HoloChemie: Sustainable Fabrication of Soft Biochemical Holographic Devices for Ubiquitous Sensing

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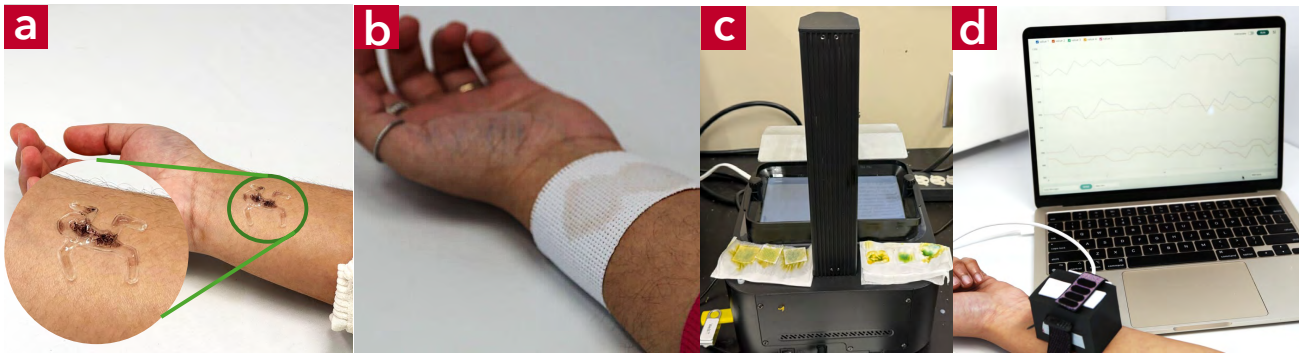

Figure 1: We contribute sustainable fabrication of biochemical holographic sensors derived from bacteria, enzymes and organic biochemical sources. These open up new avenues for biological and environmental sensing for HCI. (a) A biochemical sensor made from flavin enzyme derived from *Aerococcus viridans* bacteria. It measures the lactate levels in the sweat to indicate the intensity of physical activities. (b) A wearable sweat sensor that is functionalized with a glucose-sensing assay derived from *Aspergillus niger* mold. (c) We also demonstrate the fabrication of gas sensors. Carbon dioxide sensors made on diverse soft biodegradable, bio-sourced and vegan-friendly material substrates visually indicating the amounts of carbon dioxide emissions from an SLA printer (darker the yellow tone, higher the emissions). (d) Low-cost, wearable holographic sensing for self-contained real-time quantitative data streaming.

ABSTRACT

Sustainable fabrication approaches and biomaterials are increasingly being used in HCI to fabricate interactive devices. However, the majority of the work has focused on integrating electronics. This paper takes a sustainable approach to exploring the fabrication of biochemical sensing devices. Firstly, we contribute a set of biochemical formulations for biological and environmental sensing with bio-sourced and environment-friendly substrate materials. Our formulations are based on a combination of enzymes derived from bacteria and fungi, plant extracts and commercially available chemicals to sense both liquid and gaseous analytes: glucose, lactic acid, pH levels and carbon dioxide. Our novel holographic sensing scheme allows for detecting the presence of analytes and enables quantitative estimation of the analyte levels. We present a set of application scenarios that demonstrate the versatility of our approach and discuss the sustainability aspects, its limitations, and the implications for bio-chemical systems in HCI.

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CCS CONCEPTS

• **Human-centered computing** → **Interaction devices**; **Ubiquitous computing**; Interaction techniques.

KEYWORDS

Epidermal Devices, Wearables, Physiological Sensing, Biochemical devices Sensing

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1 INTRODUCTION

DIY (Do-It-Yourself) prototyping of soft interactive devices is receiving increased attention fueled by a broad set of accessible fabrication techniques contributed by the HCI community. For instance, soft devices of diverse form factors and custom embedded circuitry can be realized with silicone casting [56, 80, 83], cutting and layering techniques [58, 82], through ink-jet or screen printing on soft substrates [84]. They can also be woven [14, 90], knitted [35], or embroidered [23].

While the fabrication of soft devices has traditionally focused on electrical [56, 83], mechanical [24] or electro-mechanical [35, 69] approaches for various applications such as tactile sensing, haptics, physiological sensing and kinematic sensing, a less explored modality is biochemical sensing. This novel approach, as evidenced by limited research in the area [60], presents a unique opportunity in the fabrication of soft interactive devices.

The integration of biochemical sensing into soft interactive devices holds significant potential. These devices enable non-invasive sensing of chemical and biological analytes, such as biomarkers in the body or pollutants in the environment. They can function without sophisticated interfacing circuitry, can be easily deployed in diverse environmental settings for non-invasive sensing of hazardous chemicals, and can be seamlessly integrated with other sensing modalities within the same device (e.g. a touch sensor can be supplemented with an additional glucose sensing layer).

Recognizing these advantages, the HCI community has also been actively exploring chemical interfaces. These include chemical sensors for UV sensing [50], pH sensing [28], cosmetic chemical sensors for detecting exposure to environmental hazards [29], sensing biomarkers in sweat [25, 64, 90]. However, all these works focused on only one sensing modality (e.g. environmental [50], pH levels [28], or biosensing [90]) and with a specific substrate material such as yarn [90], tattoo paper [50] or cosmetic powder [29]. However, a diverse exploration of biochemical devices for both environmental and biological sensing is missing. Pioneering work from materials and chemistry has explored the development of soft biochemical sensors [3, 36, 89]. Despite these advancements, the focus has largely been on new materials and functional compositions rather than on sustainable materials or the fabrication of interactive devices.

In this work, we for the first time introduce Analyte-Sensitive holographic sensing for interactive applications. We contribute sustainable fabrication of soft holographic devices for biochemical sensing.

This work makes the following contributions:

- We for the first time introduce **Analyte-Sensitive Holographic Devices** for interactive sensing. While this approach has been prevalent in physics and chemistry, it is yet to be explored in the context of biological and environmental sensing for HCI. We engineered a low-cost portable interfacing circuitry to implement this sensing principle.
- For the first time, we explore a unified fabrication approach for diverse sensing modalities. Our sensors can detect not only common biomarkers like glucose and pH but also more complex biomarkers such as lactate levels in sweat (previously unexplored in HCI) and gaseous compounds like carbon dioxide.
- We contribute sustainable fabrication approaches for creating biochemical sensors in a simple lab setting. We present the formulation of enzymes and biochemical solutions for biological and environmental sensing. All components of our sensor stack—substrates, enzymatic, and biochemical layers—are bio-sourced, biodegradable, and vegan-friendly.
- We performed a series of technical experiments to characterize and evaluate the response of our sensors. Results from our Spectrophotometry analysis show that the biochemical sensors produce distinct responses dependent on the concentration of the analytes. Results from a user study show that the sensors function on human skin. Finally, with a simple machine learning model, we can accurately predict the concentration levels of all the analytes with our sensing assays.
- Finally, we demonstrate application scenarios to showcase the potential of the devices fabricated through our approach.

2 RELATED WORK

Our work falls at the intersection of HCI, biochemistry and sustainable fabrication.

2.1 Sustainable Fabrication Approaches

Recent research has shown that researchers still heavily rely on petroleum-based materials for prototyping physical objects [37, 64]. In response, and often under the banner of sustainable interaction design in HCI [7, 16], researchers have created and prototyped with several bio-based materials, including agar-based or cellulose-based bioplastics [4, 37], SCOBY leather [57], compost-based clay [6], biofoam [40] and, mycelium skin [80]. These bio-based materials, with their ability to fully biodegrade, are potential replacements for less-sustainable materials, such as bioplastics for petroleum-based plastics and SCOBY leather for animal leather. Thus far the focus of this line of research has been to integrating electronics capability by making them conductive [37, 40] or using these as substrate materials to augment them with electronic functinality [80]. However, using such sustainable approaches for creating biochemical sensors from biodegradable and bio-sourced materials are yet to be explained. Secondly, not all sustainable approaches are vegan-friendly i.e. many of these approaches still use animal byproducts (e.g. gelatin, chitosan etc.). We believe that an important design consideration for sustainable fabrication is also to explore vegan-friendly alternatives and hope our attempt will drive this research theme further. Table 1 compares this work with all the previous work that contributed to sustainable fabrication, living matter interfaces and biosensing devices in HCI.

Related Work	Context	BioSensing with Sweat	Environmental Sensing	Sustainable	Vegan-Friendly
BioWeave [90]	Biosensors for sweat	✓(Glucose, pH)	✗	✓	✓*a .
Vim [74]	Printed batteries for prototyping	✗	✗	✓	✓.
Interactive Bioplastics [37]	Integration of electronics with bioplastics	✗	✗	✓	✗.
BioHybrid Devices [57]	Integration of electronics with living matter	✗	✗	✓	✓.
SCOBY Breastplate [5]	interactive breastplate fabricated from SCOBY	✗	✗	✓	✓.
EcoPatches [50]	UV Sensing patches for Skin	✗	✓(UV exposure)	✓	✓.
Organic Primitives [28]	pH-reactive materials for interaction	✗	✓	✓(pH)	✓*a .
Flavorium [22]	Flavobacteria as living colour interfaces	✗	✗	✓	✓.
Bioluminiscent Algae [62]	using natural visual feedback of bioluminescent algae	✗	✗	✓	✓.
BioFoam [40]	Biofoam as a design material	✗	✗	✓	✗.
Myco-Accessories [80]	embedding electronic circuits into mycelium skin	✗	✗	✓	✓.
Care-Based interaction [45]	Slime mold for care-based interactions	✗	✗	✓	✓.
BioSparks [76]	Glucose sensing embedded into jewellery	✓(electrochemical sensing)	✗	✗	✓.
Dermal Abyss [81]	Invasive biosensing of interstitial fluids in the skin	✓(glucose, pH, Na^+)	✗	✓	✓.
Chitosan Biofilm Actuators [12]	Humidity sensing with chitosan films	✗	✓(humidity)	✓	✗.
This work	**Sustainable vegan-friendly biochemical sensing**	✓ **(lactate, glucose)**	✓ **(CO_2, pH)**	✓	✓ .

Table 1: Comparison of related work in HCI that has contributed living matter interfaces, sustainable fabrication approaches. (*a) While these works had vegan-friendly components, they used Chitosan as one of the components for their prototypes.

