ECE 445 Design Lab Proposal
Kombucha Brewer

By
Rudy Beauchesne
John Puthiaparambil
Edwin Xiao

Proposal for ECE 445, Senior Design, Spring 2026
TA: Haocheng Bill Yang

Project No. 27

1.1 Introduction

Kombucha is a fermented tea made by combining sweetened tea with a SCOBY (a symbiotic culture of bacteria and yeast) and letting it sit for days while the microbes convert sugar into organic acids and other compounds. During this process, the culture also produces a cellulose pellicle, often treated as a byproduct by home brewers but increasingly valued as a biomaterial that can be processed into a vegan leather-like sheet. Because both the drink and the cellulose depend on the same fermentation environment, consistent conditions matter for flavor and for reliably producing usable cellulose.

The issue is that home kombucha fermentation is easy to start but hard to repeat. Most people brew in a jar on the counter, cover it with cloth, and rely on rough rules of thumb: keep it warm, keep it slightly acidic, and wait until it tastes right. In practice, small day-to-day changes—like room temperature swings, different starter strength, or inconsistent timing—can make fermentation run too fast, too slow, or stall entirely. That leads to batches that don't match the intended taste, take longer than expected, or get discarded due to off-smells, mold concerns, or other signs something went wrong—wasting time and ingredients. For anyone trying to make cellulose consistently, the variability is even more frustrating because pellicle thickness and quality can change significantly from batch to batch.

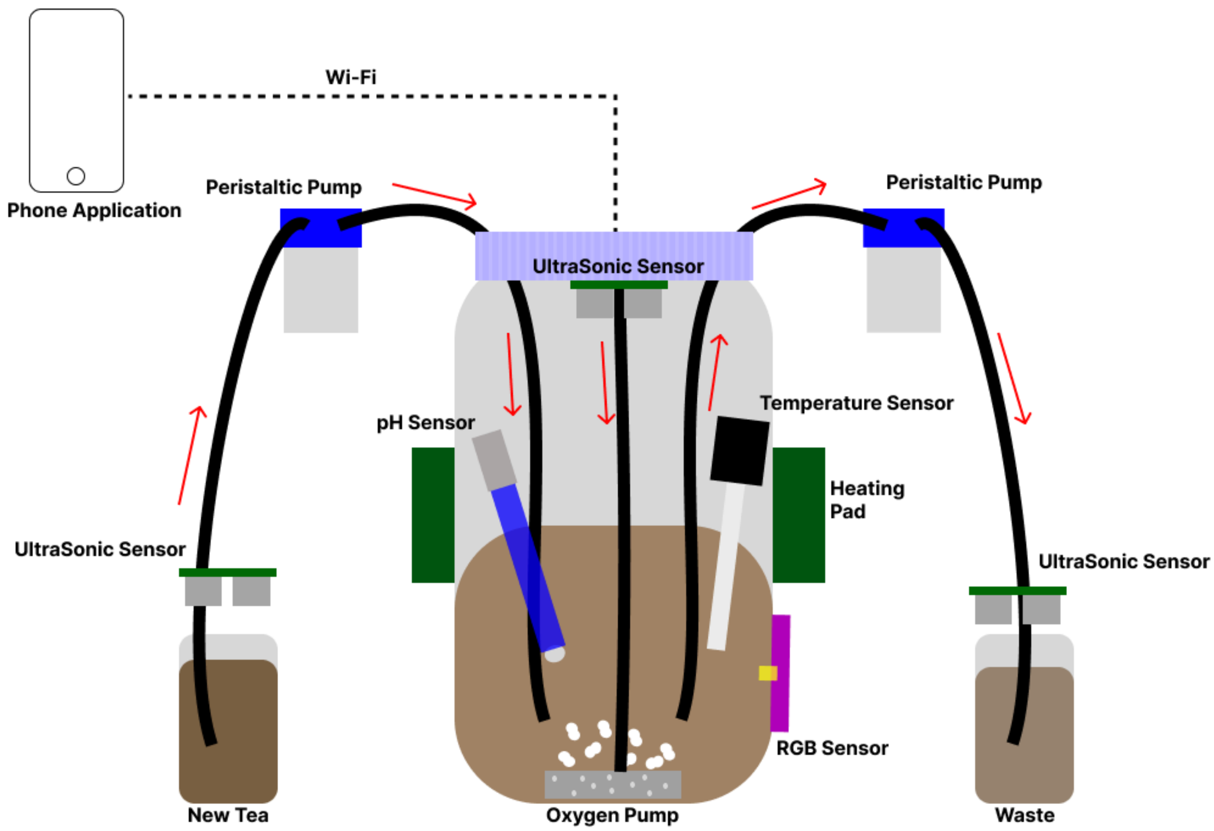
Current solutions mostly fall into two extremes: expensive all-in-one brewers that automate the process, or low-cost DIY setups that still depend on manual checks and intuition. There's a gap in the middle for a practical, low-cost system that helps people get repeatable results by tracking core conditions (mainly warmth and acidity) and giving clear feedback throughout fermentation, without turning home brewing into a constant monitoring chore.

