

KOMBUCHA FERMENTATION SYSTEM
ECE 445 DESIGN DOCUMENT - SPRING 2026

Project No. 27

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1 Introduction

1.1 Problem

Kombucha is a fermented tea produced by combining sweetened tea with a SCOBY, a symbiotic culture of bacteria and yeast, and allowing the mixture to ferment over several days. During this process, yeast and bacteria consume sugar and generate acids, ethanol, and a cellulose pellicle, with these fermentation pathways interacting in a biologically coupled system as shown in Figure 1. Because both the beverage and the cellulose depend on the same microbial environment, successful fermentation requires reasonably stable process conditions rather than simple passive waiting.

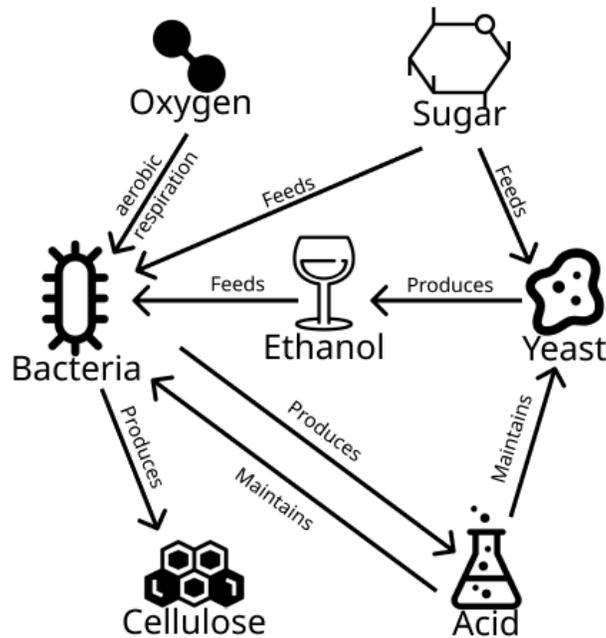


Figure 1: Kombucha fermentation interaction map

Despite how common home kombucha brewing has become, most home setups provide little control over the variables that most strongly influence fermentation behavior. Brewers typically rely on a jar-based countertop process with minimal instrumentation, judging progress through taste, appearance, or rough timing estimates rather than continuous measurements. In many cases, temperature is left to fluctuate with room conditions, acidity is checked infrequently or not at all, and process timing is based more on intuition than data. These limitations make it difficult to determine whether fermentation is progressing as intended or to understand why one batch succeeds while another does not.

As a result, home kombucha fermentation often suffers from several repeatability issues. If the brew environment is too cool, fermentation may proceed too slowly or stall; if it is too warm or left unchecked for too long, the final product may become overly acidic or inconsistent in taste. Variations in fermentation conditions can also affect pellicle growth, causing cellulose thickness and quality to change significantly from batch to batch. These inconsistencies can lead to wasted ingredients, longer brewing times, discarded batches, and poor reliability for users interested in either beverage production or cellulose harvesting.

Existing solutions generally fall into two extremes: expensive commercial brewing systems that automate portions of the process, or low-cost DIY methods that still depend heavily on manual observation and intervention. This creates a need for a practical, low-cost fermentation control platform that can monitor key brewing variables, provide clear feedback, and support more repeatable home fermentation without requiring constant user supervision.

1.2 Solution

To improve the consistency and repeatability of home kombucha fermentation, we will develop a low-cost closed-loop brewing system that monitors key process conditions and actively responds to them. First, a microcontroller on a custom PCB will continuously collect data from temperature, pH, RGB color, and ultrasonic level sensors in order to track fermentation conditions and overall batch progress. We will then use this sensor data to regulate the brewing environment and support repeatable operation. When the measured temperature falls below the desired range, the system will activate a heating pad to maintain a warm and stable fermentation temperature. The system will also interface with peristaltic pumps to add fresh tea or remove liquid according to user-defined process goals such as maintaining volume, scheduling feed cycles, or supporting more consistent batch timing. In addition, the design will include an aeration module using a small air pump to provide controlled airflow during primary fermentation. Finally, a web-based dashboard will display real-time sensor readings and logged fermentation trends so that users can monitor the brew and identify abnormal behavior without relying solely on manual checks.

