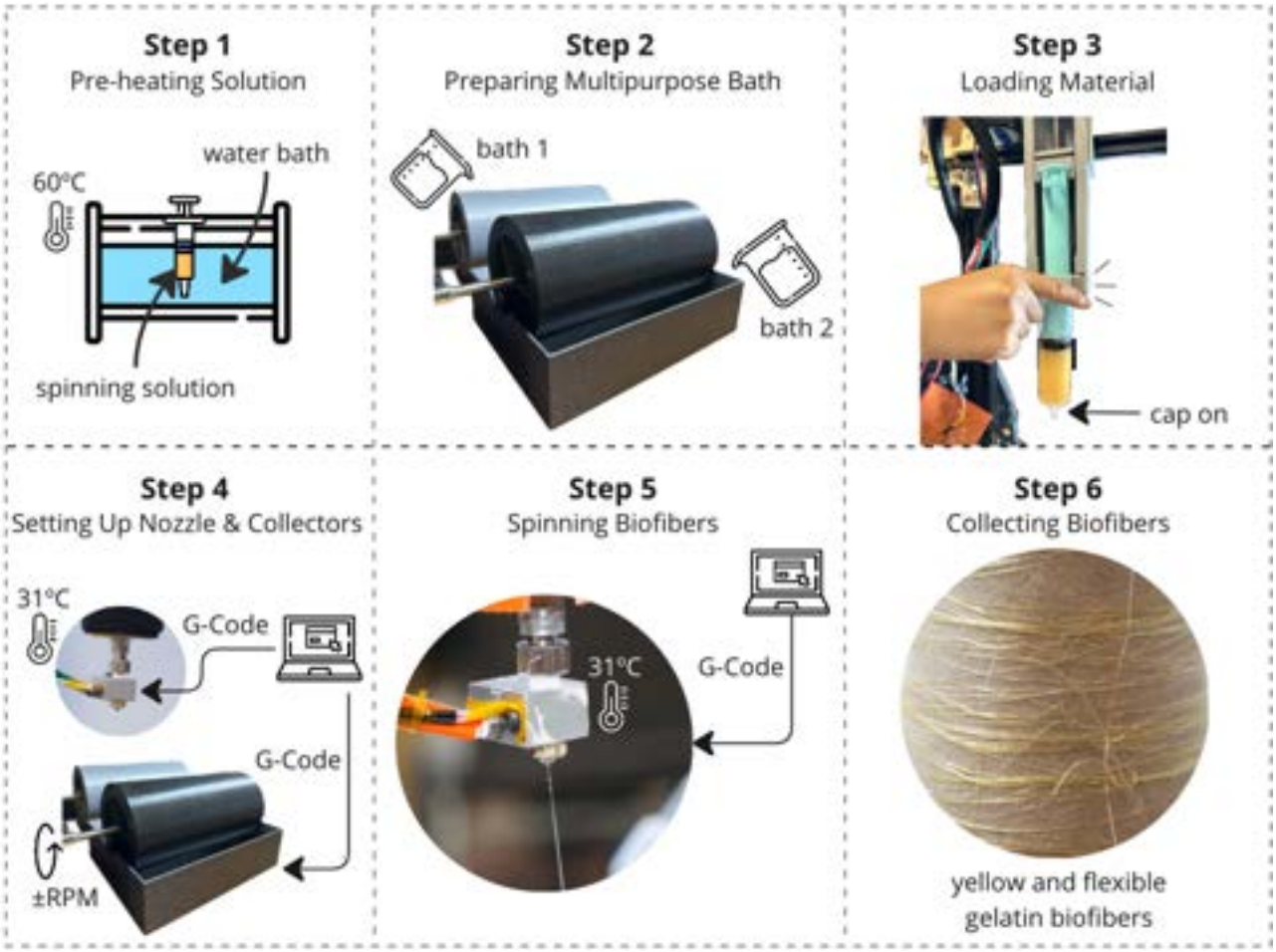

Figure 5: Biofiber spinning machine walkthrough to make yellow and flexible gelatin biofibers.

3.2.5 Step 5: Spinning Biofibers. Once the collectors are in motion, we send the following G-code commands to home and zero the X-axis; set the machine and the extruder into relative movement mode; and reset the extrusion distances to zero:

```
G28     ; Home and zero the X-axis
G91     ; Enable relative mode for X-axis
M83     ; Set extruder to relative mode
G92 E0  ; Reset extrusion distances
```

Next, we compute a spinning command with our calculator spreadsheet[9] by inputting the following parameters: the amount of material to be extruded (0.1 mm); X-axis movement distance (2 mm); extrusion speed (0.2 mm/min); and X-axis speed (4 mm/min). We send the generated spinning command, , to the machine and follow a draw-down process (Figure 8) to pull the material from the nozzle onto the first collector. This initiates the spinning of the first biofiber. As the fiber passes through the first bath, then attach it to the second collector. This causes the fiber to pass through the second bath, gaining a coating that provides the fiber flexibility and color. We then repeatedly send the spinning command to continue biofiber spinning through the length of the X-axis.

3.2.6 Step 6: Collecting the Biofibers. Once the biofibers are produced, we either remove the last collector by unscrewing the shaft coupler and sliding the latch mechanism open. Alternatively, the basins can be removed and the biofibers left to dry on the machine. After drying, the biofibers are wound onto a bobbin to be integrated into textiles using different techniques such as weaving and knitting. Refer to Section 6 for example applications. While this walkthrough gives an overview of making gelatin biofibers with our machine, it is important to note that it only offers a glimpse into what is possible with fiber spinning. In the next section (Section 4), we provide a detailed description of what is involved in fiber spinning and various aspects we considered before beginning the fiber production process and in our machine's design. We then offer various material explorations with our machine in Section 5.

4 FIBER WET SPINNING CONSIDERATIONS

This section presents each stage of fiber dry-jet wet spinning (process captured in Figure 6) and explains the rationale behind our

[9] https://github.com/utilityresearchlab/desktop-biofibers-spinning/

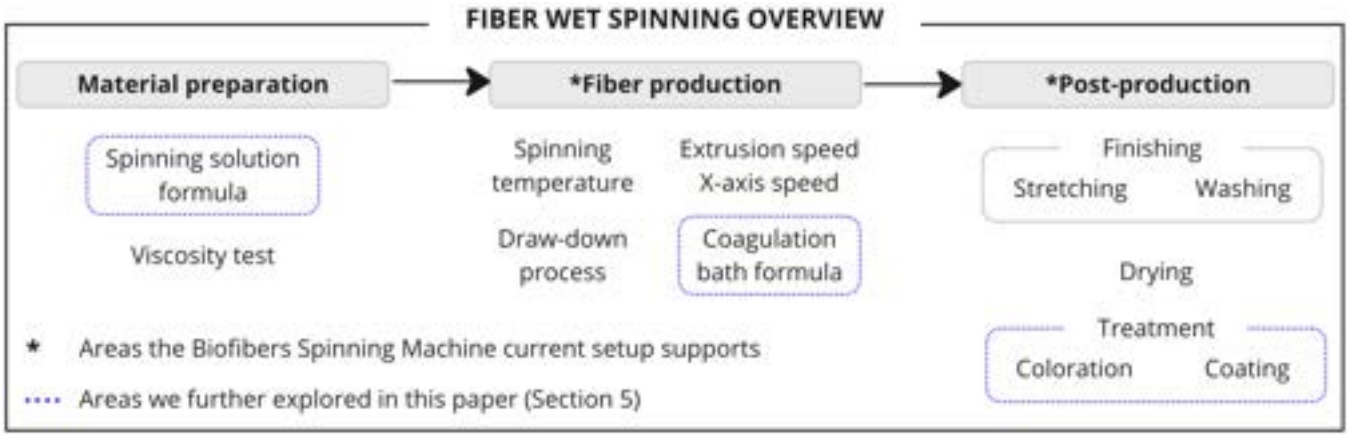

Figure 6: Overview of fiber wet spinning; we marked the steps supported by our machine and what we further explored in this paper.

own design and material approach. We also describe associated experiments that we performed at ITA and how they were carried out with our Desktop Biofibers Spinning Machine. The goal of this section is to offer other HCI researchers and designers an understanding of what is involved in the fiber spinning process as well as support their potential exploration in fiber spinning.

