

Controlled Sampling Electronic Nose for Fruit Identification and Freshness Classification

ECE 445 Project Proposal

Team Number: 29

Team Members

Zhenyu Zhang

Haotian Li

Haoran Zhang

September 18, 2026
University of Illinois Urbana-Champaign

Department of Electrical and Computer Engineering

1 Introduction

1.1 Problem

Households, food-service operators, and small retailers often judge fruit freshness by appearance, purchase date, or human smell. These methods are subjective, while external color and internal biochemical change need not progress together. Apples and bananas release mixed volatile organic compounds (VOCs) as they ripen, experience storage stress, and undergo fermentative or microbial degradation. A low-cost electronic nose can measure a response pattern from several partially selective sensors instead of claiming a single sensor identifies a compound concentration [1]-[4].

The engineering challenge is not only the sensor circuit. Metal-oxide (MQ) sensors are cross-sensitive, humidity dependent, and susceptible to drift. The instrument therefore needs a sampling method that is simple enough to build yet controlled enough to produce repeatable measurements and a validation protocol that separates individual fruit specimens between training and test data.

1.2 Solution

We propose a single-container electronic nose. Fruit and the gas-sensor array will share one defined headspace volume, and a fixed sensor lid will control the sensor-to-fruit distance. Separate feedthroughs will carry 5 V power and 3.3 V UART signals between the enclosure and the external equipment. The system will not use an air pump, transfer tubing, an independent fruit chamber, or a separate sensor chamber. During equilibration and exposure, the lid and vent will remain closed and the externally powered top fan will remain off. After the measurement, the user will remove the fruit, open the vent, and manually activate the fan to refresh the chamber and recover the clean-air baseline.

The proposed Rev A PCB will implement four MQ channels (MQ-3B, MQ135, MQ136, and MQ138), four 100 k Ω /150 k Ω voltage-divider channels with load resistors, an MCP6004 quad buffer, an STM32F072CBT6 microcontroller, an SHT31 temperature and humidity sensor, USB-C power input, SWD, and a 3.3 V UART header. The design will use the complete multi-sensor response together with temperature and humidity as an odor fingerprint; it will not interpret a single channel as a food-safety or compound-specific measurement.

Firmware will record raw and normalized analog responses, temperature, humidity, response magnitude, slope, peak, and recovery behavior. A model trained offline with fruit-level train/test separation will classify apple versus banana and Fresh versus Overripe/Spoiled. The reported result will be a prototype quality estimate rather than a food-safety determination.

1.3 Visual Aid

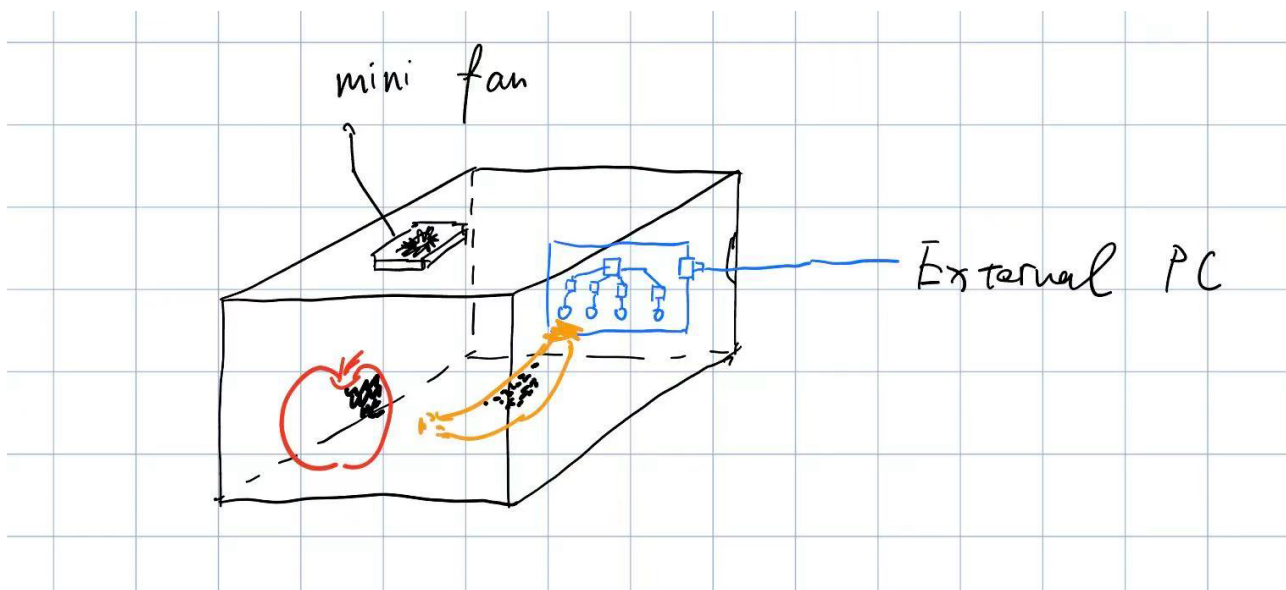


Figure 1 Single-container headspace sampling and controlled ventilation

1.4 High-Level Requirements

The following requirements apply only to the documented container, fruit protocol, sensor conditioning state, and environmental range used during validation.