1.3 Visual Aid

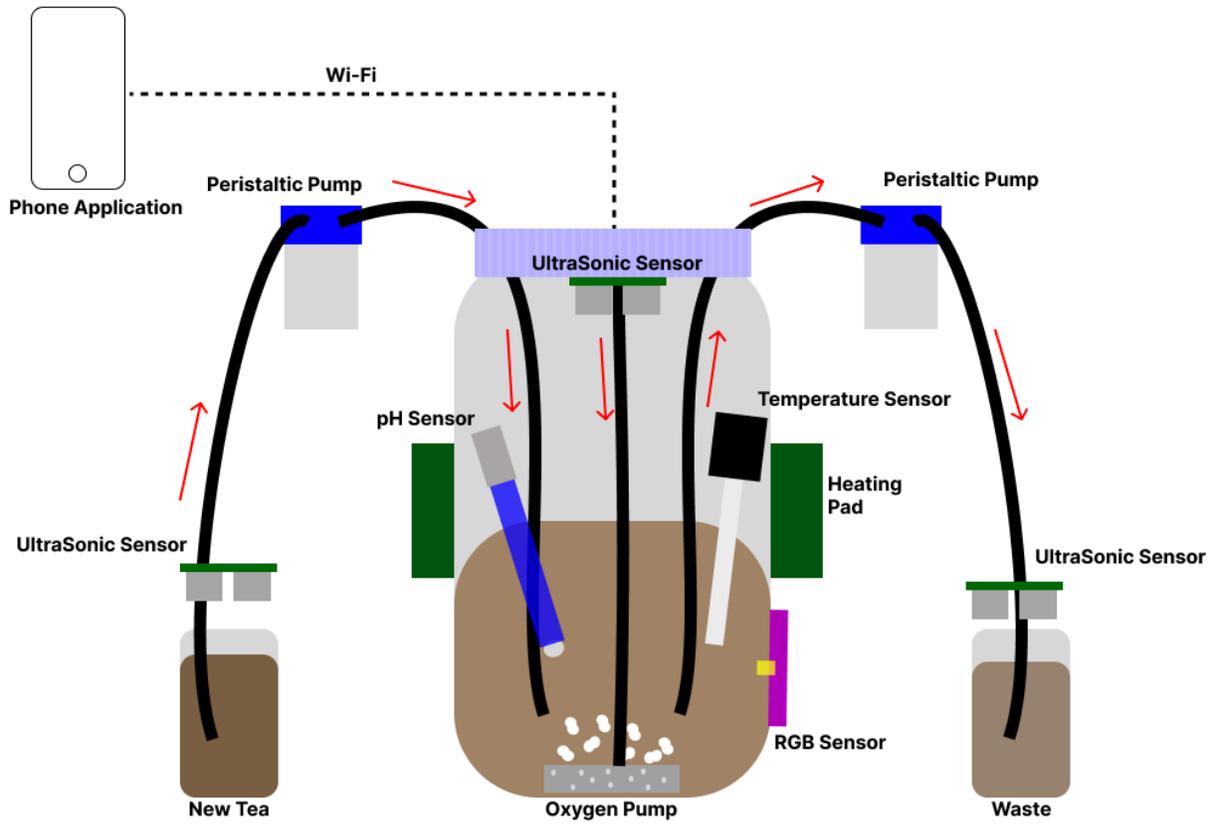


Figure 2: Visual aid of the proposed kombucha fermentation control system

The proposed solution is centered around a primary fermentation vessel instrumented with multiple sensors and connected to supporting external modules. As shown in **Figure 2**, the vessel contains temperature, pH, RGB color, and ultrasonic sensing elements used to track brewing conditions and visible changes throughout fermentation. The system also interfaces with a heating pad to maintain a suitable fermentation temperature, an aeration pump to provide controlled airflow, and peristaltic pumps that move liquid between the main vessel, a fresh tea reservoir, and a waste reservoir. A Wi-Fi-connected web dashboard allows the user to monitor fermentation status, view real-time sensor readings, and supervise system operation without constant manual inspection. Because fermentation occurs over multiple days, the system is designed for continuous wall-powered operation rather than battery-powered use.

1.4 High-level Requirements

Because full kombucha fermentation occurs over multiple days, project validation will be performed through a short demonstration beginning from intentionally off-target conditions, including low temperature, shifted acidity, and a non-target color state. This approach allows the system response to be evaluated within a single demo session rather than over a full multi-day fermentation cycle. To consider the project successful, the proposed kombucha fermentation control system must satisfy the following high-level requirements:

- The system shall continuously monitor key brewing variables, including temperature, pH, and color-based visual state, and shall display these measurements on a Wi-Fi-connected dashboard.
- The system shall actively regulate liquid temperature and shall drive the measured temperature to within ± 1.0 °C of a user-defined setpoint during demonstration testing.
- The system shall actively modify liquid acidity using pump-driven dosing and shall produce a measurable decrease in pH during demonstration testing.
- The system shall detect and report a measurable visual-state shift using color-sensor-derived HLS values during demonstration testing.

2 Design

2.1 Physical Design

The physical design is centered around a primary fermentation vessel and supporting external hardware arranged for continuous tabletop operation. While the visual aid in **Figure 2** shows the intended final system configuration, the early prototype in **Figure 3** demonstrates the practical feasibility of integrating the jar, tubing, pumps, and support structure into a real bench-top setup. Although Figure 3 is not fully representative of the final design, it provides a reference for the overall physical integration of the system.

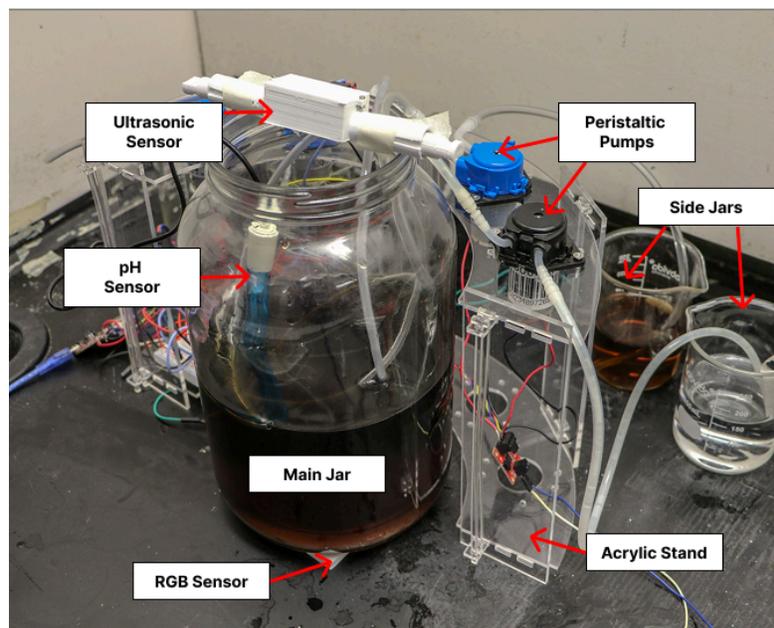


Figure 3: Early prototype of the kombucha fermentation control system

In the final design, several updates will be made to improve subsystem organization and better reflect the intended functionality. The number of peristaltic pumps will be limited to two, and these pumps will be mounted on a laser-cut acrylic stand positioned beside the main fermentation jar. A heating mat will wrap around the circumference of the main jar to provide controlled thermal input. Three tubing lines will interface with the main vessel: one for fresh tea input, one for removal of old tea or finished product, and one for controlled oxygen delivery from a side-mounted oxygen pump. Two auxiliary jars will be placed alongside the main vessel to hold fresh tea and waste liquid, and each of these side jars will be monitored by an ultrasonic sensor mounted above the container. A separate ultrasonic sensor will also be mounted above the main fermentation jar to monitor the liquid level in the primary vessel.