1.2 Solution

We propose a low-cost, closed-loop kombucha brewing system designed to make home fermentation more consistent and repeatable. Kombucha quality is strongly influenced by environmental and process conditions—especially temperature, oxygen exposure, nutrient availability (tea/sugar), acidity (pH), and cleanliness—and small variations can cause fermentation to run too quickly, too slowly, or stall.

To address this, a microcontroller on a custom PCB continuously reads a set of sensors to track fermentation conditions and progress, including temperature, pH, RGB color (as a proxy for visual changes), and ultrasonic for liquid level. Using these measurements, the system can drive a heating pad to maintain a warm, stable environment and control peristaltic pumps to add fresh tea or remove liquid based on user-defined targets (e.g., maintaining volume, managing feed timing, or supporting consistent batch scheduling). The design will also support an aeration module (small air pump) to provide controlled airflow during primary fermentation. A companion web-based dashboard displays real-time status and logs trends over time, allowing users to monitor fermentation at a glance without constant manual checks.

1.3 Visual Aid

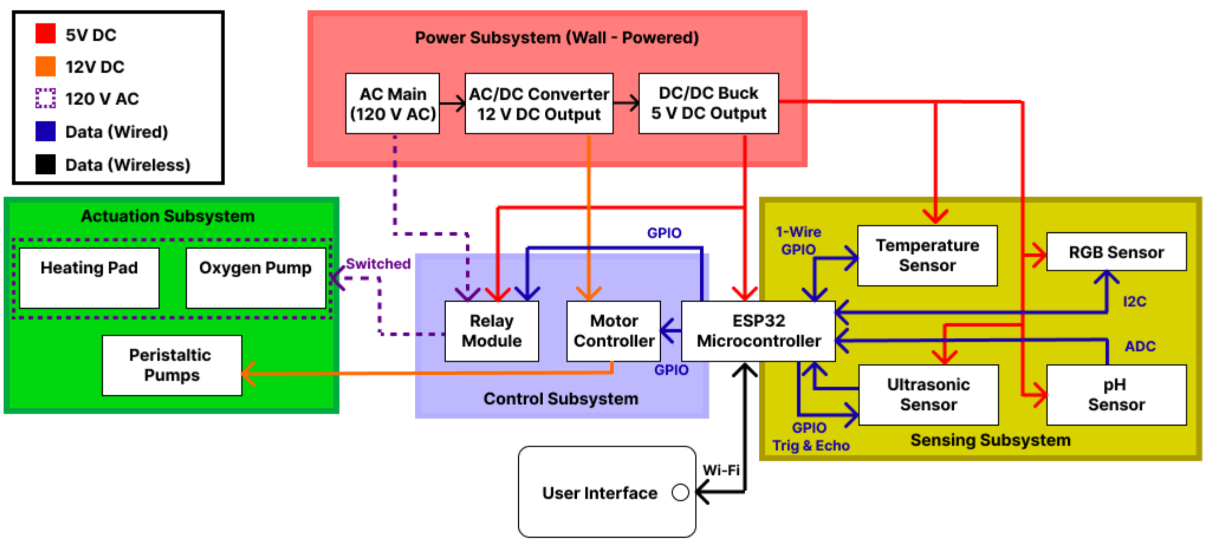


1.4 High-level Requirements

Because full kombucha fermentation takes days, we will validate the system using a short demonstration that begins from deliberately “off-condition” states (cold liquid, shifted acidity, and an incorrect color proxy) and then shows the system measuring conditions in real time, responding appropriately, and trending back toward user-defined target ranges. These high-level requirements are therefore chosen to be measurable within a single demo session while demonstrating the project’s core capabilities: closed-loop temperature control, pH sensing, and color-based feedback with live logging to the dashboard.