2.2 Fabrication of Epidermal BioSensors

The human-computer interaction community has recently started to investigate epidermal devices for interaction. These devices augment the human skin with input and visual or tactile output capabilities [15, 30, 43, 55, 56, 59, 61, 75, 79, 82–84]. Human skin serves as a promising interface for capturing biosignals, and recent work in HCI contributed the fabrication of epidermal devices for health monitoring [48, 52, 58]. More recent research has explored the chemical sensing of biomarkers from sweat and interstitial fluids [76, 81, 90]. BioWeave [90] presented weaving thread-based sweat sensors for detecting glucose, pH and electrolytes while BioSparks [76] integrated electrochemical sensors for detecting glucose. While the fabrication of chemical biosensors is an emerging stream of research and is still not fully explored in HCI, a few external venues, such as [20, 33], have used complex biochemical synthesis and enzymatic reactions for the detection of sweat lactate levels. We are proposing simpler fabrication methods for detection of complex biomarkers such as lactate levels in sweat. In this work, we for the first time demonstrate lactate detection of sweat through analyte-sensitive holographic sensing using sustainable and vegan-friendly materials.

2.3 Chemical Interfaces in HCI

The use of chemical processes for designing novel interactions is gaining recent attention in HCI. These include supercapacitors that are fabricated using sustainable materials [74], and wearable patches that can show exposure to UV light through changes in color [51]. Lotio is a skin-worn interface that senses lotion and enacts visual, tactile, or digital transformation [73]. Chemical haptics provides haptic sensations by delivering liquid stimulants to the user's skin [44]. Jensen et al. used the principle of electrochromism to fabricate flexible displays [26]. Recent work has also demonstrated chemical sensing for various interactive applications [12, 28].However, these are limited to sensing a single modality i.e. pH and humidity respectively.

While the use of chemicals and chemical reactions has been leveraged for designing novel interfaces in HCI, to the best of our knowledge, we are yet to see the fabrication of soft biochemical sensors using sustainable fabrication methods. Also, to the best of our knowledge none of the previous works systematically explores the intricate relationship between the substrate materials, chemical analytes and fabrication approaches for realizing soft chemical sensors to sense diverse set of chemicals.

2.4 Bio and Environmental Sensing in Materials and Chemistry

The development of epidermal biosensors and environmental sensors is an active research area within various fields in science. The core function of these sensors is to detect and quantify specific biochemical markers or analytes in the body's sweat or interstitial fluid, which can provide valuable insights into an individual's health status [19, 65, 85]. The detection of lactate sensors is of active interest various approaches such as using electrochemical [34], optical [88] and holographic [67] approaches have been employed [39]. Similarly, glucose is one of the most studied biomarkers [87]. Environmental elements such as carbon dioxide and extreme pH levels have been well explored in chemistry [10]. While these research works have demonstrated the fabrication of all the sensors that are being presented in this work, there are several limitations to those works: firstly, not all those sensors work with sweat, for e.g. the holographic lactate sensors work with blood [67]. Secondly, they typically use complex material formulations (e.g., nanofilm composites, rare-earth materials like gold, platinum, etc.) and functionalization schemes and require sophisticated infrastructure (e.g.,

fume hood, wet lab, etc.) for fabrication, rendering them unsustainable. Thirdly, an in-depth exploration of biochemical formulations with sustainable substrate materials has yet to be explored in these domains. Here, we demonstrate the fabrication of these sensors in three simple steps: formulation, fabrication, and use. Additionally, our entire sensor stack is biodegradable and environment-friendly.

3 DESIGN GOALS

Continuing to draw on related work and our own personal experiences with designing and fabricating soft chemical sensors, in this section we outline several design considerations for the realization of HoloChemie devices.

3.1 Sustainable Prototyping

Functional prototyping plays a significant role in HCI design interactivity. However, there is a tension between HCI's traditional practice of prototyping and sustainability goals [70], as the commonly employed materials can have adverse environmental effects. This is due to their provenance and scarcity (e.g., metal mining causing loss of biodiversity [17]), synthesis, processing (e.g., toxic effluents from PCB creation [9]), and disposal (e.g., acrylic sheets ending up in landfill [18]). Hence, our primary design requirement is to use bio-sourced and eco-friendly materials. Once no longer in use, the sensors can be remolten and re-fabricated into other prototypes or degraded or composted, allowing for a safe and *sustainable life cycle*. Finally, because chemical sensing typically involves chemical analytes, we must ensure that the sensors degrade organically and do not harm the soil once they decompose.

3.2 Diversity in Sensing

Designers, practitioners and makers typically require wide range of sensing capabilities for diverse applications. Hence we employed a breadth-first approach, in which we explore the sensing of multiple chemical substances that are found in human body and our environment. This enables designers, practitioners and researchers to fabricate custom soft chemical sensors for diverse applications.

3.3 Simple Readout Scheme for Quantitative Measurements

Chemical sensors typically show the presence of an analyte. However, in many scenarios, it is not only important to detect the presence but also to quantify the amount of an analyte. When the sensors show a colorimetric response this can be achieved through computer vision approach where a smartphone can detect changes in the colour through a RGB camera. However such approaches can fail when the responses are not colorimetric. Hence our goal is to create a simple setup which can provide a quantitative estimation of the analyte that can work with colorimetric and non-colorimetric response.

3.4 Wide-Accessibility and Vegan Materials

The current state-of-the-art methods for the fabrication of chemical sensors (typically used in the materials science and research communities) predominantly use highly expensive materials (e.g. gold) or complex material formulations. This significantly prohibits wider adoption. Second, sophisticated fabrication equipment is typically used (e.g. vacuum deposition, sputtering, centrifuge, etc.) to create the electrodes. Thirdly, recent work in HCI has developed soft devices using materials that are derived from animal products (e.g. gelatin, chitosan etc.) [12, 37, 90]. However, the use of certain animal products does not fit into the cultural practices of a few communities. Therefore, a key design requirement for us has been to use widely-accessible, bio-sourced organic materials and low-cost fabrication approaches.

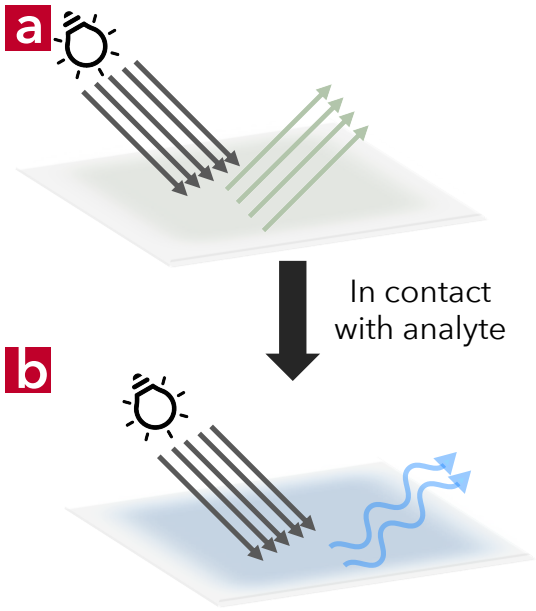


Figure 2: Working principle of the analyte-sensitive holographic sensing. (a) A substrate functionalized with a chemical sensing layer that responds to a specific analyte. When exposed to a light source, the sensor has default optical properties (e.g. absorption/reflectance levels, color, transparency etc.). (b) When the sensor comes in contact the chemical sensing layer, it changes the optical properties of the sensor. This can be identified by the way the rays interact with the surface.

3.5 Prototyping Passive Sensors

A massive advantage of holographic chemical sensors is that they can be completely passive without needing external power source (for detecting the presence of an analyte and coarse quantitative estimation based on the colorimetric response). Our design goal here is to leverage this powerful feature of chemical sensing so that passive chemical sensors can be fabricated rapidly, thereby unleashing them for diverse ubiquitous sensing applications.

4 WORKING PRINCIPLE AND BIOMATERIALS

To the best of our knowledge, we are the first to explore sustainable fabrication of Analyte-Sensitive Holographic sensing for interactive sensing. In this section, we outline the sensing principle, and discuss

the core biomaterials that we have explored for fabricating our biochemical sensors.

4.1 Holographic Sensing

Holographic sensors are a class of sensors at the intersection of optics, materials science, and chemistry, offering unique advantages for detecting and quantitatively analyzing chemical substances and physical conditions. These sensors operate based on the principle that the holographic patterns—specifically, the spacing between recorded nanoparticles and the material's effective index of refraction (n_O)—can alter in response to environmental stimuli. These changes, in turn, affect the hologram's optical properties, such as the peak wavelength ($\lambda_p f$), its color distribution, and intensity (brightness), enabling the detection of specific analytes.

Holographic sensing can be realized through multiple schemes [46, 53]. One approach is Diffraction or Bragg gratings-based technique in which the surface features of a soft material (e.g. hydrogels, gelatin films etc.) are modified to form Bragg gratings (regularly separated parallel fringes). These gratings diffract light in different directions due to their periodic structure [46]. This approach is more appropriate for physical stimulants. Another class of holographic sensors is the Anlayte-Sensitive holographic sensors. In this approach, instead of modifying the surface structure, the substrate material is functionalized with a chemical sensing layer that responds to specific analyte (e.g. glucose). This chemical sensing layer changes one/more optical properties (e.g. color, absorption/reflectance properties, refraction index, transparency etc.) of the underlying substrate material when it comes in contact with the analyte. Figure 2 illustrates this sensing technique [53].

There are several advantages of Analyte-based holographic sensors making them highly suitable for several interactive applications. Firstly, they enable the determination of the presence/absence or concentrations of analytes [86] through a visual direct readout scheme without, the requirement of expensive equipment such as spectrophotometer. Because they can be passive, they do not need any external power source, unlike other electrical or electrochemical sensors. Finally, they are more sensitive and specific to a given analyte. For instance, a glucose holographic sensor will only react with glucose even in the presence of other analytes.

4.2 Biomaterials

Our goal is to fabricate the chemical sensing layers of Analyte-Sensitive holographic sensors using materials that can easily decompose. While there are several such biochemical sources in nature, here we are interested in those materials and sources that (1) are relevant for HCI, (2) are easy and safe to handle and (3) can be fabricated in a simple lab setting (without the requirement of sophisticated infrastructure like wet lab space, fume hood etc.). This exploration is crucial for pushing the boundaries of sustainable biochemical device fabrication. We believe that this work will inspire the community to explore more of such biomaterials for diverse use cases.