Within the main vessel, the temperature sensor and pH sensor will be immersed to directly monitor fermentation conditions, while the color sensor will be positioned beneath the jar to observe bulk color changes from below. This arrangement is intended to keep fluid-handling components accessible while separating wet fermentation elements from control electronics as much as possible for safer and more organized continuous operation.

2.2 Block Diagram

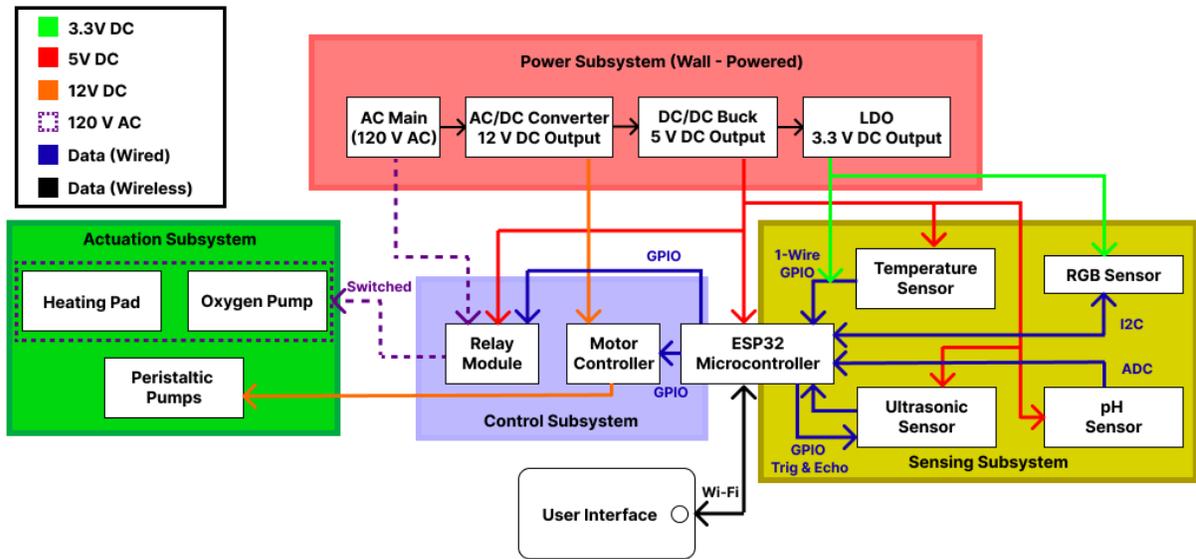


Figure 4: Kombucha Fermentation System Block Diagram

2.3 Functional Overview & Block Diagram Requirements

2.3.1 Power Subsystem

The Power Subsystem is responsible for distributing electrical power to all sensing, control, and actuation hardware used in the kombucha fermentation control system. This subsystem supports the project’s high-level requirements by enabling continuous wall-powered operation over long fermentation periods while supplying stable power to the ESP32, sensors, relay logic, and pump-driving electronics. In the proposed design, the system will be powered from a standard 120 VAC wall outlet through a bench-top power strip. One power-strip outlet will feed a store-bought AC/DC adapter that converts wall power to a regulated 12 V DC supply for the low-voltage subsystem. This 12 V rail will power the peristaltic pump driver directly and will also feed a 12 V-to-5 V DC converter used to power the ESP32 development board, sensors, and relay module logic.

The remaining AC outlets on the power strip will be used for the heating pad and oxygen pump. These AC-powered loads will be controlled through a relay-switched interface so that the low-voltage controller can enable or disable them as needed during operation. Because the design includes both low-voltage DC electronics and mains-powered AC loads, the Power Subsystem also establishes the physical and electrical separation needed for safe operation. In particular, the AC switching interface must prevent exposed mains conductors, and all relay-switched wiring must be enclosed and strain-relieved in the final implementation. By maintaining regulated DC rails and controlled AC switching, the Power Subsystem enables reliable sensing, stable control, and long-duration operation without battery dependence.

Interfaces

Input

- 120 VAC wall power, 60 Hz

Power distribution

- Wall outlet → power strip
- Power strip outlet 1 → AC/DC adapter → 12 V DC rail
- 12 V DC rail → motor driver / peristaltic pumps
- 12 V DC rail → 12 V-to-5 V converter → ESP32, sensors, relay logic
- Power strip outlet 2 → relay-switched heating pad
- Power strip outlet 3 → relay-switched oxygen pump

Outputs

- 12 V DC rail → peristaltic pump drive hardware
- 5 V DC rail → ESP32 development board, sensors, relay module logic
- Shared DC ground → ESP32, sensors, 12 V-to-5 V converter output, and pump driver logic
- Relay-controlled AC outputs → heating pad and oxygen pump

To ensure that the Power Subsystem fulfills its responsibilities for regulated DC power conversion, controlled AC load switching, and stable simultaneous operation of the system electronics and actuators, the following requirements and verification procedures are defined.