- **Temperature control:** Starting with the jar filled with ice water (liquid temperature ≤ 5 °C), the system shall heat the liquid to a user-defined setpoint and reach within ±1.0 °C of that setpoint within 15 minutes.
- **pH trending (demo acidification):** Starting from the initial ice-water condition, the system shall decrease the measured pH by at least 1.5 pH units within 10 minutes by pumping in an acidic (vinegar-based) solution, and the pH reading shall have ±0.3 pH repeatability over any 5-minute window during the demo.
- **Color sensing:** During the same demo interval, the system shall compute HLS values from the color sensor and detect a clear shift toward a predefined "tea-brown" target band as the brown vinegar solution is introduced, demonstrated by either a hue change of at least 15° or a saturation change of at least 0.10 (normalized 0–1).

2.1 Design



2.2 Subsystem Overview

Power Subsystem (Wall-Powered): The power subsystem converts wall power (120 VAC) into the regulated DC rails needed by the electronics. An AC/DC converter generates a 12 V DC rail, which is used for higher-power loads (e.g., peristaltic pumps via the motor driver) and is stepped down through a DC/DC buck converter to a 5 V DC rail for the ESP32, relay module, and sensors. This subsystem connects to the Control Subsystem by supplying 5 V/12 V for control hardware, and it connects to the Actuation Subsystem by providing the power used by the actuators (directly or through switching elements).

Control Subsystem: The control subsystem is the “brain” of the system and consists of the ESP32 microcontroller along with the relay module and motor driver circuitry. The ESP32 reads sensor measurements from the Sensing Subsystem, runs the control logic (setpoints, thresholds, and recovery behavior), and then commands the actuators through control signals. It interfaces to the relay module using GPIO (on/off control) to switch the AC heating pad and oxygen pump, and it interfaces to the motor driver using GPIO/PWM to control the 12 V peristaltic pumps. The control subsystem also communicates wirelessly with the User Interface over Wi-Fi for live status and logging.

Sensing Subsystem: The sensing subsystem measures the key fermentation conditions and provides those measurements to the ESP32 for monitoring and control. It includes a temperature sensor (1-Wire), an RGB color sensor (I^2C, later converted to HLS in software), an ultrasonic sensor (GPIO trig/echo) for liquid level/height, and an analog pH sensor interface (ADC) for acidity tracking. This subsystem connects to the Power Subsystem for regulated sensor power and connects to the Control Subsystem through wired data lines so the ESP32 can continuously sample and log conditions.

Actuation Subsystem: The actuation subsystem contains the components that physically change the brewing conditions based on commands from the controller. It includes the heating pad and oxygen pump, which are powered from 120 VAC and switched through the relay module, and the peristaltic pumps, which are powered from 12 V DC and driven through the motor driver. This subsystem connects to the Power Subsystem for the energy required to run the loads and connects to the Control Subsystem through the relay/motor driver control inputs that determine when each actuator is turned on and how strongly it is driven (e.g., PWM for pump speed).

User Interface: The user interface provides an accessible way for a user to view system status without needing manual measurements. The ESP32 hosts or communicates with a simple dashboard over Wi-Fi that displays live readings (temperature, pH, color/HLS, and level) and logs trends over time for debugging and repeatability. This subsystem connects to the Control Subsystem wirelessly and does not directly power or control any hardware; it primarily supports monitoring, configuration (setpoints), and demonstration of real-time operation.

2.3 Subsystem Requirements

Power Subsystem (Wall-Powered)

The Power Subsystem distributes energy to all subsystems and enables the high-level demo requirements by ensuring the controller, sensors, and actuators can operate simultaneously without brownouts or measurement instability. It converts 120 VAC wall power into regulated DC rails for the ESP32, sensors, relay module logic, and motor driver/pumps, while also providing the AC feed that is switched to the heating pad and oxygen pump.