As shown in Figure 6, making fibers through wet spinning requires an initial spinning solution, often referred to as *spinning dope*. To obtain strong and flexible fibers, the formulation of the spinning dope must consider the length of polymer chains and their alignment and distribution during the spinning process. In the realm of gelatin-based spinning solutions, materials science researchers have proposed formulations that often use expensive chemicals (e.g., crosslinkers that cost over USD 200 per 50 mg [24]); require a controlled environment (e.g., precise humidity and temperature levels); and are handled with specialized lab equipment (e.g., high-temperature ovens, fume hoods) [7]. Acknowledging that these requirements may not be accessible to HCI researchers and designers, we opted for a formula based on prior research [58, 59] that relies on only three relatively easy-to-find ingredients: gelatin, water, and isopropanol. Furthermore, our own fabrication experience at ITA using lab-scale equipment (e.g., DIENES LabLine), led us to develop methods and tools to make gelatin spinning solutions without specialized equipment.

Spinning Solution Formula: We mix gelatin (12.5 wt%), water (38.9 wt%), and isopropanol (48.6 wt%) (Figure 7), in a heat-resistant container, and place the mixture in an off-the-shelf water bath[10] at 60°C. Across the next 60 minutes, we shake the container for 30 s to 40 s every 5 minutes. This process induces a 2-phase separation known as precipitation due to gelatin chain aggregation and the formation of longer polymer chains. After overnight cooling, we decant the top layer (a mixture primarily consisting of isopropanol with gelatin and water) for reuse and retain our *spinning solution*

[10]Electric Lab Water Bath (2 openings): https://a.co/d/aFHgRin

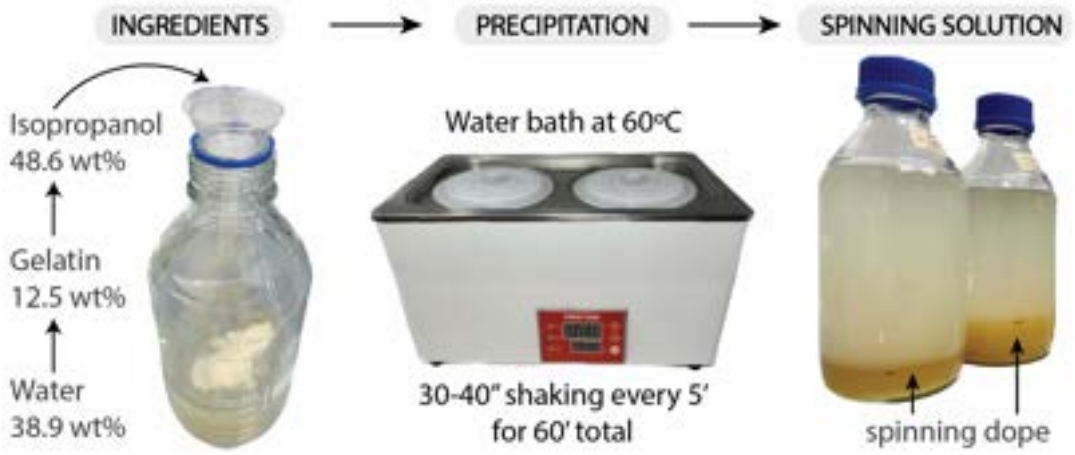

Figure 7: Spinning solution formula and preparation process to obtain spinning solution

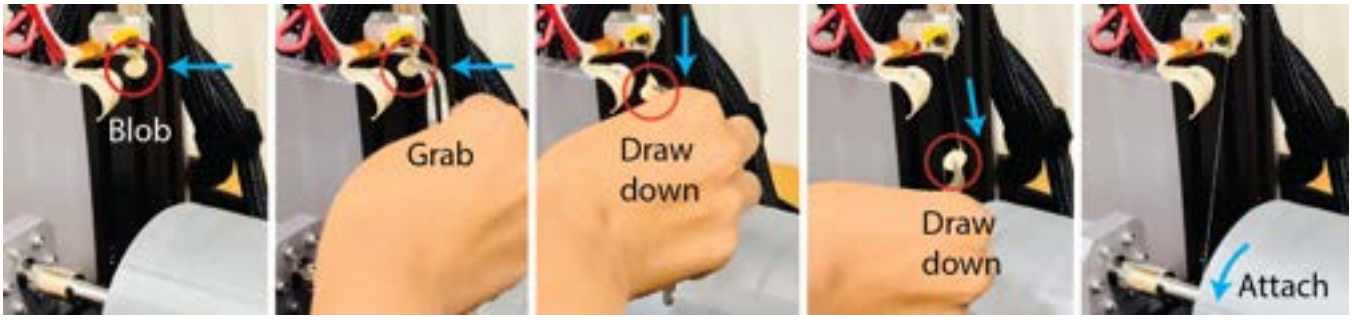

Figure 8: Step-by-step of the draw-down process: blob formation, grab the blob, draw down the blob, and attach the drawn fiber tangentially to the collector.

precipitated at the bottom. We then refrigerate our spinning solution and have found that it can last for more than a year, supporting material experimentation. s

Viscosity Test: Upon learning that the optimal viscosity for the DIENES LabLine at ITA is between 10 Pa to 12 Pa, we conducted experiments with various polymeric concentrations (5 wt%, 7.5 wt%, 10 wt%, and 12.5 wt%) at temperatures ranging from 27 °C to 60 °C, covering temperatures below and above gelatin's melting point [22]. These experiments involved measuring viscosity with a rheometer and establishing a correlation with the gelling temperature, commonly referred to as the "sweet spot" [22]. We found that at 35 °C, the viscosity remains unaffected by shear rate. While at 27 °C, the solution is more viscous but gels quickly. Based on these results, our "sweet spot" is a spinning solution with 10 wt% or 12.5 wt% polymeric concentration spun at a temperature between 30 °C to 40 °C. Consequently, we adjusted the original formula [58, 59] to increase the polymeric concentration to 12.5 wt%. This adjustment allowed us to replace the more expensive pure gelatin used in previous research ($54 per 110 g [2]) with a locally-sourced commercial 300-bloom gelatin[11] ($4.60 per 100g). Our experiments, including tests run on the ITA RWTH Aachen's DIENES LabLine machine, demonstrated that the 12.5 wt% solution was able to compensate for the potential lower purity of the gelatin which could have affected the length of the polymeric chains.

Spinning Temperature: Synthetic fibers like acrylics can be spun at room temperature, while biobased materials like gelatin and agar-agar typically require additional heat for melting. Due to the higher polymeric concentration in our spinning solution, we had to modify the ITA setup to include additional heating, which involved adding a heating wire around the nozzle and insulating the contact area with the coagulation bath using a foamy material (Figure 2b). We achieved the best results spinning pure gelatin fibers by heating the nozzle to 31 °C when the room temperature was about 22 °C and setting up the syringe wrap to 52 °C. This experience highlighted the essential role of a heated nozzle in spinning biobased materials, which we carried over to the design of our machine.