Table 1: Power Subsystem - Requirements & Verification

Requirements	Verification
The Power Subsystem shall accept 120 VAC $\pm 10\%$ at 60 Hz from a standard wall outlet through the power-strip input	<ul style="list-style-type: none">• Connect the system power strip to a standard wall outlet.• Use a DMM to measure the AC input voltage and record the result.• Confirm that the measured input is within the acceptable operating range.
The Power Subsystem shall provide a 12.0 V DC output within $\pm 10\%$ while supplying at least 0.5 A continuous current to the peristaltic pump subsystem and downstream converter input.	<ul style="list-style-type: none">• Energize the AC/DC adapter from the power strip and operate both peristaltic pumps simultaneously.• Use a DMM to measure the 12 V rail under load.• Record the voltage and current and confirm that the measured voltage remains between 10.8 V and 13.2 V.
The Power Subsystem shall provide a 5.0 V DC output within $\pm 5\%$ while supplying at least 1.0 A continuous current to the ESP32, sensors, and relay logic.	<ul style="list-style-type: none">• Power the ESP32, sensor modules, and relay logic from the 5 V rail during normal operation.• Measure the 5 V rail using a DMM and record the result.• Confirm that the measured voltage remains between 4.75 V and 5.25 V.
The Power Subsystem shall maintain stable operation of the ESP32 and sensing subsystem during simultaneous operation of both peristaltic pumps and relay switching, without brownout reset or loss of valid sensor data over a 5-minute interval.	<ul style="list-style-type: none">• Run the full low-voltage subsystem with both peristaltic pumps active while toggling the relay-controlled loads.• Monitor the ESP32 output and dashboard readings over a 5-minute interval.• Confirm that no reset occurs and that valid sensor data is maintained throughout the test.
The Power Subsystem shall provide a 3.3 V DC output within $\pm 5\%$ for low-voltage sensor or logic interfaces that require 3.3 V operation.	<ul style="list-style-type: none">• Power the system under normal operating conditions and measure the 3.3 V rail or ESP32-provided 3.3 V output using a DMM.• Record the measured voltage and confirm that it remains between 3.135 V and 3.465 V during operation.

2.3.2 Control Subsystem

The Control Subsystem is the central decision-making block of the kombucha fermentation control system. It is responsible for receiving measurement data from the sensing subsystem, executing the control logic for the demonstration, and commanding the actuation subsystem in response to off-target conditions. Based on the measured fermentation state, the Control Subsystem determines when to switch the heating pad, when to actuate the peristaltic pumps, and when to enable controlled oxygen delivery in order to drive the system back toward user-defined target conditions. The subsystem is implemented around an ESP32 microcontroller, which receives sensor inputs and drives the relay module and motor driver through GPIO-based control signals. By coordinating sensed inputs and actuator commands, the Control Subsystem directly enables the project's high-level requirements for closed-loop temperature response, controlled fluid transfer, and automated system behavior during the demonstration. To ensure that the Control Subsystem fulfills these responsibilities, the following requirements and verification procedures are defined.

Interfaces

Inputs

- Sensor measurements from the sensing subsystem:
 - Temperature
 - pH
 - color/HLS state
 - liquid-level information

Outputs

- Relay module input(s) → GPIO on/off control
- Motor driver input(s) → GPIO/PWM for peristaltic pump control
- Control/state outputs → heating, pumping, and aeration commands

Power

- 5 V DC rail to ESP32 development board and relay module VCC
- 3.3 V logic generated by the ESP32 for digital control

To ensure that the Control Subsystem fulfills its responsibilities for receiving sensor data, executing control decisions, and commanding the appropriate system responses, the following requirements and verification procedures are defined.

Table 2: Control Subsystem - Requirements & Verification Pt. 1

Requirements	Verification
When the Control Subsystem detects that the measured liquid temperature is outside the user-defined temperature range, it shall command the heating pad appropriately to drive the system back toward the acceptable range.	<ul style="list-style-type: none">• Begin operation from a low-temperature condition and observe controller output and relay behavior. Confirm that the heating pad is enabled when the temperature is below range and disabled once the measured temperature returns to the acceptable band.
When the Control Subsystem detects that the liquid level in the main fermentation jar is outside the allowed range, it shall command the peristaltic pump subsystem to add or remove tea as needed to drive the level back toward the acceptable range.	<ul style="list-style-type: none">• Create both low-level and high-level conditions in the main jar and observe controller output and pump behavior. Confirm that the controller commands tea input when the level is too low and commands liquid removal when the level is too high.
When the Control Subsystem detects that the measured color state is below the user-defined target band, it shall initiate a liquid refresh sequence to move the brew back toward the desired color condition.	<ul style="list-style-type: none">• Begin operation from an off-target low-saturation color condition and observe controller output and pump behavior. Confirm that the controller initiates the intended pump sequence and that the measured color state trends toward the target band.
The Control Subsystem shall monitor pH as an indicator of fermentation progression and batch condition and shall make this information available for logging and user review without requiring direct pH-based actuation during normal operation.	<ul style="list-style-type: none">• Operate the system while collecting pH data and confirm that the controller receives and processes pH measurements during operation without requiring direct pH-triggered actuator commands.

Table 3: Control Subsystem - Requirements & Verification Pt. 2

Requirements	Verification
The Control Subsystem shall enable oxygen delivery according to a programmed timing schedule during operation.	<ul style="list-style-type: none">• Run the system with the oxygen schedule enabled and observe the oxygen pump control output over the programmed interval. Confirm that the pump is activated and deactivated according to the intended timing sequence.
When the system boots or resets, the Control Subsystem shall default all actuator outputs to the OFF state until valid control operation begins.	<ul style="list-style-type: none">• Power cycle or reset the controller and observe the actuator outputs immediately after startup. Confirm that all actuators remain off until the controller intentionally begins normal operation.

2.3.3 Sensing Subsystem

This subsystem is responsible for sensing the brewing conditions needed to monitor kombucha fermentation and support automated control. Our ultrasonic sensors are used to monitor liquid levels in the main fermentation jar and auxiliary containers. The ultrasonic sensor above the main jar is used to detect evaporation and determine whether fluid transfer has caused the brew level to become too high or too low. The two ultrasonic sensors above the side jars are used to alert the user when the fresh-tea reservoir is running low or when the waste reservoir is approaching overflow. Our temperature sensor is used to track the brew temperature so the system can maintain the kombucha within its desired fermentation range. Our RGB color sensor is used to monitor visible changes in the liquid, since the brew color shifts over time as nutrients are consumed during fermentation. Our pH sensing board and probe are used to monitor acidity, since fermentation gradually produces organic acids and pH serves as an indicator of fermentation progression. The ultrasonic sensors are implemented using time-of-flight distance measurement, the temperature sensor uses a digital 1-Wire interface, the RGB sensor communicates over I²C, and the pH probe is read through an analog sensing board. The ESP32 receives these measurements and uses them for control decisions and user monitoring. To ensure that the Sensing Subsystem is fulfilling its responsibilities for measuring liquid level, temperature, color state, and pH, a requirements and verification table is provided below.