Interfaces:

- Input: 120 VAC (outlet), 60 Hz
- Outputs:
  - 12 V DC rail → Motor driver and peristaltic pumps
  - 5 V DC rail → ESP32 dev board, sensors, relay module logic
  - Common GND shared across DC subsystems

Subsystem requirements:

- Must accept 120 VAC ±10%, 60 Hz input power.
- Must supply 12.0 V DC ±10% at ≥0.5 A continuous (supports two 12 V pumps at 80 mA nominal each with margin for startup).
- Must supply 5.0 V DC ±5% at ≥1.5 A continuous (ESP32 peaks + relay coils + sensors).
- Must keep 5 V rail noise/ripple low enough to avoid resets and unstable ADC behavior (e.g., ≤200 mVpp ripple under typical load).
- Must provide a shared ground reference between ESP32, motor driver, and sensor grounds.

Control Subsystem

The Control Subsystem is the “brain” of the system. It reads the sensor measurements, executes control logic, and generates commands for the actuators. It enables the high-level requirements by switching the heating pad to raise temperature from an off-condition start, commanding peristaltic pumping to drive a measurable pH decrease and visible color shift, and streaming/logging sensor data to the dashboard for the demo.

Interfaces:

- 5 V DC rail (to ESP32 dev board VIN/5V and relay module VCC)

- **Sensor interfaces:**
  - TCS34725 color sensor: I^2C (100 kHz or 400 kHz)
  - DS18B20 temperature sensor: 1-Wire on one GPIO
  - Ultrasonic sensor(s): GPIO timing (TRIG output, ECHO input)
  - pH board: ADC input (scaled to ESP32 ADC range)
- **Actuator interfaces:**
  - Relay module input(s): GPIO on/off
  - Motor driver input(s): GPIO/PWM for pump control
- **Wireless:** Wi-Fi link to dashboard

Subsystem requirements:

- Must sample and log temperature, pH, and color/HLS data at ≥1 sample/second during the demo.
- Must update actuator outputs (relay and pump commands) with a control update period of ≤1 s.
- Must drive relay module inputs using 3.3 V logic-level GPIO and ensure relay default state is OFF at boot (pin choice + pull-ups).
- Must provide pump control signals to the motor driver using GPIO/PWM, where PWM (if used) is ≥500 Hz to avoid very slow pulsing behavior.
- Must ensure any analog signal entering ESP32 ADC is ≤3.3 V under all conditions (divider/conditioning on pH output if board is 5 V powered).
- Must stream dashboard updates with ≤2 s end-to-end latency during the demo.

Sensing Subsystem

The Sensing Subsystem measures the brew conditions and generates the data needed to demonstrate the high-level requirements: temperature recovery, pH trending, and color/HLS trending. Sensor outputs are read by the ESP32 and displayed/logged in real time on the dashboard to verify performance during the demo.

Interfaces:

- 5 V DC rail (sensor boards); 3.3 V logic where applicable
- Data outputs to ESP32:
  - I^2C (color sensor)
  - 1-Wire (temperature sensor)
  - GPIO timing (ultrasonic TRIG/ECHO)
  - Analog voltage (pH board → ADC)

Subsystem requirements:

- **Temperature (DS18B20):** must provide temperature readings at ≥1 Hz and support verifying control within ±1.0 °C of setpoint at steady state.
- **Color (TCS34725 → HLS in software):** must provide RGB readings at ≥1 Hz to compute HLS and demonstrate a color trend toward a target band, with detectable change defined as Hue shift ≥15° or Saturation change ≥0.10 (normalized).
- **pH (analog board + probe):** after calibration, must show ±0.3 pH repeatability over any 5-minute window in a well-mixed solution and must be able to track a ≥1.5 pH unit change during the demo.
- **Ultrasonic level:** must produce stable readings suitable for trend logging, with ≤±1 cm repeatability in a stationary jar and a sampling rate of ≥1 Hz.

Actuation Subsystem

The Actuation Subsystem is responsible for physically changing the system state. It enables the demo high-level requirements by applying heat to raise a cold starting solution toward a setpoint and by pumping in a tea-colored acidic solution to drive measurable decreases in pH and shifts in HLS color values. The heating pad and oxygen pump are AC loads switched by relay contacts, while the peristaltic pumps are 12 V DC loads controlled through the motor driver.