To give the reader the background to replicate our technical implementation, we provide an overview of the biological and chemical components and their sources used in our devices. :

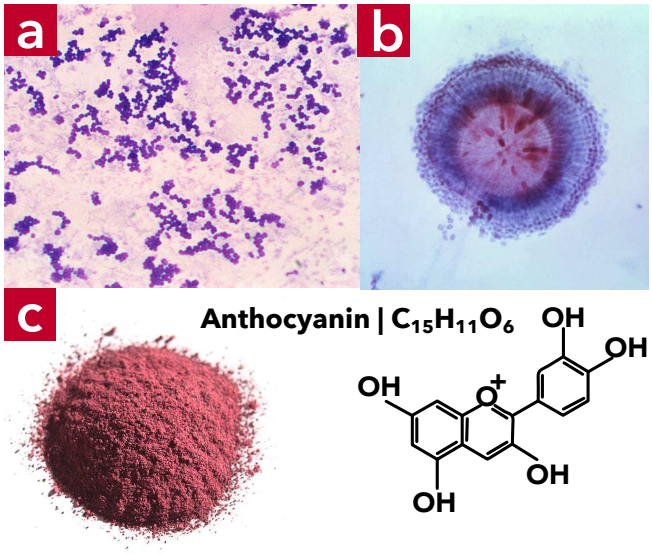


Figure 3: Living matter and bio-sourced materials that are central to the formulation of our enzymes and flavonoids. (a) *Aerococcus viridans* Bacteria: source for Lactate Oxidase Enzyme (b) *Aspergilus niger* Mold: source for the Glucose Oxidase Enzyme (c) Anthocyanins: class of water-soluble flavonoids widely present in fruits and vegetables. Images in (a) and (b) are courtesy Center for Disease Prevention and Control.

- ***Aerococcus viridans* bacteria as source for Lactate Oxidase (LOx)**: *Aerococcus viridans* is a member of the bacterial genus *Aerococcus*(Figure 3(a)). This bacteria produces an enzyme called L-lactate oxidase (LOx). LOx is a flavoenzyme[1] catalyzes oxidation of L-lactate and O_2 into pyruvate and H_2O_2. A major clinical use of LOx is in the determination of L-lactate indirectly via the H_2O_2 formed in the reaction. The determination of L-lactate can be useful for many interactive applications. For e.g. measuring the L-lactate levels in sweat indicates the metabolic activity, physical activity and even the tissue health [49].
- **Glucose Oxidase (GOx) from *Aspergillus niger* mold**: *Aspergillus niger* is a mold classified within the Nigri section of the *Aspergillus* genus (Figure 3(b)). The *Aspergillus* genus consists of common molds found throughout the environment within soil and water, on vegetation, in fecal matter, and on decomposing matter. It secretes an enzyme called Glucose Oxidase (GOx) [42] which can be used for sensing glucose.
- **Anthocyanins in Hibiscus Tea**: Anthocyanins are a class of water-soluble flavonoids(widely present in fruits and vegetables). Anthocyanins in Hibiscus flowers can be excellent pH indicators [21](Figure 3(c)).

[1]Flavoenzymes catalyze an impressive variety of chemical transformations, ranging from oxidation-reduction reactions to substitutions of hydrogen atoms with oxygens or halogens to carbon-carbon bond formations.

Material	Source	Function	Sustainable Property
Alginate	Sigma (https://www.sigmaaldrich.com/CA/en/product/aldrich/w201502)	Substrate material	Bio-sourced and biodegradable
Agarose	Sigma (https://www.sigmaaldrich.com/CA/en/product/sial/a4718)	Substrate material	Bio-sourced and biodegradable
Fabric	Amazon (https://www.amazon.ca/Cotton-Muslin-Fabric-Unbleached-Linen/dp/B0C6ZCPGPX)	Substrate material	Made from cotton. Bio-sourced and biodegradable.
Chromatography Paper	Sigma (https://www.sigmaaldrich.com/CA/en/product/aldrich/wha3017820)	Substrate material	Pure cellulose derived from cotton. Bio-sourced and biodegradable.
Potassium Iodide (KI)	Sigma (https://www.sigmaaldrich.com/CA/en/product/sigald/221945)	Produces the holographic response	Water soluble. Enhances the antioxidant defense system in plants [20]
Phosphate Buffer (PB)	Sigma (https://www.sigmaaldrich.com/CA/en/product/sigma/p3619)	maintaining appropriate pH levels	Used for evaluating organic nitrogen in soil [77].
Glucose Oxidase (GOx)	Sigma (https://www.sigmaaldrich.com/CA/en/product/sigma/g2133)	Enzyme for glucose detection	Bio-sourced from mold.
Lactic Oxidase (LOx)	Sigma (https://www.sigmaaldrich.com/CA/en/product/sigma/l9795)	Enzyme for lactate detection	bio-sourced from bacteria.
Hibiscus Tea	Amazon (https://www.amazon.ca/Foothills-Naturals-Hibiscus-Flowers-Organic/dp/B07R243C38)	pH indicator	bio-sourced and biodegradable.
Bromothymol Blue	Sigma (https://www.sigmaaldrich.com/CA/en/product/sial/114413)	pH indicator	Water soluble and decomposes in soil.

Table 2: Materials used for fabricating the sensors, their functionality and sustainable properties

4.3 Substrate Materials

Our main goal is to fabricate the entire sensor stack using sustainable materials while ensuring they are functional and allow for holographic sensing. Hence we meticulously chose the substrate materials and biochemical formulations to ensure that all components are entirely environment-friendly (i.e. they decompose naturally, can be reused if required and are bio-sourced).

We chose six substrate materials for our fabrication experiments: (1) Alginate (2) Agarose (3) Tattoo paper (4) Chromatography paper (5) Woven fabric and (6) Non-woven fabric. All our substrates are derived from plant extracts and chosen for diverse HCI applications. Alginate and agarose are for soft wearables, tattoo paper and chromatography for rapid and paper prototyping, and fabrics for e-textiles.

We chose these substrates because of the following reasons:

(1) they are commercially available, safe and easy to handle, widely-accessible and low-cost materials.
(2) they are being actively used in the HCI research community because of their flexibility, stretchability and bio-compatibility [28, 37].
(3) they are completely bio-sourced and biodegradable, which is a crucial requirement for sustainable fabrication [37, 71]. We systematically analyzed material composition before selection: chromatography paper (Whatman) is pure cellulose derived from cotton; tattoo paper (Silhouette) is composed of ethyl cellulose prepared from wood pulp [8]. The fabric substrates are made from cotton.

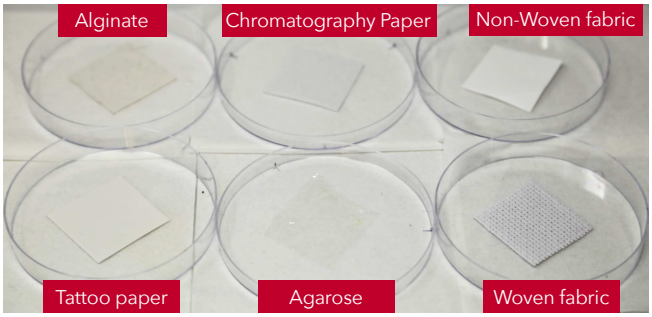


Figure 4: Substrate materials used for fabrication. All the materials bio-sourced and biodegradable.

4.3.1 *Substrate Preparation.*

- **Alginate Sheets:** Alginate is a hydrocolloid (a substance which forms a gel in the presence of water) from algae, specifically brown algae, which is a group that includes many of the seaweeds, like kelps and an extracellular polymer of some bacteria. Sodium alginate (Food Grade Sodium Alginate [2]) is one of the best-known members of the hydrogel group, and has been extensively used in diverse domains such as food industry, medicine and tissue engineering [1].

[2]https://www.amazon.com/Alginate-Calucium-Luxurious-Desserts-Meatloaves/dp/B0C55JRQCX/

Alginate sheets were prepared by mixing sodium alginate (Food Grade Sodium Alginate [3]), glycerol [4], and distilled water in a 1:25:1 ratio by weight. The mixture was stirred at room temperature until homogeneous and viscous. It was then poured into predefined moulds and allowed to dry at ambient conditions for 8-10 hours. Once dry, the sheets were carefully removed using tweezers.

- **Agarose Sheets:** Agar-Agar Sheets: Agarose is a polysaccharide that is isolated and purified from agar or agar-bearing marine algae (sea kelp).
  Agarose sheets were produced by dissolving agarose powder([5] in distilled water to a final concentration of 2% (w/v). This solution was heated in a microwave until boiling to ensure complete dissolution. The hot solution was then poured into moulds and left to solidify at room temperature for 6-8 hours. The solidified sheets were subsequently removed from the moulds.
- **Chromatography Sheets:** We included commercially available chromatography sheets (cellulose as the base material) because of their versatile and widespread use.
- **Tattoo Paper:** Tattoo paper is a substrate that allows for the fabrication of highly skin-conformal devices. It is also made of cellulose and has been a very popular substrate material choice in HCI [30, 43, 61, 84].
- **Fabrics:** Due to their popularity and support for various fabrication techniques, we considered fabric (woven and non-woven). They are being increasing explored in HCI [14, 23, 35, 90].

5 FABRICATION

In this section, we provide the fabrication details for formulating the sensing layers and report our explorations on coating the sensing layers onto the substrates. For fabricating the sensing layers, we employed three different methods:

- **Drop coating**: A micropipette (PuroPET) with a range of 20 μL to 200 μL was utilized for this process. To ensure uniform dispersion of the fluid, the same amount of solution was carefully dispensed from the micropipette onto the substrate at 2-second intervals. This technique allowed for precise control over the volume of fluid applied, contributing to an even distribution on the substrate.
- **Spraying**: A 5 ml clear cylindrical spray bottle purchased from Amazon[6] was employed for the spraying method. From the 5 ml stock of solution fluid, a fine mist was generated by pressing the fingertip-operated spray mechanism. This method facilitated the application of the solution in a mist form, ensuring a consistent and thin layer of fluid on the substrate.
- **Brushing**: A regular watercolour paintbrush, also acquired from Amazon[7], was used for the brushing technique. The solution fluid was evenly spread on the substrate using the brush, ensuring thorough and uniform coverage. This manual method allowed for controlled application, particularly useful for covering specific areas or achieving a desired thickness of the fluid layer.
  Each of these methods provided a different approach to applying the sensing layers, offering flexibility in achieving the desired uniformity and thickness for the final application.