Interfaces

Power

- 5 V DC rail → pH sensing board, ultrasonic sensors, and temperature sensor
- 3.3 V DC rail → TCS34725 RGB color sensor, DS18B20 temperature sensor pull up
- 3.3 V logic-level interface to ESP32 for all sensor outputs delivered to the microcontroller

Outputs to ESP32

- TCS34725 color sensor → I²C
- DS18B20 temperature sensor → 1-Wire GPIO
- Ultrasonic sensors → shared TRIG GPIO and separate ECHO GPIO inputs
- pH sensing board → conditioned analog voltage to ESP32 ADC

Signal conditioning

- Ultrasonic ECHO outputs reduced from 5 V logic to ESP32-safe 3.3 V logic using resistor dividers
- pH sensing board output scaled to remain within the 0–3.3 V ADC input range of the ESP32
- RGB sensor operates natively at 3.3 V and does not require additional level shifting

To ensure that the Sensing Subsystem fulfills its responsibilities for measuring liquid level, temperature, color state, and pH, the following requirements and verification procedures are defined.

Table 4: Sensing Subsystem - Requirements & Verification Pt. 1

Requirements	Verification
Taking the ultrasonic sensors as input, the sensing subsystem must determine the liquid levels in the main fermentation jar and auxiliary side jars with repeatability of ± 1 cm.	<ul style="list-style-type: none">• Ensure the main fermentation jar and both auxiliary jars are each filled to fixed stationary levels and record the measured liquid levels from the ESP32 via serial debugging. Repeat these measurements several times and confirm the readings remain within ± 1 cm for each sensor.• Next, increase the liquid level in each jar and record the updated readings. Confirm that each sensed level changes in the correct direction and reflects the higher fill condition.• Then, decrease the liquid level in each jar and record the updated readings. Confirm that each sensed level changes in the correct direction and reflects the lower fill condition.
Taking the temperature sensor as input, the sensing subsystem must determine the brew temperature at a rate of at least 1 sample per second and with sufficient stability to verify whether the system is within ± 1.0 °C of the target range.	<ul style="list-style-type: none">• Ensure the temperature sensor is placed in a stable liquid bath and record the reported temperature from the ESP32 via serial debugging for at least 1 minute. Confirm that the subsystem updates temperature readings at a rate of at least 1 sample per second.• Next, place the sensor in a colder liquid condition and record the measured temperature. Then place the sensor in a warmer liquid condition and record the measured temperature. Confirm that the sensed temperature changes in the correct direction for both cases.• Finally, hold the liquid near a fixed temperature and confirm that the readings remain stable enough to verify whether the system is within ± 1.0 °C of the desired target range.
Taking the RGB color sensor as input, the sensing subsystem must determine the color state of the brew and provide values sufficient to compute HLS measurements at a rate of at least 1 sample per second.	<ul style="list-style-type: none">• Ensure the color sensor is positioned beneath a stationary liquid sample of known appearance and record the RGB values as read from the ESP32 via serial debugging for at least 1 minute. Confirm that the subsystem updates readings at a rate of at least 1 sample per second.• Next, replace the sample with a lighter or less saturated liquid and record the new RGB and computed HLS values. Confirm that the reported values change from the original reading.• Then, replace the sample with a darker or more tea-colored liquid and record the updated RGB and HLS values. Confirm that the subsystem detects a measurable trend toward the desired color band.

Table 5: Sensing Subsystem - Requirements & Verification Pt. 2

Requirements	Verification
Taking the pH sensing board and probe as input, the sensing subsystem must determine the pH of the brew with repeatability of ± 0.3 pH over a 5-minute interval and must be capable of tracking a pH change of at least 1.5 pH units.	<ul style="list-style-type: none">• Calibrate the pH probe using appropriate buffer solutions according to the sensor procedure.• Then, place the probe in a stable, well-mixed solution and record the measured pH over a 5-minute interval via serial debugging. Confirm that the readings remain within ± 0.3 pH over that interval.• Next, place the probe in a second solution whose pH differs significantly from the first, or introduce an acidic solution into the sample. Record the updated pH values and confirm that the subsystem detects a change of at least 1.5 pH units.
Taking all sensing inputs together, the sensing subsystem must provide simultaneous valid measurements of liquid level, temperature, color state, and pH without loss of sensor data over a 5-minute interval.	<ul style="list-style-type: none">• Run the full sensing subsystem with the main-jar ultrasonic sensor, side-jar ultrasonic sensors, temperature sensor, RGB sensor, and pH sensor all active at the same time.• Record all sensor outputs from the ESP32 via serial debugging or dashboard logging over a 5-minute interval.• Confirm that each sensing channel continues to report valid data throughout the test and that no sensor stream is lost during simultaneous operation.
Taking all sensing outputs as input, the sensing subsystem must ensure that any signal delivered to the ESP32 remains within the allowable 0–3.3 V input range during normal operation.	<ul style="list-style-type: none">• Power the sensing subsystem under normal operating conditions with the pH sensing board, ultrasonic sensors, temperature sensor, and RGB sensor connected.• Measure the conditioned pH output and each ultrasonic ECHO line at the ESP32 input pins using a DMM or oscilloscope.• Record the measured voltages and confirm that no sensing signal applied to the ESP32 exceeds 3.3 V during operation.

2.3.4 Actuation Subsystem

This subsystem is responsible for physically changing the state of the kombucha brewing system in response to commands from the controller. Our heating pad is used to raise the temperature of the fermentation jar when the measured brew temperature is below the desired range. Our peristaltic pumps are used to add fresh tea or remove liquid from the main vessel in order to correct liquid level and refresh brew conditions during operation. Our oxygen pump is used to provide scheduled aeration during fermentation. The heating pad and oxygen pump are implemented as AC-powered loads switched through relay contacts, while the two peristaltic pumps are implemented as 12 V DC loads driven through a motor driver. The controller commands this subsystem through relay control signals and motor-driver control inputs. To ensure that the Actuation Subsystem is fulfilling its responsibilities for heating, pumping, and aeration, the following requirements and verification procedures are defined.