Extrusion Speed: In our experiments at ITA, the DIENES LabLine machine constrained the spinning speed to 2.5 to 3 RPM, varied in the Z-axis only, using a gear pump with a flow rate of 0.6 ml/RPM, and a nozzle with 150 holes of 120 µm diameter. Our machine, on the other hand, uses an X-axis carriage feed rate of 0.01 mm/min and an X-axis movement of 4 mm, regardless of the amount to extrude. The speed of the collector is 3.9 RPM. In our experiments, we started by extruding 0.05 mm of material at a time. After we found the "sweet spot" for extrusion, we sent a G-code command in the host controller software to extrude 0.1 mm of material continuously across the 180 mm length of the collector.

Draw-Down Process (Drawing): Drawing is a technique that mechanically pulls a blob of material (mass of spinning dope accumulated around the nozzle) while it is still in a semi-molten state to align and orient the polymer chains along the length of a fiber. In a wet spinning process, drawing happens inside the coagulation bath, however, in a dry-jet wet spinning process as with our machine, the fiber is extruded in an air gap before reaching the coagulation bath (Figure 4). As shown in Figure 8, we wait until a blob (approximately 3 mm in diameter) forms on the tip of the heated nozzle. Then, with 90-degree tweezers, we grab the blob and draw it down towards the first collector which is already in movement, to tangentially attach the fiber to it. If unsuccessful, we restart using the same blob, which means tapping the blob on the tip of the nozzle until we see a fiber forming while drawing it down.

Coagulation Bath: The coagulation bath is the liquid environment that immerses the extruded spinning solution. It triggers a process where the solvent in the spinning solution diffuses into the bath, causing the polymer to precipitate and solidify into fibers. At ITA, we obtained the best results using 40% isopropanol only near the nozzle to allow extrusion without clogging, followed by immersion in isopropanol (80-90% concentration). The complexity of a dual bath setup with an immersed nozzle led us to use dry-jet wet spinning instead. In our machine, the newly spun fiber passes through an air gap before the coagulation bath, simplifying the previous process by avoiding liquid concentration differences (Figure 4). We obtained the most flexible biofibers using 5 wt% glycerin in isopropanol (80% concentration) coagulation bath. Refer to Section 5 for more experiments in the coagulation bath.

Stretching and Washing (Finishing): For many polymers, washing in water removes impurities from the spinning process, neutralizing any chemical treatments applied during spinning. Since water is a solvent of gelatin, it will dissolve our biofibers. As a result, we skipped washing from our workflow until we found a more

[11] Meinmetzger: https://www.meinmetzger.de/index.php/aspik-eins-a-qualitaet-300-bloom.html

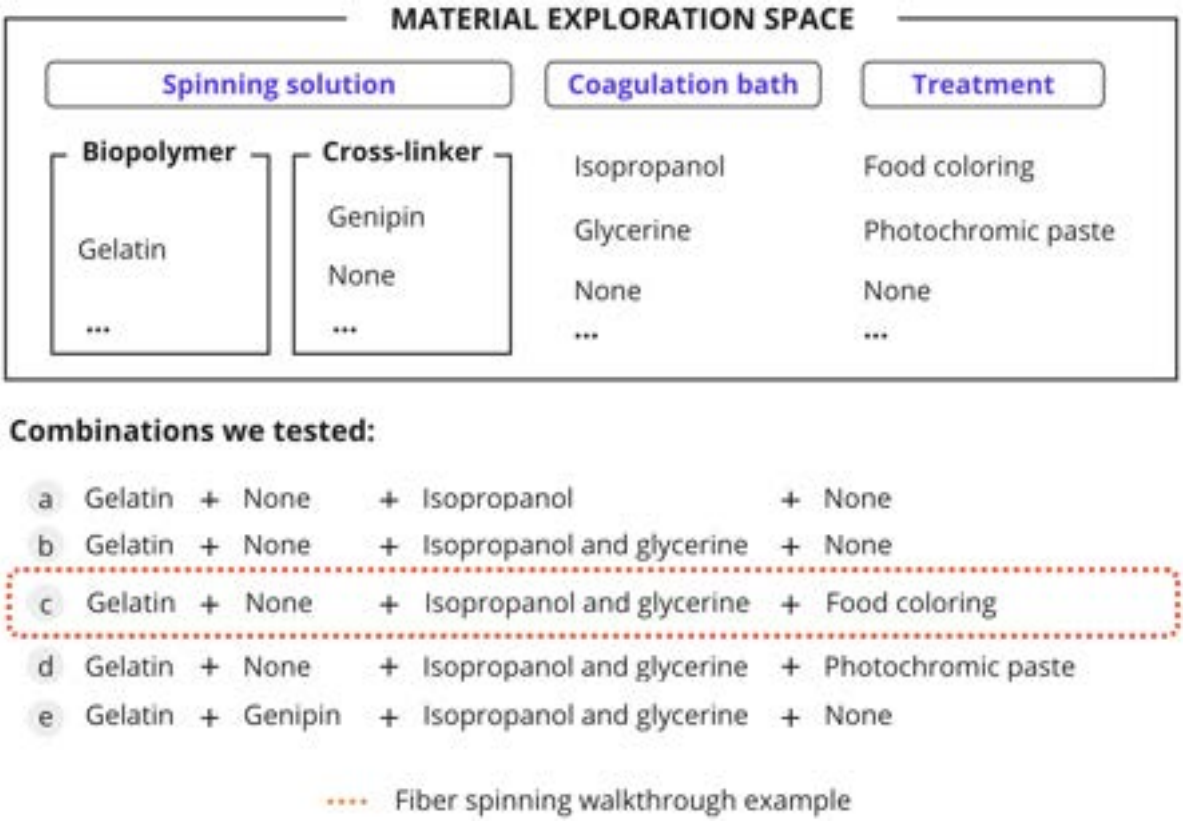

Figure 9: Material exploration space for fiber wet spinning, the various material formulations that we tested (a-e), which includes the material formulation used in the fiber spinning walkthrough (c).

suitable washing formula. Fibers like polyester, or nylon, benefit from a stretching process because it improves the orientation of the polymer chains along the fiber axis. At ITA, this process was achieved by rotating the godet rolls at different speeds in the washing baths. However, we found that gelatin fibers become weaker the more we stretch them when they are in a semi-molten state. We thus skipped stretching from our workflow as well.

Drying: Various methods can be used to remove excess water from the cured biofibers, such as air drying, hot rollers, or ovens. The temperature and humidity levels during drying can affect the fiber's structure and properties. In our case, we have chosen to let the fibers dry at room temperature since our main objective in this paper is to explore an accessible fiber design space that can be replicated without additional equipment specialized equipment.

Treatment: In a conventional fiber wet-spinning process, the fibers are first dried and subsequently subjected to further treatments, such as coloration or coatings. We designed our machine with flexibility in mind, thus the baths are multipurpose and can be used for treatment. We present our treatment experiments performed in the second bath in Section 5.

This section offers an overview of fiber wet spinning (Figure 6) of this process and all the various aspects involved such as spinning solution formula, viscosity, spinning temperature, extrusion speed and feed rates, draw-down, coagulation bath, finishing (stretching and washing), drying, and treatment, which collectively contribute to the production of fibers. We aimed to offer other HCI designers and researchers a deep insight into the fiber wet spinning process, hoping this can motivate and facilitate their material and design explorations within this new fiber design space.