Interfaces:

- **Power in:**
  - 120 VAC (switched) → heating pad (6.5 W) and oxygen pump (1.25 W)
  - 12 V DC → peristaltic pumps via motor driver
- **Control in:**
  - GPIO on/off to relay module
  - GPIO/PWM to motor driver

Subsystem requirements:

- **Relay switching (AC):** must switch 120 VAC loads up to at least 0.1 A continuous (covers ~0.064 A expected with margin) and support independent control of heater and oxygen pump.
- **Heating pad:** must be controllable via relay switching and provide 6.5 W of heating power to the jar. For the demo, the actuator system shall demonstrate a measurable heating response defined as either:

    - a temperature rise rate of ≥0.15 °C/min sustained for 10 minutes, or
    - reaching within ±1.0 °C of the setpoint within a time bound appropriate to the chosen demo volume (to be verified during testing).
- **Oxygen pump:** must be switchable on/off via relay control
- **Peristaltic pumps:** two pumps shall operate from 12 V DC and draw ≤80 mA nominal each, and the pumping system shall deliver a net flow rate of ≥70 mL/min (use "per pump" if that is the spec) to achieve the pH/color trending demo within the allotted time.

User Interface (Wi-Fi Dashboard)

The User Interface presents real-time sensor readings and logs trends so the user can monitor fermentation without manual measurements. It supports the high-level demo requirements by clearly showing temperature rise, pH decrease, and HLS color shift over time and by providing timestamped plots/logs that verify continuous monitoring.

Interfaces:

- Wireless: Wi-Fi between ESP32 and phone/laptop dashboard
- Data: temperature, pH, color/HLS, and (optionally) level updates

Subsystem requirements:

- Must display updated temperature, pH, and HLS/color metrics at ≥1 update/second during the demo.
- Must maintain ≤2 s latency from sensor sampling to on-screen update.
- Must log time-stamped sensor data continuously for ≥10 minutes

2.4 Tolerance Analysis

A major risk for successful completion is the pH measurement chain, because the pH probe + conditioning board can drift, is sensitive to noise, and (most importantly) many Arduino-style pH boards output an analog voltage up to ~5 V while the ESP32 ADC input range is 0–3.3 V. If the pH output is not properly scaled, the ESP32 reading will saturate, giving incorrect pH values and preventing us from verifying the high-level requirement of a ≥1.5 pH-unit change during the demo.

To demonstrate feasibility, we design a simple resistor divider so the maximum pH-board output is safely mapped into the ESP32 ADC range. If the pH board output is $V_{pH} \in [0,5]$V and the ESP32 ADC must satisfy $V_{ADC} \leq 3.3$V, we choose a divider:

$$VADC = VpH \frac{R2}{R1 + R2}$$

Select R1=20 and R2=39 kΩ. Then the nominal scaling is:

$$\frac{R2}{R1 + R2} = \frac{39}{20 + 39} = \frac{39}{59} \approx 0.661$$

So at the worst-case input VpH=5V:

$$VADC \approx 5(0.661) = 3.305\,V$$

which stays within the 3.3 V limit (and avoids ADC saturation). With a properly chosen divider (and 1% resistors), the pH board output can be safely and repeatedly measured by the ESP32 ADC. This analysis shows the feasibility of the pH sensing chain and reduces the key project risk by preventing ADC saturation and ensuring meaningful pH trend measurements during the demo.

3.1 Ethical Considerations

Our kombucha brewing system involves food, which we need to be safe about and adhere to the IEEE Code of Ethics. We will be honest in disclosing our limitations and regard public safety with the highest regard. While our system does monitor pH, temperature, and other variables, this does not mean that it is a substitute for actual food safety practices. We will make it clear to users that our system does not detect mold or any kind of contamination. We will also make sure that all users follow proper sanitization methods when handling our system. While the system does monitor pH to aid in food safety, it does not guarantee it. This system is also for home use only and not meant for commercial production. To avoid violating the IEEE Code of Ethics, we will have disclaimers in our documentation and on our system itself when, for example, our pH readings show that it is at a level at which mold and/or bacteria can grow (pH > 4.5).

Our WiFi Dashboard will log data on our fermentation over time. To make sure that this data is private and confidential, we will make sure to follow the ACM Code of Ethics. We will avoid collecting personal information and provide clear documentation on what data we collect and where it is. We will also store all data locally on users' devices. This will make sure our data is not accessed by an unauthorized user.