Interfaces

Power

- 120 VAC (relay-switched) → heating pad and oxygen pump
- 12 V DC → peristaltic pumps through motor driver

Control in

- GPIO on/off → relay module
- GPIO/PWM → motor driver for peristaltic pump control

Actuated outputs

- Heating applied to fermentation jar
- Oxygen delivery to main fermentation jar
- Tea input to main jar
- Liquid removal from main jar

To ensure that the Sensing Subsystem fulfills its responsibilities for measuring liquid level, temperature, color state, and pH, the following requirements and verification procedures are defined.

Table 6: Actuation Subsystem - Requirements & Verification

Requirements	Verification
Taking controller relay commands as input, the Actuation Subsystem must switch the heating pad and oxygen pump on and off through the relay-controlled AC interface without exposing accessible energized conductors during normal operation.	<ul style="list-style-type: none">• Connect the heating pad and oxygen pump through the relay-controlled AC interface.• Command each load on and off from the controller and confirm correct activation and deactivation.• Inspect the final assembly and confirm that the switched AC wiring is enclosed and strain-relieved during normal operation.
Taking controller commands as input, the Actuation Subsystem must allow the heating pad to provide measurable heating to the fermentation jar.	<ul style="list-style-type: none">• Begin with the fermentation jar below the desired operating range.• Command the heating pad on and record the measured liquid temperature over time.• Confirm either a sustained temperature rise of at least 0.15 °C/min for 10 minutes or that the liquid reaches within ± 1.0 °C of the selected setpoint during testing.
Taking controller commands as input, the Actuation Subsystem must allow the oxygen pump to switch on and off according to the programmed aeration schedule.	<ul style="list-style-type: none">• Connect the oxygen pump through the relay-controlled AC interface.• Run the system with the aeration schedule enabled and observe pump activation over the test interval.• Confirm that the pump turns on and off according to the commanded schedule.
Taking controller motor-driver commands as input, the Actuation Subsystem must operate the two 12 V peristaltic pumps and provide sufficient fluid transfer for system operation.	<ul style="list-style-type: none">• Connect both peristaltic pumps to the motor driver and command each pump during normal operation.• Measure the volume transferred over a known time interval and compute the corresponding flow rate.• Confirm that the pumps respond correctly to controller commands and that the measured net flow rate meets the required operating value.

2.3.5 User Interface

This subsystem is responsible for presenting system information to the user and allowing user interaction with the kombucha fermentation control system. The web-based dashboard displays real-time measurements of liquid level, temperature, color state, and pH so that the user can monitor fermentation without taking manual measurements. It also logs timestamped sensor data and actuator states over time, allowing the user to review brewing trends and verify system behavior. In addition, the interface allows the user to enter operating parameters such as target temperature range, liquid-level limits, color targets, and oxygen timing settings. For testing and supervision, the dashboard also provides manual access to actuator controls and displays system alerts such as low fresh-tea level, waste-reservoir overflow risk, or invalid sensor readings. By combining monitoring, logging, parameter entry, and system messaging, the User Interface Subsystem provides the primary point of interaction between the user and the brewing system.

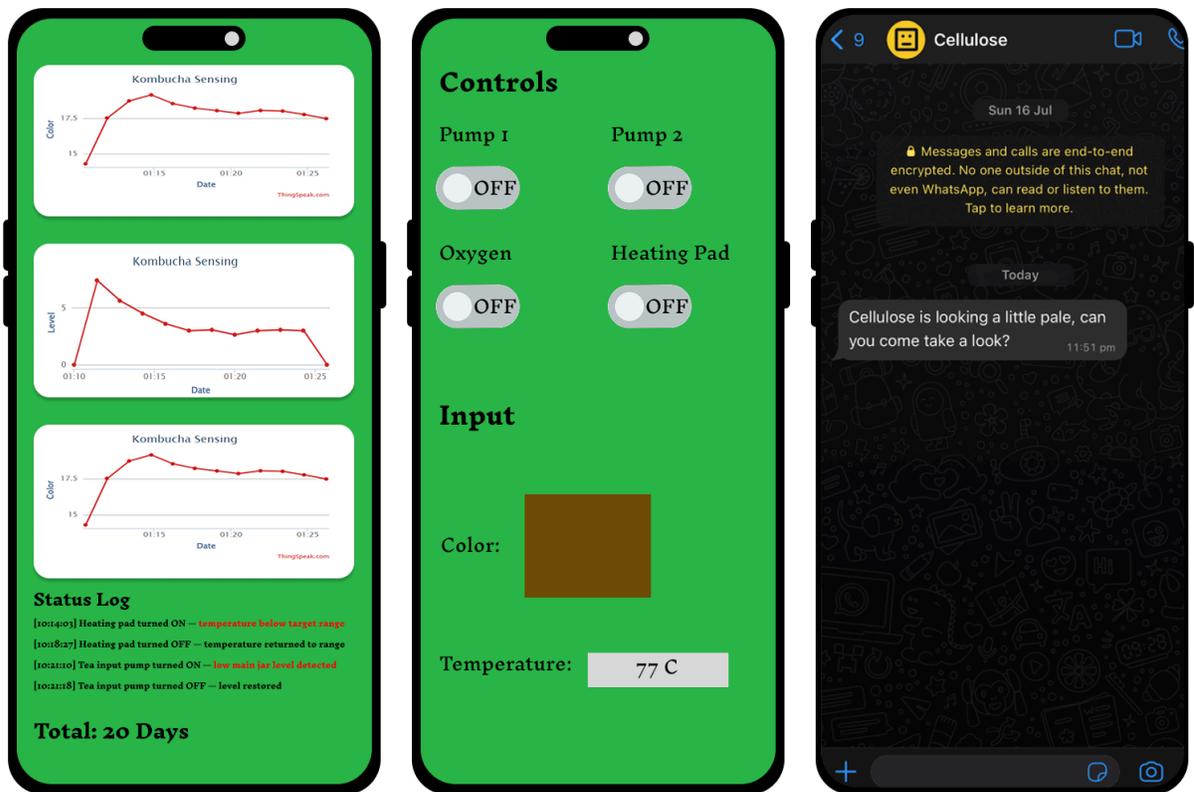


Figure 5: Web dashboard mockup for the kombucha fermentation control system

Interfaces

Communication

- Wi-Fi link between ESP32 and web dashboard

Data received by dashboard

- Temperature
- pH
- RGB/HLS color state
- Main-jar and side-jar level data
- Actuator state (heater, oxygen pump, tea in/out pumps)
- System alerts and fault/status messages