5 MATERIAL EXPLORATION USING THE BIOFIBERS SPINNING MACHINE

The primary motivation for our material exploration is to customize biofibers at different stages of the fiber spinning process using the Desktop Biofibers Spinning Machine. In this paper, our material exploration focused on customizing gelatin fibers by altering the spinning solution formula (material preparation), adjusting the fiber diameter by fine-tuning the collectors' speed using our machine (fiber production), and modifying the formula of the multipurpose baths during fiber production and post-production. The visual representation in Figure 9 illustrates the wide range of possibilities and potential combinations that can be tested, all stemming from using a single biopolymer as the starting point—in our case, gelatin. The text highlighted in purple within the material exploration space indicates the areas we examine in this section and the listed material combinations (Figure 9a-e) are the ones we have tested and summarized their outcomes.

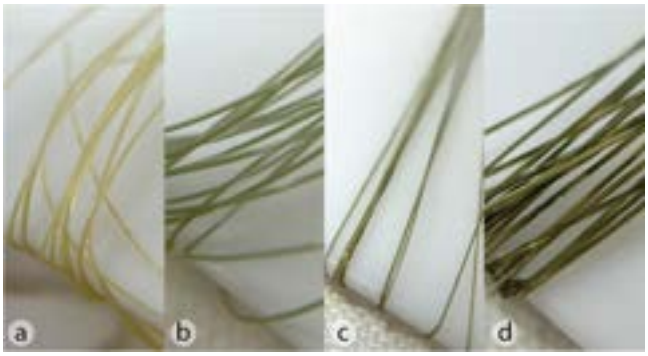

Figure 10: (a-d) Gelatin biofibers change color from light to dark green as the genipin content in its material formula increases in the following increments: (a) no genipin; (b) 0.12 wt% genipin; (c) 0.18 wt% genipin; (d) 0.24 wt% genipin.

Through customization, we achieved a range of qualities in our gelatin fibers: (1) altering the spinning solution led to variations in strength, flexibility, and color-change properties; (2) adjusting the collector's speed allowed us to explore a wide range of fiber diameters; (3) adjusting the coagulation bath formula had an impact on the fibers' flexibility and elasticity; and (4) implementing treatment processes enabled us to introduce color into the fibers and facilitated color-change effects when coating the fibers with a photochromic paste.

5.1 Adjusting Spinning Solutions for Tuning Color and Strength

Our initial spinning solution (Figure 9a) contained gelatin, water, and isopropanol. To enhance the strength and flexibility of the resulting fibers (Figure 10a), we added a biobased crosslinker to the spinning solution formula and a plasticizer to the coagulation bath. Conventional crosslinkers used in previous research are costly, alter gelatin's biodegradability, and require specialized equipment and controlled environments due to potential toxicity concerns [8]. Seeking an alternative, we explored genipin—a natural crosslinker derived from the gardenia fruit (Gardenia jasminoides) [49].

Genipin is known for its biocompatibility and safety in biomedical and food-related applications [42]. In our use, genipin not only improved the mechanical properties of the gelatin fibers but also introduced color-changing effects transforming the natural color of gelatin fibers (Figure 10a) into various green tonalities (Figure 10b-d). Employing concentrations of 0.12 wt% (Figure 10b), 0.18 wt% (Figure 10c), and 0.24 wt% (Figure 10d) in 10 mL of the spinning dope respectively, genipin significantly increased the overall strength of the fibers in both dry and wet states (Figure 11). Adjustments in extrusion speed on our machine accommodated the increased viscosity of the spinning solution with genipin.

Dry crosslinked gelatin fibers had a tensile strength of approximately 71 MPa—the highest among all samples and conditions. Furthermore, through tactile observation, we noticed that genipin increased the flexibility of the biofibers. Gelatin biofibers, regardless of the concentration of genipin, retained their flexibility even after being spun and stored at room temperature for over 2 months.

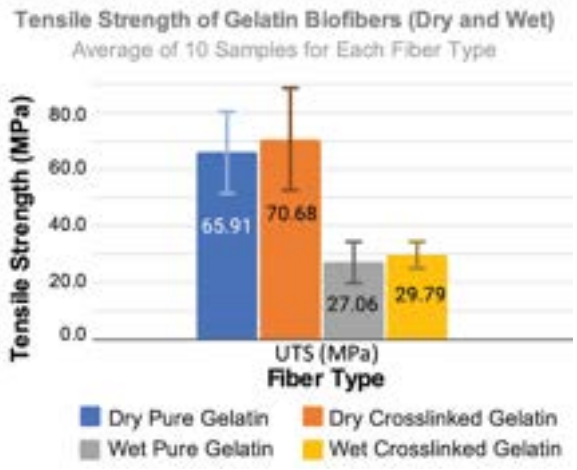

Figure 11: Tensile strength of gelatin biofibers—pure and crosslinked—in both dry and wet conditions. Gelatin biofibers crosslinked with genipin were stronger in comparison to pure gelatin biofibers when dry and wet.

Inspired by these positive outcomes, we delved into further enhancing flexibility through various coagulation bath formulas, as detailed in Section 5.3.

5.2 Fine-Tuning Biofiber Diameter through Collector Speed

After extensive experimentation with various spinning solution formulations, we found a method to adjust the diameter of biofibers—by controlling our machine's collector speed. We systematically modified the first collector's speed from 2.3 RPM to 3.9 RPM during our tests, while keeping the extruded amount and extrusion speed constant. The resulting diameters, shown in Figure 12a, ranged from 0.03 mm to 0.20 mm, with a clear trend of decreasing diameter with higher collector speed. To maintain a consistent fiber diameter at the same collector speed across different spinning solutions, we

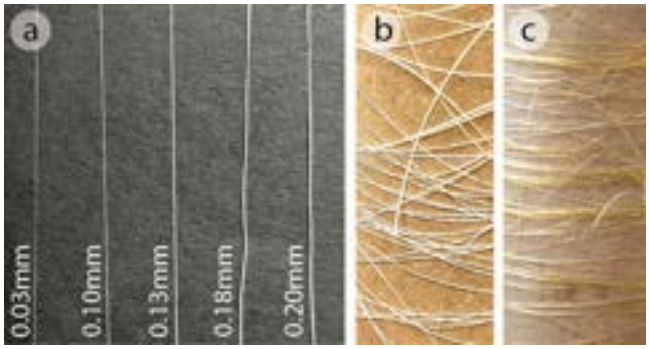

Figure 12: Material Explorations: (a) adjusting fiber diameter (thickness) via collector speed, (b) natural color of biofibers, (c) and yellow biofibers resulting from post-production food-coloring dye.

adjust the extrusion temperature based on the specific solution's viscosity. For instance, with the gelatin and genipin spinning solution (Figure 9e), we increase the extrusion temperature due to its higher viscosity compared to pure gelatin. Importantly, the diameter of the fiber affects its properties. The thinnest gelatin fibers (0.03 mm) can easily dissolve with moisture from hands, while the thickest ones (0.20 mm) are more resilient and feel stiffer to the touch. The medium-thickness fibers (0.10 mm to 0.13 mm) are notably softer, more flexible, and easier to handle. Consequently, we primarily used biofibers of this diameter for our example applications in Section 6.