5.1 Biological Sensing

With our fabrication approach, we contribute the fabrication of skin-conformal soft biosensors that can detect biomarkers in sweat. We are primarily interested in two crucial biomarkers that inform the health and metabolic state: Lactate and Glucose.

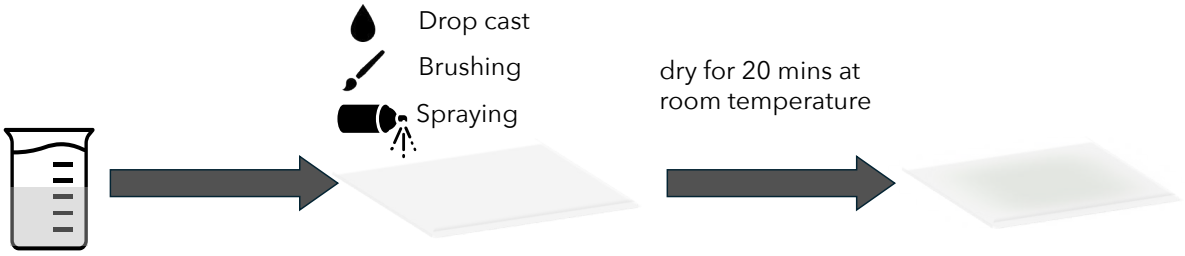
Lactate: Lactate is considered an important biomarker for such purpose due to its involvement in anaerobic metabolism. Prior studies have shown a correlation between sweat lactate and exercise intensity [66]. Lactate in sweat provides unique information about the general health status of the individual, including pressure ischemia and insufficient oxidative metabolism [13]. As a result, the real-time and continuous monitoring of lactate in sweat has been claimed as a rich source of information to preserve the health status [11, 31]. Despite these potential benefits, we are yet to see sustainable and widely-accessible approaches for fabricating lactate sensors.

Glucose: To demonstrate the versatility of our approach, we also fabricated glucose sensors. Prior work in HCI has explored sweat-based glucose sensors [76, 81, 90]. However, these are electrochemical devices which do not support passive battery-free sensing. Bioweave [90] and Dermal Abyss [81] did contribute colorimetric glucose sensors by incubating commercial urinalysis test strips. However, this method was not compatible with our substrate materials. Hence, we contribute an alternate approach for fabricating glucose sensors.

5.1.1 Assay Preparation. The sensing of lactate and glucose levels is based on the preparation of enzymes. To create a conducive environment for these enzymes to flourish, we need to maintain appropriate pH levels. This is done using Phosphate Buffer Saline (PBS) which has a close to neutral pH level (around 7.2-7.4). Additionally, to produce a noticeable colour change, we use Potassium Iodide and Starch solution. This is because both Lactate Oxidase (LOx) and Glucose Oxidase (GOx) produce Hydrogen Peroxide (H_2O_2) which induces the oxidation of potassium iodide (KI) to iodine which in presence of starch produces dark noticeable colours. We modeled this formulation based on the underlying chemical reactions that occur between GOx-Glucose pair and LOx-Lactate pair as shown in Figure 6.

Lactate Assay: We used Lactate oxidase derived from the bacteria Aerococcus Viridans as the key enzyme for preparing the assay. To create the lactate sensing assay, firstly, we prepared 30 mL of 1 mM (Millimolar) PBS (Phosphate Buffer Saline, PBS, Sigma-Aldrich 806552) buffer by diluting 1000 times 1 M PBS stock solution with distilled water. We then added 2.49 g of KI (Potassium Iodide, Molecular wt- 166 g/mol, Sigma-Aldrich, 221945) to 15 ml of 1 mM PBS to obtain 1 M KI solution. To prepare the Lactate Oxidase (LOx) Solution, 100 U of Lactate Oxidase (Sigma Aldrich, L9795) was added to 1 ml of PBS. Starch (Potato Starch, Sigma-Aldrich, 101252) is also

[3] https://www.amazon.com/Alginate-Calucium-Luxurious-Desserts-Meatloaves/dp/B0C55JRQCX/
[4] https://www.amazon.com/SimpleNature-100-Pure-Vegetable-Glycerin/dp/B0B1N7QKBN/
[5] https://www.amazon.com/RPI-Agarose-Molecular-Strength-Electrophoresis/dp/B00I31YMRU/
[6] https://www.amazon.ca/NewZoll-Bottles-Atomizer-Container-Essential/dp/B08MZZPHNQ
[7] https://www.amazon.ca/Brushes-Watercolor-Acrylic-Different-Artists/dp/B01DDHTQZG



Sensing Assay

Target Analyte	Phosphate Buffer	Potassium Iodide	Oxidase	Starch
Glucose	1 mM	150 mM	0.1 U/mL (GOx)	10 mg/mL
Lactic Acid	1 mM	150 mM	16 U/mL (LOx)	10 mg/mL

GOx = Glucose Oxidase, 0.1 U = 160mg LOx = Lactate Oxidase, 16 U = 0.4mg

Figure 5: We contribute a very simple and easy fabrication process that works on both soft material and fabric substrates. Once the sensing assay is prepared, they can be drop-casted, brushed with a paintbrush or sprayed on the substrate. The sensors are ready to use once they are allowed to dry for about 20 mins at room temperature. The proportions shown here are optimized for healthy participants. For sensing higher levels, please refer to the supplementary material.

used as a component at a desired concentration of 10 mg/mL. Once the PBS, KI stock solution and lactate oxidase stock solutions are prepared, we created an assay of 180 μL by adding all these components in the following proportions: 118 μL of PBS, 32 μL of LOX, and 30 μL of KI solution and 2 mg of Starch (in powdered form) to obtain the desired concentration of each components and then they are gently mixed. These proportions have been optimized for sensing lactate levels in healthy participants (i.e. in range 5-20 mM). However, for monitoring excessive lactate levels that go beyond the healthy levels, the levels of lactate oxidase need to be fine-tuned accordingly. Our supplementary material provides more detailed calculations in this regard and shows the mathematical calculations based on molecular weights of the compounds we are using. Table 2 provides an overview of all the materials we used, their function and sustainable properties.

Glucose Assay: We used Glucose oxidase derived from the bacteria *Aspergillus niger* Mold as the key enzyme for preparing the assay. To create the glucose sensing assay, firstly, we prepared 30 mL of 1 mM (Millimolar) PBS (Phosphate Buffer Saline, PBS, Sigma-Aldrich 806552) buffer by diluting 1000 times 1 M PBS stock solution with distilled water. We then added 2.49 g of KI (Potassium Iodide, Molecular wt- 166 g/mol, Sigma-Aldrich, 221945) to 15 ml of 1 mM PBS to obtain 1 M KI solution. To prepare the Glucose Oxidase (GOx) Solution, 160 mg of Glucose Oxidase (Sigma Aldrich, G7141) was added to 10 ml 1 mM PBS to obtain the desired 100 μM concentration. Starch (Potato Starch, Sigma-Aldrich, 101252) is also used as a component at a desired concentration of 10 mg/mL. Once the PBS, KI stock solution and Glucose oxidase stock solutions are prepared, we created a 160 μL assay by adding all these components in the following proportions: 110 μL of PBS, 20 μL of GOx, and 30

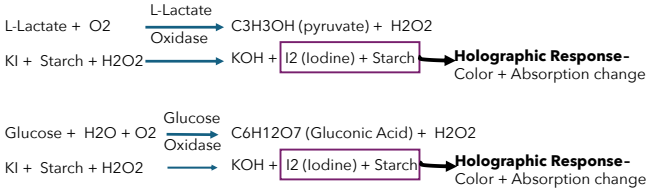


Figure 6: We designed our biochemical formulation based on the underlying chemical reactions of lactate and glucose in the presence of Lactate oxidase and glucose oxidase respectively.

μL of KI solution and 2 mg of Starch (in powdered form) to obtain the desired concentration of each component and then they are gently mixed. These proportions have been optimized for sensing glucose levels in healthy participants (i.e. in the range of 0.1-0.20 mM). However, for monitoring excessive Glucose levels that go beyond the healthy levels, the levels of Glucose oxidase need to be fine-tuned accordingly. Our supplementary material provides more detailed calculations in this regard and shows the mathematical calculations based on the molecular weights of the compounds we are using.

5.2 Environmental Sensing

To diversity the sensing modalities, we also explored sensing of environmental factors. These include pH levels and carbon dioxide levels. We chose these because the environmental sensors made for these modalities can also be repurposed to function on the human body. For e.g. carbon dioxide in human breath increases after exercising.

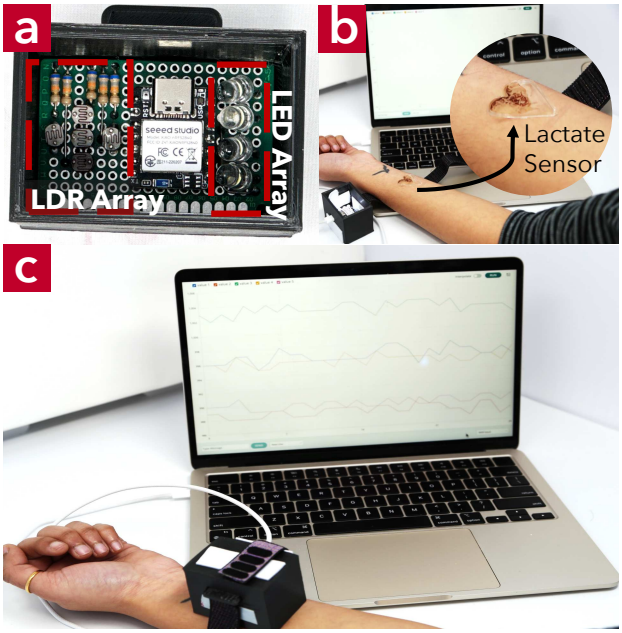


Figure 7: Hardware Setup for holographic sensing. (a) A set of LEDs and LDRs are used to measure the amount of ththlight that is reflected from the sensing assay (b) before putting on the hardware, the sensor is applied onto the skin (c) real-time light intensity values captured by the hardware setup.