User inputs

- Temperature target or acceptable range
- Liquid-level thresholds
- Color target band
- Oxygen timing parameters
- Manual actuator commands for testing and override

To ensure that the User Interface Subsystem fulfills its responsibilities for system monitoring, data logging, user input, and operator feedback, the following requirements and verification procedures are defined.

Table 7: User Interface Subsystem - Requirements & Verification

Requirements	Verification
Taking system data as input, the User Interface Subsystem must display temperature, pH, color-state, liquid-level, and actuator-state information during operation.	<ul style="list-style-type: none">• Run the full system under normal operating conditions and observe the web dashboard. Confirm that the major sensor values and actuator states are visible during operation.
Taking system data as input, the User Interface Subsystem must log timestamped sensor values and actuator states continuously for at least 10 minutes.	<ul style="list-style-type: none">• Operate the system for at least 10 minutes while the dashboard is active.• Confirm that the log contains timestamped entries for the major sensor channels and actuator states throughout the test interval.
Taking user input as input, the User Interface Subsystem must allow the user to enter operating parameters and manually command actuators for testing and supervision.	<ul style="list-style-type: none">• Enter updated operating parameters through the dashboard and confirm that the new values are accepted by the system. Then manually command each actuator from the interface and confirm the expected system response.
Taking system status as input, the User Interface Subsystem must display alerts for important operating conditions such as low fresh-tea level, near-overflow waste level, or invalid sensor readings.	<ul style="list-style-type: none">• Create at least one alert condition, such as lowering the fresh-tea jar level, raising the waste-jar level, or disconnecting a sensor input. Confirm that the appropriate warning or status message appears on the dashboard.

2.4 Tolerance Analysis

2.4.1 pH Sensing

The pH sensing path is another sensitive subsystem because acidity changes more slowly than temperature or pump state, yet it is one of the most important indicators of fermentation progress. Unlike the temperature loop, pH in this design is not used as a fast closed-loop control variable;

instead, it is used to track batch progression and confirm that fermentation is trending in the expected direction. DFRobot's industrial analog pH meter is specified for 0–14 pH operation with stated accuracy around ± 0.1 pH, and the associated electrode documentation emphasizes good reproducibility and approximately linear voltage response across the pH range.

For the purposes of this project, a tighter datasheet-level accuracy is not actually required. The more important system-level requirement is that the measured pH be repeatable within ± 0.3 pH over a 5-minute interval in a well-mixed solution and that the subsystem be able to distinguish a large process change, such as a shift of at least 1.5 pH units. A ± 0.3 pH repeatability band is small compared with a 1.5 pH change, so even if the analog front end, probe calibration, and ADC introduce some error, the system should still be able to resolve meaningful fermentation-state movement. That is why pH is better treated as a trend variable than as a direct actuator trigger in this design.

However, another 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 $V_{ADC} \leq 3.3V$, we choose a divider:

$$V_{ADC} = V_{pH} \frac{R_2}{R_1 + R_2}$$

Select $R_1=20$ and $R_2=39k\Omega$. Then the nominal scaling is:

$$\frac{R_2}{R_1 + R_2} = \frac{39}{20 + 39} = \frac{39}{59} \approx 0.661$$

So at the worst-case input $V_{pH}=5V$:

$$V_{ADC} \approx 5(0.661) = 3.305 V$$

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.

2.4.2 Temperature Sensing and Heating Control

Temperature sensing and heating control form the most critical closed-loop part of the kombucha fermentation control system because fermentation quality depends strongly on maintaining the brew within a narrow temperature range. In normal operation, the system is intended to keep the kombucha slightly above room temperature and recover from moderate temperature drift during indoor fermentation. For demonstration purposes, the heating subsystem will be validated using a reduced liquid volume of approximately 500 mL so that measurable closed-loop thermal response can be observed within the available test interval.

The temperature sensor used in the system is a DS18B20, which is appropriate for the project's requirement of maintaining the brew within $\pm 1.0^\circ\text{C}$ of the desired range. Since the allowed control tolerance is wider than the expected measurement error of the sensor, the controller can reliably determine whether the liquid is below, within, or above the acceptable temperature band.

To estimate the heating feasibility, the brew can be approximated as water. A 500 mL sample has a mass of about 0.50 kg, and the heat required to raise it by ΔT is

$$Q = mc\Delta T$$

where $c \approx 4186 \text{ J/g }^\circ\text{C}$. For a temperature increase of 3°C above room temperature,

$$Q = (0.50)(4186)(3) = 6279 \text{ J}$$

Using a 20 W heating pad, the ideal no-loss heating time is

$$t = \frac{6279}{20} = 313 \text{ s} = 5.2 \text{ min}$$

Although real operation will take somewhat longer because of heat loss to the jar and surrounding air, this calculation shows that the heater is capable of producing a measurable upward temperature trend and moving the liquid toward the desired range within a reasonable demo interval.

Because the thermal response is slow compared with the controller update rate, simple on/off heating control with a target band is sufficient. In this scheme, the controller turns the heater on when the measured temperature falls below the acceptable range and turns it off once the measured temperature returns to the desired band. This avoids unnecessary relay switching while still maintaining suitable brewing conditions.