5.3 Adjusting Coagulation Bath for Enhanced Flexibility and Elasticity

In our initial coagulation bath formulation (Figure 9a), we used off-the-shelf isopropanol (90% concentration) to precipitate pure gelatin biofibers. To enhance the flexibility of the resulting fibers, we experimented by introducing vegetable glycerine (Figure 9b) as a plasticizer in various drying stages. For instance, we mixed vegetable glycerine (5% concentration) with isopropanol (85% concentration) and added this mixture to the second multipurpose bath. By varying the drying time before exposing the fibers to the second bath, we tested different immersion timings: immediately after leaving the coagulation bath while still wet; after 15 minutes while semi-dry; and after 30 minutes when fully dry. Immersing the fibers immediately (fully wet) resulted in elastic but less robust biofibers. Waiting 30 minutes for drying before immersion resulted in less malleable biofibers, likely due to insufficient moisture for glycerine bonding. Submerging semi-dry biofibers (after 15 minutes) yielded the best results in terms of tactile flexibility.

We also evaluated the impact of the first coagulation bath of 90% isopropanol concentration on the biofibers' flexibility. We removed this first bath from the process and precipitated the biofibers directly into the second bath of isopropanol (85% concentration) and glycerine (5% concentration). The produced biofibers exhibited similar tactile qualities and flexibility as those produced using the two-bath setup. Thus, for simplicity and consistent results, we opted to use the formulation containing isopropanol and glycerine as our first coagulation bath. We also explored the elasticity of the biofibers by submerging them into a *non-solvent* solution after they were completely dried. In this context, a non-solvent solution refers to a solution that doesn't chemically interact with or disintegrate the biofibers. For example, we wet crosslinked gelatin fibers in a 70% isopropanol solution, resulting in elastic fibers while wet and a permanent color change due to genipin crosslinking. This unique quality is showcased in one of our example applications in Section 6.

5.4 Implementing Treatment Processes for Color and Coatings

Building on insights from our prior experiments, we made isopropanol (85% concentration) and glycerine (5% concentration) our preferred first coagulation bath and used the second one for treatment experiments involving the formulation of color solutions and coating pastes. For color, we diluted 3-4 drops of yellow food coloring in off-the-shelf isopropanol (85% concentration), supplemented with glycerine (5% concentration). After thoroughly stirring the mixture in a separate container to ensure even color dispersion, we poured it into the second multipurpose bath. This method yielded flexible, yellow-colored pure gelatin fibers, as depicted in (Figure 12c).

Figure 13: Biofibers coated with a photochromic paste.

Shifting our focus to coatings, we explored the viability of applying a photochromic[12] paste (UV-sensitive) onto dry biofibers (Figure 13). Our findings show successful adhesion of the paste to the fiber surface, transforming basic gelatin fibers into UV-sensitive ones. Because photochromic pigments are non-biobased, we limited our exploration into this space. However, we believe this customization to create sensors with biobased alternatives is an opportunity for future work.

6 EXAMPLE APPLICATIONS

To demonstrate the incorporation of biofibers into textiles, this section features applications in smart and shape-changing textiles for HCI. Our examples use dissolving as a feature, serving as a trigger for interaction while promoting sustainability through material recycling or reharvesting.

In our initial experiments, we attempted integration through plying, braiding, knitting, and crocheting, but these processes imposed forces that the gelatin biofibers couldn't withstand. Specifically, the high curvature and tensions of knitting and crochet caused fiber breakage. Hand weaving emerged as a suitable integration method that met the material requirements of gelatin biofibers, leveraging our familiarity with the process.

Unlike other techniques, hand weaving doesn't subject inserted weft yarns to tension during insertion, minimizing curving stress on the materials. Additionally, weaving allows for the integration of multiple materials within the same textile structure. By incorporating gelatin biofibers into woven assemblies, we explored how the interplay of diverse materials generates various interactive effects. The swatches presented in this section were designed using AdaCAD [14, 21], an open-source web-based weaving software.

6.1 Dissolving for Recycling and Reharvesting

Smart textiles pose a significant recycling challenge as they combine various materials (e.g., conductors, electronics) within a single fabric that are difficult to separate. For example, single-use electronic sensors (e.g., RFID tags in clothing) can significantly contribute to electronic waste concerns. We integrated gelatin biofibers into textile sensors to enable convenient recycling and reharvesting through dissolution [33] and disassembly [65]. To illustrate this

[12]Photochromic Pigment (Pink-Blue): https://www.amazon.com/dp/B0735BQQ7P

Figure 14: Woven textile sensors with biofibers integrated into the cloth: a. moisture sensor and b. pressure sensor.

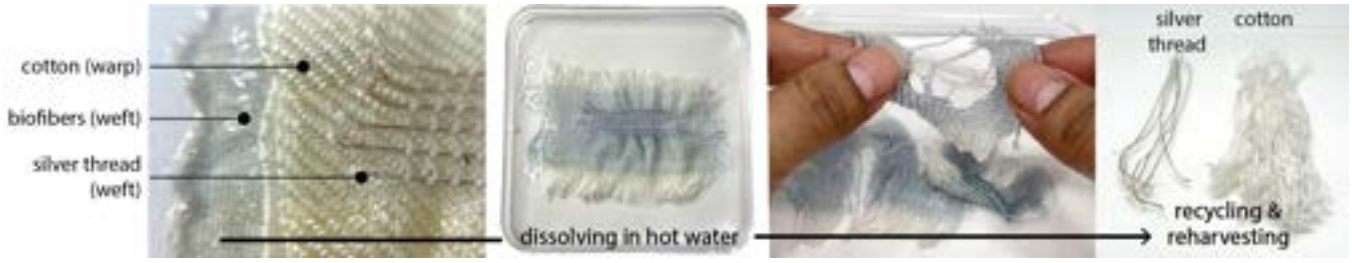

Figure 15: Dissolving biofibers in our woven moisture sensor enables reharvesting of conductive and non-conductive threads at the end of the sensor's life. This process also applies to our pressure sensor. The biofibers' change in color is due to the result of genipin (a crosslinker) in its composition.

concept, we developed two single-use woven sensors: a moisture sensor (Figure 14a) and a pressure sensor (Figure 14b).

In the moisture sensor, wetting the gelatin biofibers creates an electrical pathway between two embedded silver threads. At the same time, it begins to dissolve the biofibers. In the force sensor, the dimensionality of its "waffle" woven structure separates the conductive yarns. When pressure is applied, the traces touch and shorten the electrical path leading to a lower resistance. When the sensors are no longer needed, they can be submerged in hot water to dissolve out the biofibers. Dissolving the biofibers loosens the structure, enabling the conductive yarns to be easily reharvested (Figure 15).

This approach enables us to reuse the conductive yarn and recycle the cotton yarn when the sensor reaches its end of life. While these tests are small-scale and simple, they point to the potential sustainability impact of biofibers for dissolvable smart textiles, and more broadly single-use electronics. In future work, we would like to examine increasing the strength of our biofibers by further tuning the spinning solution formula. Higher strength would facilitate including these fibers into the warp during weaving, eliminating, for instance, our use of cotton.