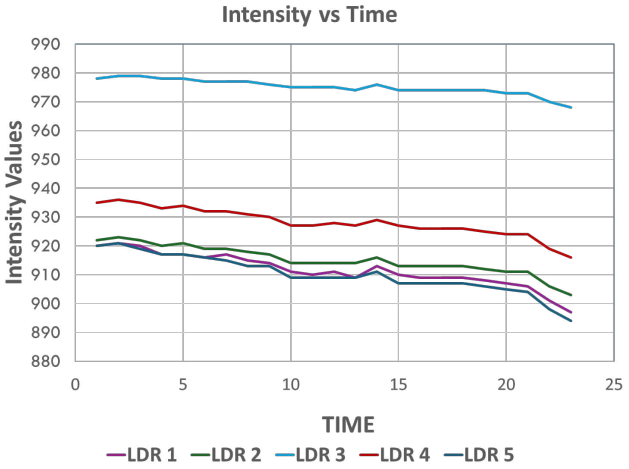


Figure 8: Noticeable decrease in the light intensity values with time (in minutes). As the chemical reaction takes place, the reflected light intensity keeps decreasing as more light is absorbed by the sensing assay.

5.2.1 Assay Preparation. Sensing gases has been less explored in HCI and we aim to enable this through simple and commercially available materials. Gas sensors pose several challenges from a fabrication perspective, firstly, they need to operate at room temperature. Secondly, they typically employ high-vacuum high-temperature fabrication processes [78]. Hence, our goal is to design sensors that address these issues. We believe that this will inspire the HCI community to create more sophisticated gas sensors in sustainable ways.

pH sensing has been previously explored in the HCI literature. These include the design of pH reactive materials [28] or sensing pH levels in sweat [81, 90]. However, the range of pH levels considered in those works is 2-10 (and 4.5-9 for pH levels in sweat). Our goal was to increase this sensing range to incorporate the more extreme levels.

Carbon Dioxide . For detecting carbon dioxide levels, we used bromothymol blue (C27H28Br2O5S) (BTB) a water-soluble dye that is slightly acidic. Bromothymol Blue acts as a weak acid in a solution. It can thus be in protonated or deprotonated form, appearing yellow or blue, respectively. It is bright aquamarine by itself, and greenish-blue in a neutral solution. While carbon dioxide sensors have been developed in chemistry [2, 10], they typically used more complex materials (e.g. carbon nanoparticles, amino alcohols and more sophisticated formulations of BTB).

We used commercially available BTB [8] solution for CO_2 detection. We prepared bromothymol blue (BTB) solution by dissolving 0.1 g of BTB in 16 ml of 0.01 N NaOH and diluting it to 250 ml with distilled water. Since BTB has a natural pH value between 6 and 7.6, making it slightly acidic, we added sodium hydroxide to adjust the pH levels so that it is more neutral (between 7 and 7.5). In this pH range, the default colour of BTB is greenish. The prepared solution was drop-cast onto the substrate and allowed to dry before CO_2 exposure. When BTB comes in contact with carbon dioxide, carbonic acid is formed which changes its color to slightly yellowish green.

Sensing extreme pH values. We used Anthocyanins sourced from Hibiscus tea to detect pH values. For preparing the sensing assay we used commercially available hibiscus tea leaves ([9]). We boiled 3 g of the tea leaves for 15-20 minutes and allowed the solution to cool to room temperature. This solution was then drop cast, brushed, or sprayed onto the substrate. This assay can detect extreme pH values (12-14) present in everyday substances such as caustic soda or corrosive substances (e.g., Sodium Hypochlorite (found in bleach)). The BTB solution can be used to detect extreme acidic levels. In the presence of pH levels below 2, it changes to yellow.

5.3 Hardware and Interfacing

The hardware setup consists of an array of LEDs arranged linearly and five LDR (light-dependent resistors) arranged to ensure that they cover the major area of the sensor (Figure 7 (a)). Initially, the sensor is placed on the body location, and then the LEDs project light onto the sensing assay(Figure 7 (b)). This allows for real-time

[8] https://www.amazon.com/Innovating-Science-0-04-Aqueous-Bromothymol/dp/B0731VJ1DG
[9] https://www.amazon.com/Organic-Hibiscus-Flowers-Jamaica-Caffeine/dp/B0C9PGR822/

logging of the sensor data (Figure 7 (c)). In a normal state, since the sensor is transparent, most of the light is reflected back to the LDRs. However, as the sensor reacts to the biomarkers, the transparency and colour change results in some of the light absorbed by the assay. This results in lower levels of light intensity which is picked up by the LDR array(Figure 8 (d)).

We used a SEEED Xiao BLE microcontroller to interface the LED and LDR arrays. A 3D-printed casing houses the entire interfacing board. We designed the entire setup to be compact and portable to ensure that the entire sensor and interfacing setup can be deployed as a self-contained unit. The intensity values are streamed at 50 frames per second.

5.4 Lessons Learned

The authors and five additional persons (an interaction designer, a biomedical engineer, a homemaker, a software engineer and a maker experienced in 3D printing) have used our sensor synthesis recipes extensively over several weeks. Here, we summarize their practical insights and lessons learned. We believe these insights would be highly valuable for researchers, makers, practitioners, and anyone who wants to fabricate these biochemical sensors.

5.4.1 Substrate Compatibility. Our experiments show that the sensing assays are compatible with all the substrates. However, Alignate sheets are naturally acidic because of their polymer chains. Hence, when they are functionalized with BTB assay, they slightly turn yellowish. To counter this, we coat an additional layer of alkaline solution (Sodium Hydroxide) to neutralize this colour change and keep the natural optical properties intact. In our initial experiments, we also tested the assays with other substrates commonly used for fabricating soft devices (e.g. PET, Silicone). While they were also compatible, these are not bio-sourced, and hence, we eliminated them from our target substrate materials.

5.4.2 Fabrication Compatibility. The most usual methods for fabricating thin-film epidermal devices are to use printing or coating techniques such as screen printing [84], inkjet printing [32], stencil printing [37]. However, these techniques require the assays to be more viscous, and since our assays are in liquid form, these techniques are unsuitable. Secondly, these techniques also use comparatively large amounts of substrates and can result in wastage (e.g. inks residues on screen). However, given the very low volumes of assays that we are using, drop casting is the technique that produces the least amount of wastage. For brushing, we recommend thoroughly spreading the assay and ensuring minimal amounts are stuck onto the bristles of the brush.

5.4.3 Handling of the Assays. While preparing the enzymatic solutions using Glucose Oxidase (GOx) and Lactate Oxidase (LOx), we recommend not shaking or mixing them rigorously as it can destroy the enzymes. Additionally, for other components of the assay (KI+Starch and PBS), if they are not used immediately, we recommend preparing aliquots and storing them in a refrigerator at -20 degrees Celsius.

5.4.4 Reusability of the Assay. During the CO_2 detection experiments, we employed bromothymol blue (BTB) coatings on various substrates to detect the presence of CO_2 and to perform colorimetric quantification. Even after initial exposure to CO_2, these substrates gradually reverted to their original green colour. Although their sensitivity was reduced, they could still be reused for CO_2 quantification. Furthermore, we identified another regeneration technique applicable to all substrates. In this technique, we applied a certain amount of 0.01 N Sodium Hydroxide (NaOH) to the BTB-coated CO_2 detection layer. This method effectively restored the assays for subsequent rounds of CO_2 detection and quantification, highlighting a sustainable and cost-effective approach for the repeated utilization of BTB assays in various environmental and maker-space scenarios.

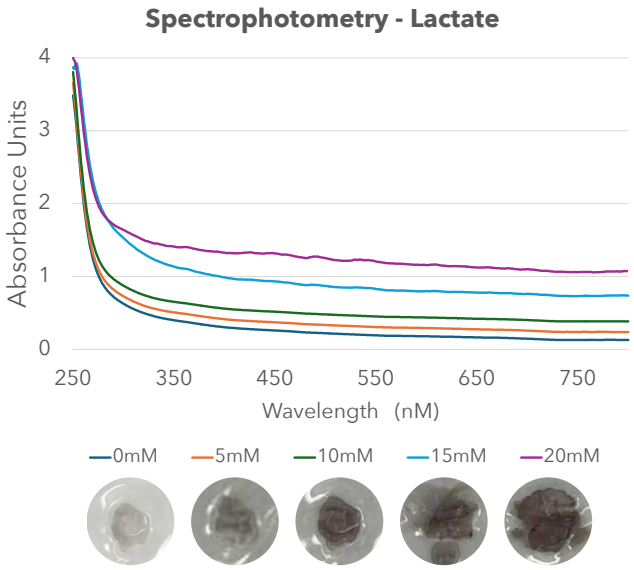


Figure 9: Spectrophotometry results from Lactate sensing assay. There is a clear difference in the absorption patterns for each concentration level.

6 TECHNICAL EXPERIMENTS

In this section, we present the technical experiments to characterize the holographic sensors. First, we are interested in understanding the spectral response of our devices. *Our research goal is to understand the absorption/reflectance characteristics of our sensors across the visible, and ultraviolet spectrum.* Based on our fabrication experiences, we hypothesized that our sensors absorbed visible light, and ultraviolet wavelengths. This is in contrast to the spectral response of simple colorimetric sensors that produce a response only in the visible light spectrum [28, 90]. In the second experiment, we measured the accuracy of our custom hardware setup to quantitatively predict the analyte concentration levels. Our research question is *Can we build a simple machine learning model to quantify the analyte concentration with our hardware setup?*

6.1 Spectral Characterization

To quantitatively analyze the spectral response of our holographic sensors, we performed spectrophotometry experiments on all of

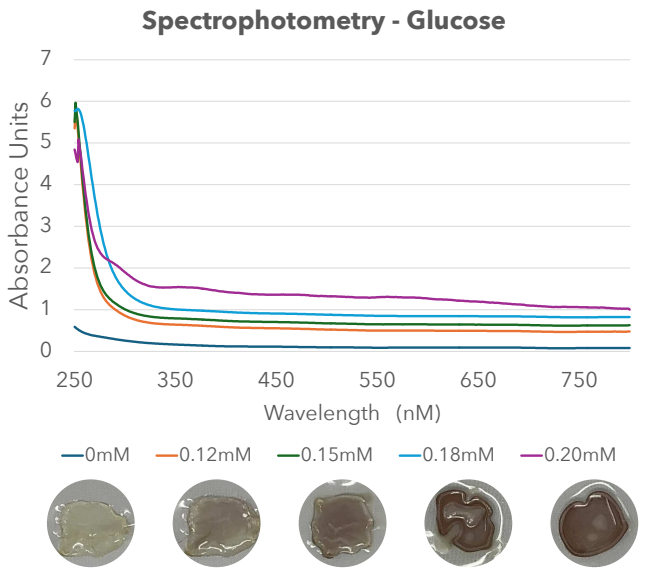


Figure 10: Spectrophotometry results from Glucose sensing assay. There is a clear difference in the absorption patterns for each concentration level.

the sensors. Spectrophotometry is an analytical method which measures the amount of light a chemical substance absorbs when exposed to light of different wavelengths. This is one of the techniques that has been employed for characterizing the optical response of holographic and colorimetric sensors [27, 28, 63, 90].