As for the accessibility and fairness of our system, we designed this system with the idea that it would address the broader market of students, those who are interested in fermentation, and those in low-income households. There are already commercial brewers, but they are expensive to maintain. There are also DIY methods out there, but they are unreliable and hard to replicate. We want to design a system that is accessible to all and does not discriminate against those of different economic backgrounds. Anyone can be interested in kombucha and fermentation, which aligns with IEEE's Code of Ethics.

3.2 Safety Considerations

Electrical Safety

AC Power Hazards: The system switches 120 VAC to power the heating pad and oxygen pump. To comply with **NFPA 70 (National Electrical Code)** and **UL 60950-1** safety standards:

- All AC wiring will be completely insulated and enclosed
- We will use a grounded 3-prong plug and make sure to have proper grounding
- AC and low-voltage DC units will be separated physically on our PCB
- Our enclosure will be non-conductive and prevent contact with live terminals

User Protection: Following campus policy and IEEE recommendations, we will:

- Include a visible warning: "High Voltage - Do Not Open While Plugged In."
- Design the enclosure so that the AC parts are unreachable without special tools
- Test all insulation to make sure it is working before our first start
- Include a circuit breaker for overcurrent protection

Chemical and Biological Safety

Food Contact Materials: All parts in contact with kombucha (the tubing, pH probe, sensors) have to be food-safe. We will use:

- Food-grade silicone tubing (FDA-compliant, BPA-free)
- Stainless steel or glass pH probe (ANSI/NSF 51 certified for food equipment)
- Verify all sensors have appropriate IP ratings for moisture resistance

Microbial Contamination: While the fermentation of kombucha is generally safe due to the low pH conditions (<4.2), unsuitable conditions can allow harmful microbes like mold grow. Safety measures include:

- Dashboard alerts when the pH exceeds 4.5 (USDA food safety threshold)
- Clear instructions for all users to sanitize the equipment before use
- Recommendation to throw away batches showing mold or weird odors

Thermal Hazards

The heating pad has a minimal risk of burning users, but long contact with the skin could cause discomfort. We will:

- Mount the heating pad outside on the jar, which won't be accessible to users when in use
- Limit the maximum temperature setpoint to 32°C (90°F) to prevent overheating
- If the temperature exceeds the setpoint by more than 3°C, we will cut power to the heater

Regulatory Compliance

- **UIUC Campus Policy:** All electrical projects must be reviewed by course staff before energizing. We will submit our power subsystem design for approval by our TA before testing with AC power.

3.3 Societal Impact

Our low-cost brewing system, which will be around $80 to $100, opens the door for students, low-income households, and communities exploring sustainable food production. This is an alternative to the expensive commercial brewers, which can cost a few hundred dollars. The system decreases waste from batches that failed and beverage containers that we only use once. We do have some e-waste from our PCBs and sensors, but we will reduce that through a modular, repairable design and clear instructions on how to recycle its parts. The system consumes the tiniest power at around 10W at its peak. Our system is self-sufficient in food production. While designed for reliable electricity and Wi-Fi, we can modify our system to have simpler displays, battery power, or even passive methods of heating our system. A lot of cultures around the world use fermentation (like Korean kimchi!), and our system respects these very diverse practices for fermentation. While respecting these cultures, we maintain food safety through our pH sensors and user alerts.

4. References

[1] D. Ozkan, M. Dade-Robertson, R. Morrow, and M. Zhang, "Designing a living material through bio-digital-fabrication - guiding the growth of fungi through a robotic system," Proceedings of the 39th International Conference on Education and Research in Computer Aided Architectural Design in Europe (eCAADe), 2021. doi:10.52842/conf.ecaade.2021.1.077

[2] F. Bell, D. Chow, H. Choi, and M. Alistar, "Scoby breastplate: Slowly growing a microbial interface," Proceedings of the Seventeenth International Conference on Tangible, Embedded, and Embodied Interaction, 2023. doi:10.1145/3569009.3572805

[3] "Hybrid Atelier - PROJECTS," *Uta.edu*, 2024. https://hybridatelier.uta.edu/projects/65-biomaterial-fabrication (accessed Feb. 13, 2026).