6.2 Dissolving and Swelling to Trigger Interaction

Drawing inspiration from prior projects like bioLogic [66] where a cloth reacts to external stimulus, we contemplated how the unique dissolving properties of biofibers coupled with an appropriate weave structure could facilitate shape-changing interactions. We

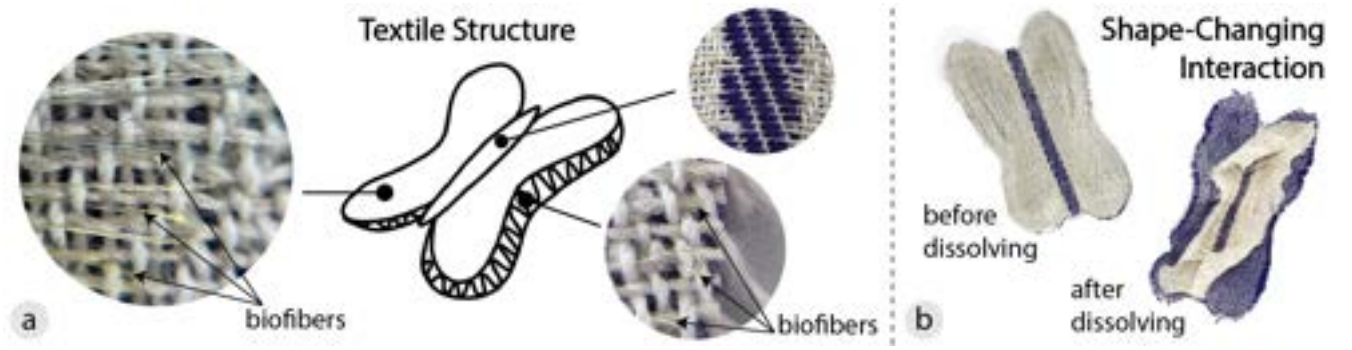

Figure 16: Dissolving as an interaction: (a) woven butterfly that (b) unravels its wings when wet with water.

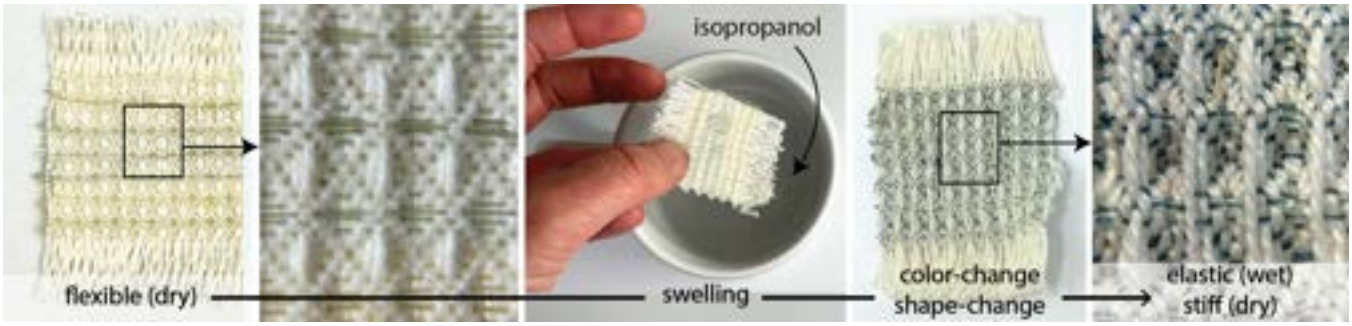

Figure 17: Swelling as an interaction: a woven structure that experiences color- and shape-change due to swelling when exposed to isopropanol.

conceptualized a butterfly-shaped swatch with a 2-layer weave structure (Figure 16a). The top layer of the cloth is made using a readily available moisture-reactive elastic yarn. The bottom layer uses a brightly colored synthetic yarn with no elastic properties. The two layers are bound together in the middle (along the body of the butterfly). They are also bound by gelatin biofibers woven around the edges of the wings.

The premise is that when the swatch becomes moist, the biofibers along its edges will dissolve. This in turn causes the layered wings to separate and the elastic material to contract along the weft direction, enabling the butterfly's wings to unfurl (Figure 16b).

While dissolving represents a distinctive feature of biofibers, we have observed varying degrees of this property. For instance, when we moisten the gelatin biofibers with a solution consisting of 70% isopropanol and 30% water, the fibers don't dissolve but instead swell enabling stretch.

We explored a controlled-swelling interaction in which biofibers are constrained to twill and crepe woven structures. Both of these structures are known to take on interesting surface textures when produced with elastic yarns. When we dampen the swatch and let the exposed biofibers absorb the solution, the swatch transitions from an inelastic state to an elastic one (Figure 17). Importantly, this swelling change is reversible—once the biofibers dry out, the swatch reverts to its original state. We envision this behavior being useful in applications such as reactive clothing and weather-responsive structures. For example, a garment could vent open to cool an individual as they exercise (as in bioLogic [66]). Similarly, a fabric awning could be designed with responsive slits such that some light can pass through in dry sunny weather, while rain causes the slits to close, protecting individuals from any downpour.

6.3 "Etching" Flexible Circuits

We explored using the biofibers to create fabrics that can be "etched" similar to the conductive traces on a printed circuit board (Figure 18). Specifically, the top layer of the cloth is created with gelatin biofiber and the bottom with a conductive yarn. Using a 2-layer structure, these layers become isolated and layered on top of each other. Because the biofiber dissolves, one may "etch" a trace in the fabric by dotting it with hot water, exposing the conductive cloth on the bottom layer.

This application could potentially enable on-body etching of flexible surfaces when prototyping a circuit in a cloth. Often, designers are unsure which areas of cloth would be best to have an electrical connection or soldering. Using biofibers to make a soluble top layer in cloth could facilitate enabling on-body etching of tracings and support the prototyping process of smart textile innovators. This approach could help minimize the amount of waste generated during the trial-and-error process.

6.4 Summary

These applications are proof-of-concepts demonstrating what we can do with gelatin biofibers that are produced with our machine. With continued development on both the machine and the material spinning solutions, we envision a much broader design space. For instance, solutions that produce stronger biofibers (not necessarily with gelatin) could unlock a wider array of textile integration techniques (e.g., knitting, crocheting). While our demonstrated applications are small, it is worth noting the fine structures in which these biofibers can be integrated and the interesting aesthetics that they provide to the cloth in luster, color, and texture.

With increasing smart textile development happening at the level of yarn [6, 12, 13, 61], we envision this machine being integrated into conventional fabrication workflows to develop customized biofibers. These biofibers can act as a support material for different textile structures or to leverage cloth structure to support sensing. Biofibers can also enable potential sustainable approaches to emerging applications, including "single-use smart textiles", which we anticipate will be a growing waste stream as companies integrate sensing and actuation into fashion products.

7 DISCUSSION

Our journey in fiber spinning has challenged our prior knowledge of textiles and biodesign. Despite the steep learning curve, the experience we gained at ITA and while developing the Desktop Biofibers Spinning Machine has yielded valuable insights worth sharing. In this section, we discuss the lessons we learned from working across disciplines, the unexpected aesthetics achieved when integrating biofibers into cloth, and our approach toward sustainable smart textile design.