6.1.1 Method. We fabricated all the sensors: lactate, glucose, carbon dioxide and pH sensors for this experiment. The sensors were prepared by drop-casting the corresponding assay onto the alginate substrate. We chose alginate as our primary substrate because it provided the best level of transparency and was easier to handle compared to the other substrates.

We formulated 4 concentration levels of glucose: 0.12 mM, 0.15 mM, 0.18 mM and 0.2 mM. We fabricated four sensor samples with the alginate substrate. Each glucose concentrations were then drop-casted onto the individual sensors. Similarly, for lactate samples, we formulated 4 concentrations of lactate: 5 mM, 10 mM, 15 mM and 20 mM.

For carbon dioxide samples, we placed the sample functionalized with Bromothymol Blue (BTB) and placed it inside an enclosed beaker. We then made a small inlet for exposing the sensor to Carbon Dioxide. To systematically measure the sensor response for varying concentration levels, we placed a commercial CO_2 sensor[10] inside the beaker for baseline ppm levels in the beaker. The baseline carbon dioxide level inside the laboratory was 400 ppm. We measured the sensor response from varying ppm levels of carbon dioxide ranging from 400-800 ppm. Higher levels of carbon dioxide can drastically deteriorate the air quality. Hence, we chose this range to keep in line with the safety measures of the laboratory environment.

[10]https://www.amazon.com/Newentor-Detector-Temperature-Classrooms-400-5000ppm/dp/B09PHHYGZK/

For pH sensors, we prepared four samples which were exposed to the following pH levels: 12, 13, 2, 1.5. Once the samples provided colorimetric response, their spectral response was analysed.

All the samples were then analyzed using a Spectrophotometer (Agilent Cary 60 UV-VIS Spectrometer). We measured the spectral response across the entire UV-VIS spectrum ranging from 250-800 nm. For all the samples, we initially took the baseline measurements i.e. measurements of just the substrate+assay (before exposing the sensor to analyte).

6.1.2 Results. Figures 9, 10 and 11 show the spectral response for each of the sensors. Firstly, it is clear that the sensor exhibit a wider range compared to the simple colorimetric sensors which usually have spectral response in the visible light spectrum [~350-700 nm] [38]. All the sensors exhibited high levels of absorption in the UV spectrum [250-300 nm]. This spectral response is very similar to the Bragg-coated 2.5D holographic sensors which exhibited a range between 300-900 nm [86].

For glucose and lactate sensors, there is a clear difference in the spectral response for each concentration level. For the carbon dioxide sensors, there is more variation in the absorption levels for each concentration. This is because the original BTB assay is darker in colour resulting in high absorption levels. However, as the sensors are exposed to high concentrations of carbon dioxide, they turn into a lighter yellow colour resulting in relatively lesser absorbance levels. As seen in Figure 11(a) there are peak absorption levels at two intervals [420-460 nm] and then at [630-650 nm]. At both these frequency ranges all the substrates demonstrated high absorption levels while maintaining distinct differences between each of the concentrations. A design implication for this is that the hardware setup can be finetuned to have LEDs emitting these wavelengths (e.g. 630-650 nm corresponds to red light, hence red LEDs can allow for optimal sensing quality).

For acidic pH sensing, again, there is a clear distinction between the original BTB solution and the rest of the pH levels. For this, there are two peaks, the first one in the range [390-410 nm] which corresponds to a violet colour. Similarly, smaller peaks can be observed at [630-650 nm]. An extremely alkaline pH value of 13 demonstrates the highest absorption level. Secondly, at ~550 nm, the absorption levels are similar across the conditions. A design implication for this is that these wavelengths should be avoided. Finally, a wavelength of [400-430 nm] seems the most suitable as the absorption levels at this wavelength are very distinctive.

6.2 Quantitative Estimation

In this experiment, we were interested in understanding the compatibility between our hardware setup and the substrate materials. Our central research question is : *Can we reliably estimate the concentration of analyte based on the LDR measurements?*. Secondly, we were also interested in understanding how substrate materials influenced this quantitative estimation.

6.2.1 Method. We performed this experiment with all the substrate materials and assay modalities. For each substrate material and an assay, we formulated the same levels of concentrations as in the previous experiment (i.e. 0.12, 0.15, 0.18, 0.20 mM for glucose and so on.). This results in a total of 6 (substrate materials) × 20 (samples)

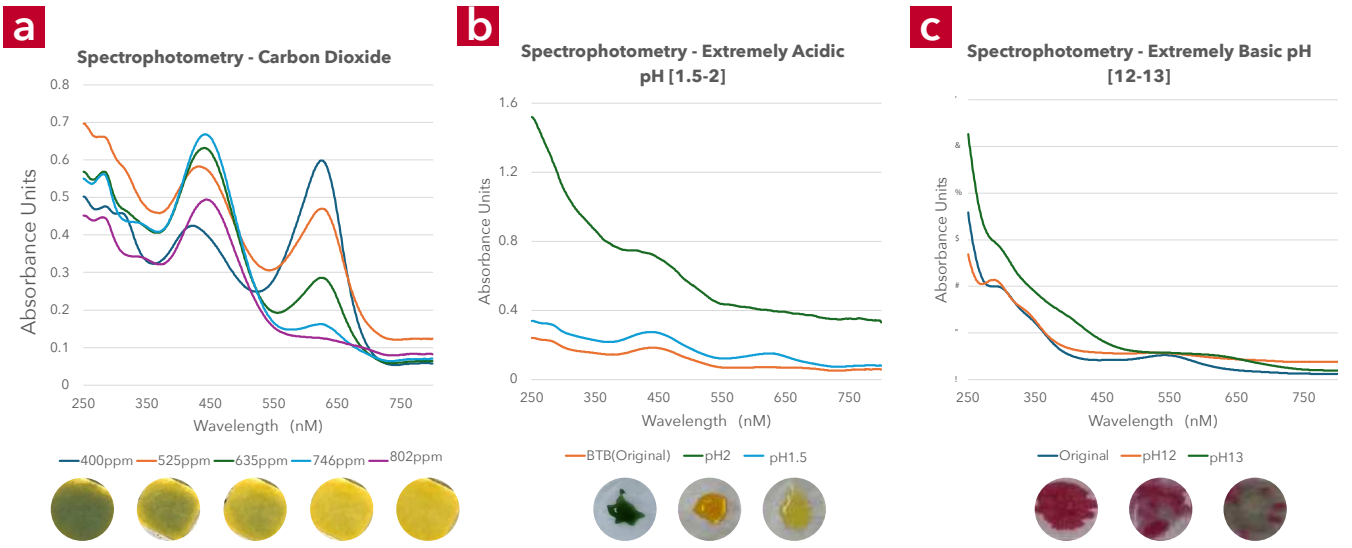


Figure 11: Spectrophotometry results for pH and Carbon Dioxide sensors.

× 4 (4 concentrations for each assay) = 480 samples. Additionally, we also collected the data from the baseline samples (i.e. samples with just the assay = 120 samples). This resulted in a total of 600 samples. Each sample was exposed to the LDR-LED setup that we designed previously. To control the ambient light, we performed this experiment inside a black cardboard box where the sensor was exposed to the LED-LDR arrays. For each sample, we collected the data from all the LDRs for 30 minutes at a sampling rate of 50Hz.

6.2.2 Results. After data collection, we annotated the data appropriately with the analyte type and the concentration levels. For each modality, we built a Time-series Random Forest regression model (default parameters) on the data to understand how each of the substrates performs in accurate quantitative estimation. Overall, our model was successful in predicting the values of glucose or lactate based on LDR values and the time elapsed. The overall goodness of fit (R^2) for glucose, lactate, carbon dioxide and pH are 0.87, 0.91, 0.94, 0.93 respectively.

7 PRELIMINARY USER STUDY

We performed a controlled experiment to understand the performance of glucose and lactate biosensors on human skin. We were interested in understanding if our sensors can detect glucose and lactate when deployed on the skin. *Can we reliably detect the levels of glucose and lactate when the corresponding biosensor is placed on the human skin?*

We recruited 8 healthy participants (4 female, 4 male, mean age:23.625, sd: 1.22) for this experiment. For each participant, we were interested in understanding whether our sensors can detect levels of glucose and lactate. For this, we prepared predefined samples of sweat. We performed this experiment in a controlled manner with predefined sweat samples for the following reasons: (1) Firstly, it allows us to systematically understand the sensor response on human skin with various concentration levels of glucose and lactate.

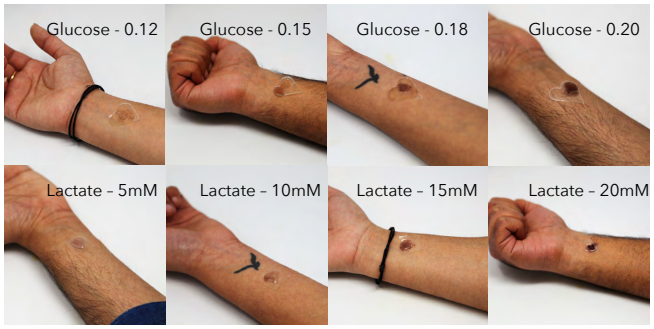


Figure 12: Results from a preliminary user evaluation demonstrate that the biosensors function on human skin and produce noticeable changes in colour for both glucose and lactate.

(2) It allows us to compare and contrast the sensor response between biomarkers and concentrations. (3) Naturally, it is hard for humans to control their perspiration to ensure that the sweat contains specific biomarkers (for example, lactate levels in sweat have a correlation with the underlying metabolic and physical activities which is hard to control involuntarily). Similarly, it is also not practically feasible for us to perspire in a way that we secrete specified levels of glucose.

7.1 Method

For each participant, we fabricated two sensor samples, one for lactate sensing and the other for glucose sensing. We formulated four concentrations of lactate: 5 mM, 10 mM, 15 mM, 20 mM. Similarly,for glucose, we formulated four concentrations: 0.12 mM, 0.15 mM, 0.18 mM and 0.2 mM. We chose these concentrations because these are the typical concentration levels of lactate and glucose found in sweat [54, 68, 87].