Therefore, the temperature-control subsystem is feasible for the project. For a 500 mL demo volume starting near room temperature, the 20 W heating pad can provide a measurable temperature increase above ambient, and the DS18B20 provides enough accuracy to verify whether the system is within the required ± 1.0 °C control band.

3 Cost and Schedule

3.1 Cost Analysis

The total cost for parts, as listed below, is approximately \$158.34 before shipping and tax. For labor, we estimate an average compensation of \$17.50/hr based on a typical UIUC ECE graduate assistant monthly pay of approximately \$2800/month, assuming a 40-hour work week. Using the course labor formula, this gives $\$17.50/\text{hr} \times 2.5 \times 50 = \2187.50 per team member for the duration of the project. With three team members, the total estimated labor cost is $\$2187.50 \times 3 = \6562.50 . Therefore, the combined estimated project cost is approximately \$6720.84.

Description	Manufacturer	Quantity	Extended Price	Source
HC-SR04 Ultrasonic Module Distance Sensor	ELEGOO	3	\$8.99	Link
2 Channel DC 5V Relay Module	SunFounder	1	\$6.79	Link
Durable Waterproof Seedling Heat Mat 3" x 20"	VIVOSUN	1	\$11.99	Link
Aquarium Air Pump Oxygen Pump	Pawfly	1	\$9.99	Link
12V Peristaltic Pump	Shutao	2	\$12.99	Link
DS18B20 Temperature Sensor	DIYables	1	\$6.99	Link
TCS-34725 RGB Light Color Sensor	HiLetgo	1	\$6.99	Link
Supply 1 Gallon Glass Jar Wide Mouth	North Mountain	1	\$12.99	Link
Pure Silicone Tubing, 3mm ID x 5mm OD	Quickun	1	\$7.99	Link
ESP32-DevKitC-32UE	Espressif Systems	1	\$8.08	Link
L298N Motor Drive Controller Board Module	Qunqi	1	\$6.99	Link
Gravity: Analog pH Sensor - SEN0161	DFRobot	1	\$29.50	Link
Supply 32oz Glass Jar	ULINE	2	\$7.25	Link
PCBWay Audit Cost (2 different PCBs)	PCBWay	20 (10 per PCB)	\$10	Link
Capacitors (3x 0.1 uF, 3x 10 uF)	Digikey	6	\$3.03	Link Link
Connectors (2 01x19, 4 01x04, 2 01x03, 1 01x02, 1 02x02)	Digikey	10	\$4.91	Link Link

				Link Link Link
Resistors (1x 10k, 3x 1k, 3x 2k, 3x 4.7 k)	Digikey	10	\$1.04	Link Link Link Link
2 Position Wire to Board Terminal Block	Digikey	1	\$0.79	Link
Tactile Switch SPST-NO Top Actuated Surface Mount	Digikey	1	\$0.43	Link
AMS1117-3.3 V, Low Voltage Dropout Regulator	Digikey	1	\$0.29	Link
Input Capacitor 470uF	DMBJ	1	\$0.0725	C1927 0690
Output Capacitor 330uF	KNSCHA	1	\$0.0218	C5155 335
Schlottsky Diode	FUXINSEMI	1	\$0.0143	C7503 125
Inductor 47uH	SHOU HAN	1	\$0.0348	C6364 681
Buck Regulator	HTC	1	\$0.1715	C1260 46

Table 8: Itemized list of Components and Costs

3.2 Schedule

Week	Task	Worker
1/19	Project pitch	Everyone
1/26	Project approval	Everyone
2/2	Project design	Everyone
2/2	Submit proposal	Everyone
2/16	Order sensors + testing them	John

2/23	PCB revision	Rudy + Edwin
3/2	PCB Assembly	Everyone
3/9	PCB Revision	Rudy + Edwin
3/16	Spring Break	N/A
3/23	Integrate parts	Everyone
3/30	Setup the user interface	John
4/6	Test the system	Everyone
4/13	Refine any errors	Everyone
4/20	Mock demo	Everyone
4/27	Final demo	Everyone
5/4	Final report	Everyone

Table 9: Schedule for Project Progression

4 Ethics and Safety

4.1 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 ($\text{pH} > 4.5$).

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.

4.2 Ethical Considerations

Relevant engineering standards include:

- IEEE electrical design best practices
- UL safety standards for consumer electronics

- NFPA 70 (National Electrical Code) for AC wiring
- ANSI/NSF 51 for food-contact materials
- FCC Part 15 requirements for WiFi devices

4.3 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 to 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.

4.4 Societal Impact

Our kombucha fermentation control system contributes positively to public welfare by making controlled home fermentation more affordable, accessible, and sustainable. Economically, the system uses approximately \$150 - 170 in parts, which is still significantly lower than many commercial brewing systems that can cost several hundred dollars. This lower-cost design can help make monitored fermentation more accessible to students, low-income households, and community groups interested in home brewing or small-scale sustainable food production. Environmentally, the system can reduce waste by helping users avoid failed batches and by encouraging repeatable homemade beverage production instead of reliance on single-use commercial containers. Although the project does introduce some electronic waste through printed circuit boards, sensors, and wiring, this impact can be reduced through a modular, repairable design and by providing clear guidance for proper disposal or recycling of components. The system also has relatively low power demand for a wall-powered device, with peak power on the order of roughly 10 - 12 W when the heating pad, oxygen pump, and low-voltage electronics are active.

Socially and culturally, the project supports a practice that already exists in many parts of the world, since fermentation is an important part of many food traditions. Rather than replacing these traditions, the system is intended to support them by giving users more visibility into brewing conditions while still allowing flexibility in fermentation style and process. The design also promotes safer fermentation by monitoring conditions such as pH and liquid level and by providing user alerts when the system detects potentially undesirable operating conditions. In a broader context, while the current design assumes access to reliable electricity and Wi-Fi, the system concept could be adapted in the future for simpler or lower-resource settings through alternate displays, reduced-power operation, or passive heating approaches.

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