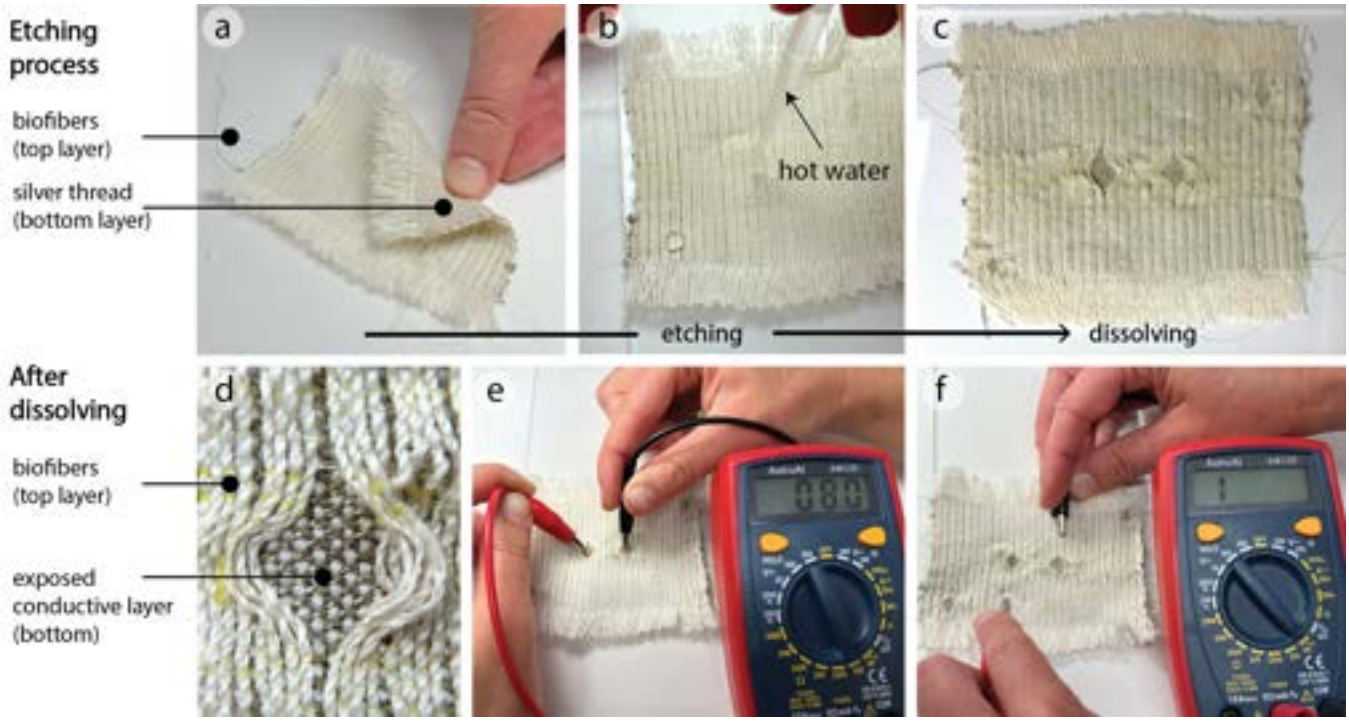

Figure 18: Example application for etching flexible woven circuits. The etching process consists of (a) a 2-layer cloth woven with the biofibers on the weft of the top layer and stainless steel on the back; (b) drops of hot water are selectively added to the top layer of the cloth; (c) areas in contact with the water are dissolved; (d) the bottom conductive layer becomes exposed conductive after dissolving; (e) testing the dissolved and exposed area shows that it is conductive; (f) testing undissolved areas are not conductive.

7.1 Lessons Learned From Working Across Disciplines

Despite our prior experience with biodesign applied in HCI contexts, the space of fiber spinning with biobased materials felt unfamiliar. Collaborating with ITA researchers revealed challenges in establishing a common vocabulary, and our initial assumptions regarding the universal spinnability of biobased liquid solutions turned out to be overly optimistic. From our experience, we offer several key lessons for HCI designers and researchers interested in further exploring this fiber design space.

Each polymer is its own world. While materials scientists in fiber spinning inherently understand the importance of the spinnable solution at the polymeric level, our learning curve highlights the need for a nuanced grasp of this knowledge. Recognizing the specificity of creating spinnable solutions for different polymers or biopolymers is crucial—what works for gelatin (protein) may not apply to agar-agar (polysaccharide). Even within the same polymer category, variations in molecular structure demand distinct solvents, concentrations, and processing conditions for spinning solutions. Although delving into intricate materials science details may seem overwhelming, possessing a fundamental understanding, as emphasized in Section 4, can greatly facilitate more effective interdisciplinary collaboration.

Where to seek for support. Initially, our assumption that consulting a materials scientist would provide the right mix of ingredients for our gelatin spinning solution proved overly simplistic. We realized that knowledge within the materials science field is highly specialized; expertise in one area, such as acrylic fibers, does not necessarily equate to proficiency in another, like sugar fibers. The key takeaway is to connect with materials scientists who specialize in the specific material relevant to your work, be it protein, carbohydrate, sugar, etc., rather than solely focusing on fiber expertise. Furthermore, our experience emphasizes the significance of actively seeking feedback and ideas beyond our immediate domain. Engaging with experts outside the realm of fiber spinning brought fresh inspiration and ideas. For instance, in a conversation with a chemist specializing in bio-compatible materials for tattoos, we learned about genipin as a natural crosslinker derived from a fruit. This led us to explore genipin as a way to increase the strength of our gelatin biofibers.

Prototyping at different scales. Our experience at ITA highlighted a significant contrast in prototyping workflows between our domain and lab-scale environments. While our skills in hacking and rapid prototyping were instrumental, we recognized the detailed planning, precise engineering, and contingency plans required in large-scale machine modification. Understanding the workflow disparity made us think that it stems from the cost and size of the equipment employed. This realization prompted reflection on the

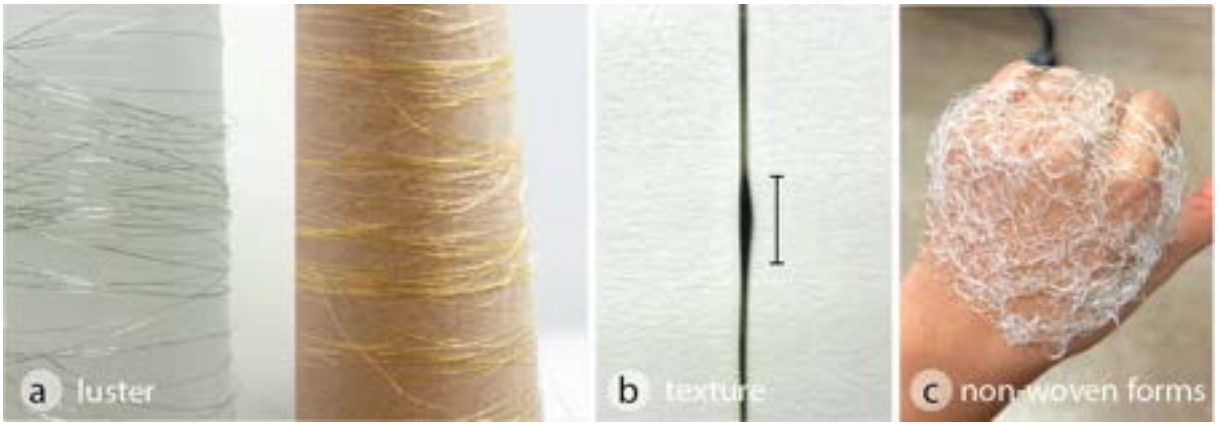

Figure 19: Qualities and forms of biofibers to further explore: (a) luster, (b) variable texture, and (c) non-woven structures.

existing gap between fiber spinning in a materials science lab scale and an HCI lab, bringing awareness to the potential intimidation HCI designers and researchers might face exploring new materials outside the HCI space. While our prototyping skills proved to be useful in modifying ITA's machinery and became pivotal in our independent development efforts, it also highlighted the interdisciplinary contributions HCI researchers can make in bridging the gap between materials science and practical applications in HCI.

7.2 The Aesthetics of Biofibers

We would like to bring attention to the aesthetics of the biofibers that we have produced. When compared with other materials, gelatin biofibers closely resemble synthetic nylon monofilament (e.g., fishing line). Many textile artists have leveraged nylon monofilament to create iridescent forms and structures [25, 38]. We believe that continued material development with a focus on strength has the potential to make biofibers a sustainable material alternative that could be considered by fiber artists. Some other aesthetic qualities, like luster (i.e., shine) and smoothness were intrinsic to the material and unpredictably arose during production. We find these unexpected qualities to be a way in which the material communicates its potential, a concept often referred to when discussing material agency [29].