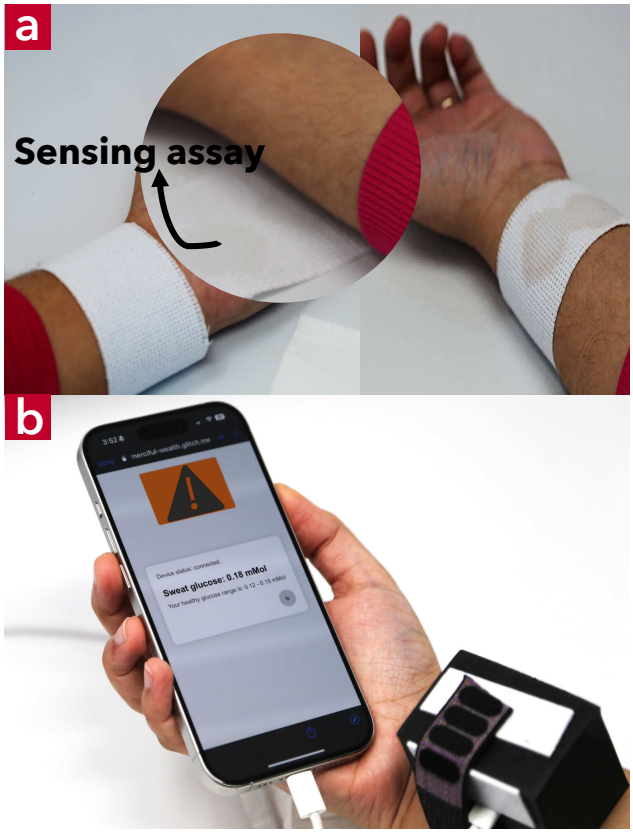


Figure 13: Sweat sensors that detect glucose levels. (a) A fabric wristband functionalized with a glucose-sensing assay on the inner side. (b) The sensor connected to a smartphone displays the sweat glucose level, indicating the measurement results.

We also had two samples of artificial sweat without these biomarkers. For each participant, there were two biomarker conditions: lactate and glucose. We counterbalanced the order of presentation of the biomarkers and randomized the concentration levels for each biomarker. We used alginate as the base substrate material and functionalized it with appropriate levels of glucose or lactate (depending on the experimental condition). We placed the sensor on the lower anterior side of the forearm, near the wrist. For each biomarker condition, we initially exposed the sensor to baseline sweat samples (without glucose or lactate) and after this, the sensor was exposed to a randomly chosen concentration of the biomarker. The user wore each sensor for 40-50 minutes. During this time, participants were free to do their routine activities. After each condition, the sensor was detached from the skin, the skin site was cleaned, and the same process was repeated for the second biomarker condition. The entire experiment took 90-120 minutes. The entire experiment was approved by our institutional research ethics board.

7.2 Results

Overall, the results from the user evaluation show that our sensors can successfully detect varying levels of glucose and lactate levels in sweat. The skin type and colour also did not influence the sensor response. All participants expressed that the lightweight form factor of the sensor was unnoticeable while wearing and did not cause any distraction during their activities. Figure 12 shows the colorimetric response of the sensors on the users' skin for different concentrations on the skin. It is worth noting that all the changes in colour are clearly visible. Our preliminary study also highlights human factor considerations in designing epidermal biosensors. We observed inconsistencies in the way sweat reacts with the assay. For instance, in the case of glucose sensors (0.15,0.18,0.20), it can be noticed that the response is produced on the edges of the sensor. Hence a crucial step in fabrication is to evenly spread the assay throughout the entire area of the sensor.

8 APPLICATIONS

While sensing biomarkers has a wide variety of applications in various domains, in this section, we highlight how our sensors can be used for various applications in biosensing and environmental monitoring.

8.1 Glucose Sensing Wristband

The glucose levels in sweat have a direct correlation with the blood-glucose levels [54]. To enable continuous sensing of glucose levels from sweat, we fabricated a wristband made of woven fabric(Figure 13(a)). Velcro straps affixed at both the ends of fabric help to maintain tight contact with the skin. On the inner side of the band, we drop-casted glucose sensing assay(Figure 13(a)(inset)). The assay is almost transparent and once dry, camouflages nicely with the fabric. When the sweat reacts with the glucose, the colorimetric response is visible as stains on the sweatband(Figure 13(a)). For providing timely interventions to the user, we developed a smartphone application which displays the glucose levels of the user and provides notifications when the levels are beyond the prescribed limits for the user. (Figure 13(b)).

8.2 Monitoring Physical Activity through Lactate Sensors

Previous studies have reported that excessive lactate concentrations in sweat can be due to exercise-induced muscle fatigue [41]. Additionally, lactate concentration can also increase when soft tissue is subjected to different degrees of pressure loading as well as local tissue ischemia and hypoxia [72]. Hence lactate measurements from sweat can be crucial for measuring muscle fatigue and also for oxygen supply in tissues. For continuous lactate measurements, we fabricated a custom-shaped (Figure 14(a)) lactate sensor with alginate as the base substrate. The device is placed near the wrist and changes its colour depending on the lactate levels in sweat(Figure 14(b)). In this scenario, we developed a VR exercising app that monitoring the muscle fatigue based on the lactate levels of the user. The application consists of a 360 degree VR video and displays the live lactate levels from our sensing hardware. As the user performs the exercise by following the instructions, the app also constantly monitors the lactate levels (Figure 14(c)). When the lactate levels are beyond the threshold (e.g. 20 mM), a notification appears on the VR headset recommending the user to take a break(Figure 14(d)).

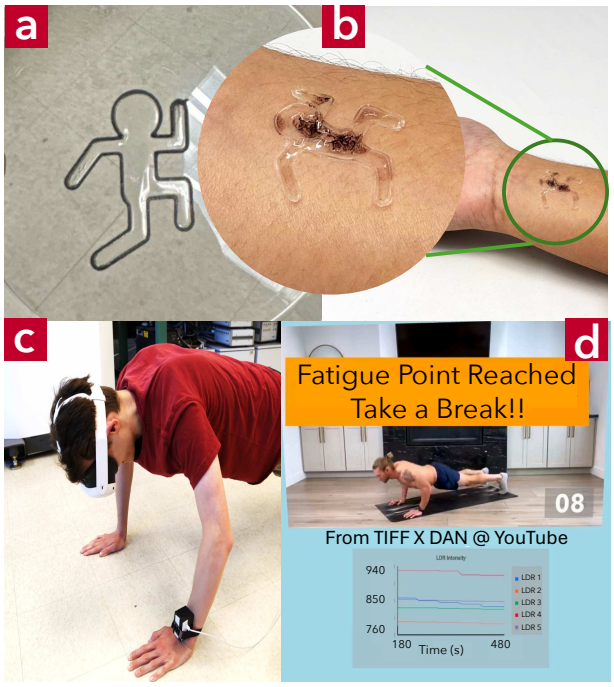


Figure 14: Monitoring physical activity and fatigue using a sweat sensor. Sweat sensors that detect lactate (a) lactate sensing patch customized to denote physical activity (b) sensor changing color from transparent to dark brown.(c)A user performing a push-up exercise while watching a VR exercise video on a head-mounted display (VR headset) and the holographic device on their wrist. (d) The sensor's data displayed on the screen and a prompt indicating that the fatigue point has been reached and suggesting the user take a break.

8.3 pH Sensing patch for Soil and Water Monitoring

Soil and water pollution are now being increasingly prevalent across the world. High levels of alkaline or acidic content in soil can lead to a deficiency of many nutrients, a decline in microbial activity, a decrease in crop yields, and a deterioration of soil health. Inspired by recent HCI research which has focused in sensing and interactive systems for agriculture [47], we fabricated sensors to test and evaluate soil health. We fabricated two fabric pH sensors (one base and one acidic) which can detect the acidity or alkaline levels in the soil. The acidic pH sensor turns from greenish-yellow to yellow indicating that the soil is highly acidic (Figure 15(a and b)). Similarly, if the soil is alkaline the sensor changes from red to gray. Similar to soil, industrial waste is one of the main reasons for polluting water and visually it is very hard to determine if the water is highly alkaline or not. A pH sensor fabricated with hibiscus tea can quickly identify if the water is safe to use or not (Figure 15(e and f)). We believe that HoloChemie devices can add an additional sensing layer to the existing approaches in smart agriculture.

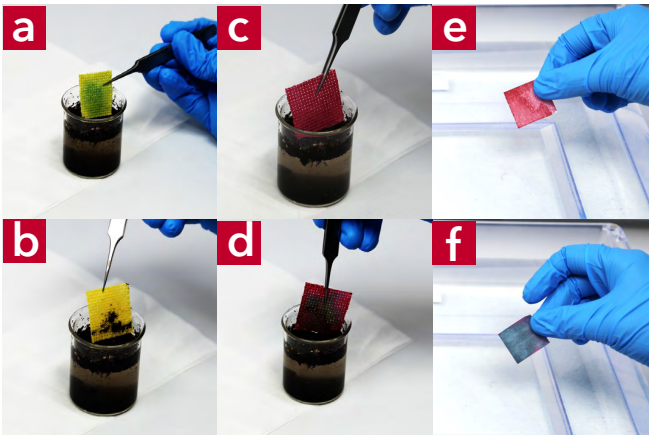


Figure 15: pH sensor for soil and water quality monitoring. (a) Sensing acidity levels in the soil. (b) After dipping the sensor changes its color to yellow. (c) Sensing alkaline content in the soil. The default colour of the sensor made from anthocyanins in hibiscus tea is red. (d) When in contact with soil that has high levels of alkaline content, it turns gray. (e) Water monitoring: chromatography paper patch coated with the pH sensing assay from hibiscus tea. (f) When dipped in alkaline water turns gray warning that water is harmful.

8.4 Indoor Air quality measurement in Maker Spaces

Maintaining high indoor air quality is one of the most important safety requirements for running maker spaces. This is because there is a lot of equipment (e.g. 3D printers, laser cutters etc.) contributing to poor air quality. While air quality monitors can give an overall measurement, highly localized equipment level measurements are challenging and expensive. To alleviate this, we fabricated carbon dioxide sensors on all six substrates and integrated them into an SLA printer(Figure 16). As the SLA printer runs the print jobs, the carbon dioxide emitted during the process turns the sensors yellowish-green. After prolonged printing, they turn dark yellow indicating that air quality needs to be improved.