The gelatin biofibers show a high degree of luster (Figure 19a), which became more apparent when integrated into cloth (e.g., Figure 17). Surprisingly, we did not observe a correlation between color and level of shine, meaning that regardless of the biofiber's color, the level of shine appeared to be the same. However, we believe it is worth conducting a systematic test to confirm this. In addition, it is worth exploring the shape and texture (Figure 19b) of the biofibers, particularly along their cross-section, as this has been associated with changes in the luster of other fibers [60].

We noticed that color gradients emerged naturally with the different additives and treatments used in biofiber production (e.g., Figure 13a), which created visually pleasing effects in cloth (Figure 17). Even "failed" biofiber samples that did not absorb as much color as we expected contributed to the aesthetics of the swatches we made by introducing a subtle tonality. Additionally, we observed a transformation in texture when biofibers were exposed to a non-solvent like isopropanol, causing them to become rough and stiff after they dried. This alteration in texture could be further explored, perhaps by experimenting with different concentrations of non-solvents being applied to the cloth. Lastly, we found particularly interesting the biofibers' ability to swell and maintain a shape after they dried, especially when constrained by a woven structure (see Figure 17). While we have only explored one degree of swelling in one of our examples, we see the potential for this quality to be used for aesthetics in applications where a shape-change is desired.

7.3 Towards Sustainable Smart Textile Design

In discussing sustainable smart textile design, we focus on two key phases within the electronic textile life cycle. Firstly, we aim to broaden the array of raw materials by facilitating the fabrication of biofibers. Secondly, we propose an alternative end-of-life strategy for electronic textiles through the dissolution of biofibers, promoting easy disassembly and the reuse of electronic components. Our machine is specifically designed to facilitate the prototyping and exploration of biofibers, with gelatin biofibers serving as an illustrative example of the potential within this domain. The unique capability of gelatin biofibers to dissolve in hot water holds promise for recycling smart textiles, yet it also poses limitations in certain consumer-level applications due to sensitivity to moisture and high temperatures. This contrast highlights the the importance of investigating fibers derived from other biobased materials that may exhibit greater resilience. We perceive our low-cost, open-source machine as a crucial tool to examine this space, empowering smart textile innovators to move towards greater sustainability in smart textile design.

8 LIMITATIONS AND FUTURE WORK

Developing new materials requires a significant investment of time. Our research exploring various material formulations and assessing specific qualities of gelatin biofibers suitable for smart textiles spanned over two years. We experienced a substantial learning curve in the realm of fiber spinning that prompted a recalibration

of our material exploration scope. We initially envisioned experimentation with various biobased spinning solutions, but practical constraints led us to focus exclusively on gelatin for this work. Although this focused approach offered valuable insights, it does present a limitation. At the same time, it's crucial to note that our machine is designed to handle a range of biobased spinning solutions, especially those requiring heat during the spinning process. This opens up opportunities to explore other biobased materials like agar-agar [4] in future work.

Our goal for creating an open-source machine for desktop biofibers spinning was to enable the prototyping and exploration of biofibers for sustainable smart textile design. In the machine's current iteration, there are several opportunities for future work that we hope the broader community will join us in exploring.

A Streamlined User-Interface. In its current iteration, we control the machine using G-code commands sent through a 3D printing host controller software. While this was sufficient for our material exploration, we recognize the potential barrier this may pose for smart textile innovators eager to engage in immediate material exploration. Developing a custom interface for our machine in close collaboration with smart textile innovators stands as a top priority for future work. We also intend to explore the correlation between different machine parameters and fiber characteristics, as observed with collector speed influencing fiber diameter (Figure 12a). Integrating such high-level fiber specifications into our interface could also streamline exploration of the fiber design space.

Enhancing Fiber Customization. Our machine currently requires manual adjustment to change the air-gap distance between the nozzle and the collector, which can slow down a prototyping workflow and potentially limit biofiber customizability. By incorporating an adjustable Z-axis in the next iteration of our machine design, we can speed up prototyping and enable fine-tuning of the air-gap distance—a critical step for materials that benefit from precuring processes. A movable Z-axis would also enable a transition from dry-jet wet spinning to wet spinning, simply by lowering the Z-axis and immersing the nozzle/spinneret into the coagulation bath. This adaptability is crucial as every polymer's curing process can vary. For example, a literature review in nanomaterials has shown that a range of spinning techniques, including dry-jet wet spinning and wet spinning, have been used to process different protein biobased materials into fibers [10]. Thus, we see the addition of an adjustable Z-axis as valuable asset for material exploration.

Customized Nozzles for Innovative Fiber Design. The opportunity to customize the nozzle with multiple holes or different shapes is another exciting space to explore. This could enable experimentation of fiber-level texture. Currently, our biofibers have a smooth surface, but with customized nozzles, we can envision spinning textured fibers (Figure 19b) that provide enhanced grip when spun into yarns—a challenge often encountered with smooth-surfaced fibers. Additionally, texture customization opens the door to tuning fiber luster. This in turn could lead to variable color reflections along a single biofiber when integrated into textiles, thus eliminating the need for different dyes.

Customized Collectors for Fiber Production. Our machine's ability to add collectors according to user needs opens an opportunity for further exploration in fiber production and post-production processes. For instance, it enables us to subject fibers to various concentrations of washing baths and other treatments using multipurpose baths. Downsizing the collectors and utilizing them as stretching rollers offers a space for exploring biobased fibers that benefit from this process. Furthermore, we see the potential of modifying the collector assemblies to support other fiber production techniques—for example, integrating a metal collector could enable melt electrospinning (as in [52]) of biofibers and support creating custom non-woven forms (Figure 19c).

9 CONCLUSION

This work introduces an open-source machine aimed at exploring biobased fibers and their applications in sustainable smart textile design. Drawing from our hands-on experience with a lab-scale wet spinning machine, we emphasize the significance of prototyping biobased materials at the foundational level of all textiles—fibers. Through our machine development and material exploration we have demonstrated that it is possible to turn sustainable biobased materials into customized biofibers. While this process can be challenging and require specialized knowledge, we see it as an opportunity for HCI researchers and designers to form interdisciplinary collaborations that elucidate the technical aspects of biofiber spinning and unlock its potential for smart textiles applications. Our exploration of biofibers that dissolve also opens up the possibility of making smart textiles that are easy to recycle or repurpose. From a broader context, we see our work as a step towards sustainable smart textile design.

ACKNOWLEDGMENTS

This work is partially supported by the National Science Foundation under Grant #1943109. This material is based upon work supported by the National Science Foundation under Grant #2127309 to the Computing Research Association for the CIFellows 2021 Project.

We are grateful to Simon Kammler, Daniel Wolters, Maximilian Mohr, Stefan Peterek, Dr. Kazim Acatay, and research assistants at the Institut für Textiltechnik (ITA) of RWTH Aachen University for working with us as we explored fiber wet-spinning in their facilities. We are thankful to Philipp R. Stoessel for explaining his previous work with gelatin fibers wet spinning in very simple words which allowed us to replicate his spinning solution formulation. We would like to thank Carson Bruns from CU Boulder for suggesting genipin as a biobased crosslinker. We would also like to acknowledge the support of Miles Henry Lewis who helped with designing and 3D printing the first version of our machine; Lily Gabriel for the initial hand-spinning feasibility test of gelatin fibers; and members of the Unstable Design and Utility Research Labs for reviewing the early drafts of this paper.

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