9 DISCUSSION LIMITATIONS AND FUTURE WORK

9.1 Degradation and Decomposability

All of our sensors are reusable and are designed to be disposable and decomposable in a very short period of time without specialized industrial conditions. As a sanity check, we buried all our samples coated with the assays in the soil to observe the decomposition. We buried the samples under 5cm of soil in an upright position. The soil was black chernozemic soil with a moisture content of 40% as measured by a handheld moisture meter at the beginning of the study. Every 3 days, we dug the soil to check the condition of the samples. Over the duration of 2 weekdays, we noticed the assay disintegrated with very small amounts of residue still present on the substrate(Figure 17). Some substrates, such as alginate, completely decomposed within 3 days. We also noticed that the fabric samples

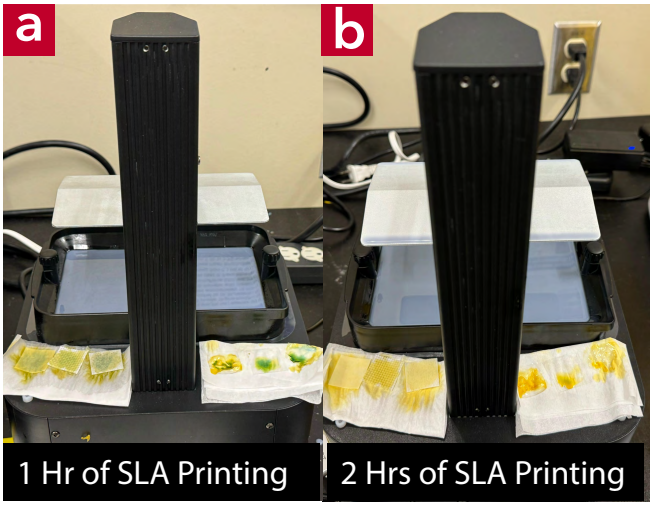


Figure 16: Passive CO_2 sensors can be great indicators of indoor air quality in maker spaces. (a) We placed the CO_2 sensors fabricated on all the substrates inside a SLA 3D printer (FormLabs). After 1 hr or printing the changed their colors from greenish to yellow and (b) after 2 hrs of printing, they turn completely yellow indicating higher volume of CO_2 in the maker space.

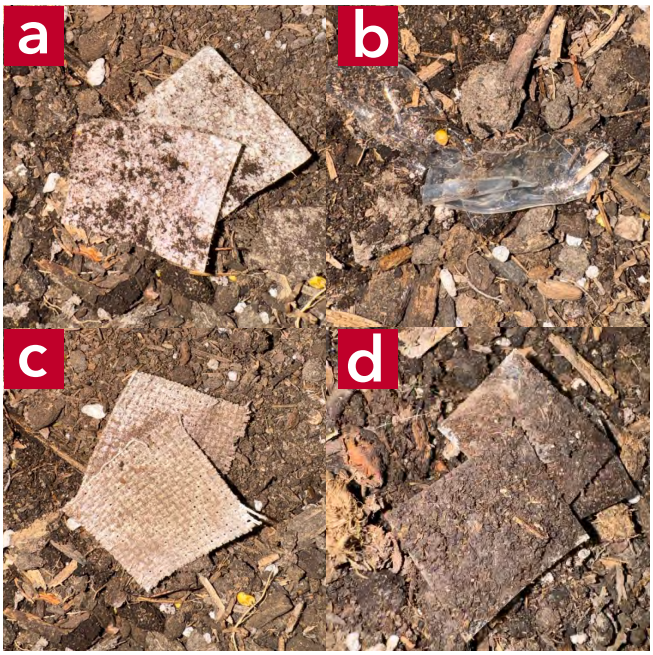


Figure 17: Biodegradability test: We buried all our substrate materials functionalized with the assays in soil. All the materials decomposed naturally.

Materials	Initial Weight (mg)	Final Weight (mg)	Weight Loss(%)
Alginate Sheet	238.0	142.8	40
Agarose Sheet	43.2	1.72	96
Woven Fabric	390.0	265.2	32
Non Woven fabric	290.4	145.2	50
Chromatography paper	369.1	184.55	50
Tattoo paper	394.5	3.95	99

Table 3: Biodegradation: Results from the biodegradation and decomposability tests.

started disintegrating but at a much slower pace when compared to other alginate or agarose. We also noticed final and microbial activity on a few of the substrates. This is unsurprising since all our components are known to be decomposable.

9.2 Sensor Customization

For biosensing, all the assays that we formulated are calibrated for healthy users. However, for measuring glucose or lactate levels that are beyond the normal range, we need to recalibrate the formulation. This is because of the underlying chemical reaction that drives the response. For sensing larger amounts of lactate, the amounts of lactate oxidase and KI-starch solution need to be increased. This is to ensure that there is a proportional amount of H_2O_2 being generated which in turn drives the colorimetric response.

9.3 Personalized Sensor Calibration

Additionally, the time for the entire chemical reaction to be completed is dependent on the analyte concentration and the catalyst in the assay. While the colorimetric responses are always the same irrespective of the volume of the assay, the time taken for the response to be visible varies. For e.g., if 5 mM lactase is dropped onto an assay designed for sensing 20 mM of lactase, then it takes a longer time for the response to show up. This is because the chemical reactions take more time to complete owing to the higher concentration of the assay. Hence, the usual practice is to optimize the assay, tailored to a user, to sense a specific range depending on the user's prior history.

9.4 Wide-Accessibility

One of the key design goals for the fabrication of HoloChemie sensors is wide accessibility. However, our fabrication process does require meticulous procedures for preparing the sensing assays. However, this is the first step in democratizing the fabrication of biochemical sensors by eliminating the need for infrastructure and equipment such as wet lab, fume hood, centrifuge, spin coater etc. We believe that future efforts will further simplify the process.

9.5 Vegan-Friendly Fabrication

A key design goal for developing our fabrication processes was vegan friendliness. As a result, all our substrates and functional materials have been bio-sourced. We aimed to create a vegan-friendly fabrication approach because the use of certain animal products does not fit into the cultural practices of a few communities. Hence, utilizing vegan-friendly materials in fabrication can lead to broader adoption. However, we acknowledge that certain aspects of our fabrication process are beyond our control (e.g., the extraction process of bacteria may be unsustainable and not vegan-friendly).

9.6 Influence of Environmental Factors

Environmental factors influence the functionality of enzymes. For instance, the pH levels and temperature are the most important factors. This is the reason, we used PBS to maintain ideal pH levels for both enzymes. The maximum operating temperature for the enzymes used in this work is 48 degrees Celsius (119 Fahrenheit). Hence all these sensors can function well on the human body (the temperature of the human body is 37 degrees Celsius). From our own experience, we did not encounter any issues in the formulation of enzymes. Improving the thermal stability and the overall resilience of enzymes is an active research area in chemistry and biomedical engineering.

9.7 Long-term and In-the-Wild Monitoring

Unlike ECG or EMG signals, biochemical reactions are not instantaneous. This is also because humans take time to sweat and the sweat gland activity highly varies across body locations due to the varying density of eccrine sweat glands. There are interpersonal differences in how people sweat. Hence to have a controlled evaluation of our sensor's response to these biomarkers we opted for an in-vitro evaluation. Secondly, we were also interested in characterizing the performance of the sensors. Hence controlled experiments are most suitable for this task. However, in the future, we aim to deploy these sensors in the wild, where participants would wear the sensor over longer durations.

9.8 Additional Biomarkers and Environmental Pollutants

In this work, we mainly focused on detecting glucose and lactate along with carbon dioxide and pH levels. To detect additional biomarkers, the main objective of future work should be to focus on understanding the biology, (what is the biomarker, what is the correlation between its composition in sweat and composition in the body), biochemistry of the biomarker (the chemical structure and its reactivity), and its usual composition in sweat. This helps in identifying the appropriate material that can catalyze redox reactions. For future work, we also aim to fabricate sensors that detect additional biomarkers such as stress biomarkers, such as cortisol, alpha-amylase, pro-inflammatory cytokines (a key signifier of mental stress levels) and ascorbic acid (Vitamin C levels) For environmental sensing, sensing VOCs in maker spaces can be a viable next step.

9.9 Advanced Holographic Setup

This work explored the simplest form of holographic sensing which is based on the absorption of light. However, sophisticated holographic setups typically employ additional parameters such as diffraction levels, reflectance levels, changes in refraction index, Bragg gratings and so on. However, these also require more complex experimental setups and hardware prohibiting wearable and portable use. Future work should look into developing novel sensors based on this principle for applications in HCI.

9.10 BioChemical Sensing for Human-Computer Interaction

The use of biochemical signals can provide richer insights by capturing the mental and physical state of the user. For instance, lactate levels have direct correlation with physical activity and can be used for designing adaptive interfaces that can predict motion sickness levels of user in VR. Similarly, they can be used for activity recognition by sensing the lactate levels in sweat (lactate is a biomarker that increases during endurance and exhaustive exercising). In addition to sensing chemical and metabolite activities in the human body, biochemical sensors can also be used for environmental sensing. For instance, they can be used for sensing exposure to pollutants (e.g. carbon monoxide) or UV exposure. In the realm of ubiquitous computing, they could also be deployed for tracking eating habits by sensing specific types of metabolites and chemicals in the food.

10 CONCLUSION

In this work, we explore the biochemical aspects of living matter to create sensors for biological and environmental sensing. Firstly, we contribute a set of biochemical formulations for biological and environmental sensing which are compatible with bio-sourced and environment-friendly substrate materials. Our formulations are based on a combination of enzymes derived from bacteria and fungi, plant extracts and commercially available chemicals to sense both liquid and gaseous analytes: glucose, lactate, pH levels and carbon dioxide. Our holographic sensing scheme not only allows for the detection of the presence of analytes but also enables quantitative estimation of the analyte levels. Results from our technical experiments show that the sensors have a spectral response that enables the differentiation of concentration levels precisely. Results from a preliminary user study show that the sensors can measure the glucose and lactate levels from sweat. We presented four application scenarios that demonstrate the versatility of our approach and finally discuss the sustainability aspects, limitations, and avenues for future work. **We believe that this work will open up the vast research of biochemical sensing for various HCI applications.**

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