- **HLR 1:** At three laboratory-approved ethanol reference levels, the median normalized response magnitude of the MQ-3B and MQ138 channels must change monotonically with increasing reference level. At each nonzero level, five repeated trials must have a coefficient of variation no greater than 10 percent after baseline and humidity correction.
- **HLR 2:** With train/test separation by physical fruit specimen, the prototype must achieve at least 80 percent held-out accuracy for fruit-type classification (apple versus banana) and at least 80 percent held-out accuracy for freshness classification (Fresh versus Overripe/Spoiled). The held-out set must contain at least 20 independent specimens and at least five specimens from each combined fruit-state class.
- **HLR 3:** After initial sensor conditioning and session warm-up, one complete measurement cycle (baseline, equilibration/exposure, feature extraction, and baseline recovery) must finish within 15 minutes under the defined container protocol. The system must not begin a new measurement cycle until every usable channel is within 10 percent of its clean-air baseline or has been reported invalid.

2 Design

2.1 Block Diagram

Figure 2 separates the mechanical headspace protocol, sensor/analog circuit, control/data system, and external computer. Airflow occurs only during the post-measurement ventilation phase. The fan is not part of the chemical sampling path and must remain off during accumulation and exposure.

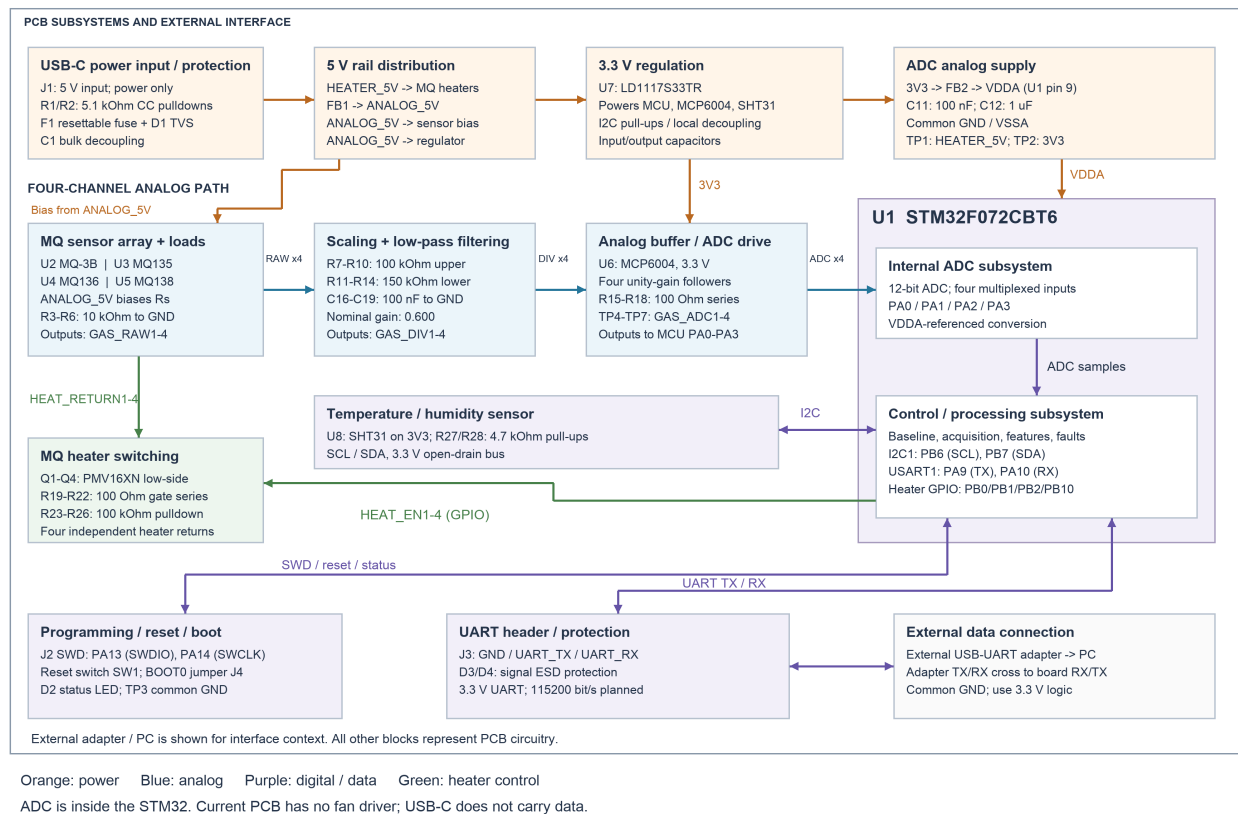


Figure 2 System block diagram for the single-container architecture

Table 1 Critical subsystem interfaces

System	Device	Type	Detail
--------	--------	------	--------

Power input	PCB and sensor heaters	Power	5.0 V DC, 2 A rated adapter through USB-C power input
MQ array	MCP6004 front end	Analog	Four raw sensor channels; design input range 0 to 5.1 V
Analog front end	STM32F072 ADC	Analog	Four buffered channels; 0 to 3.084 V worst-case divider output
SHT31	STM32F072	I2C	3.3 V open-drain SDA/SCL with 4.7 k Ω pull-ups
STM32F072	Local computer	UART	115200 bit/s, 3.3 V UART through an external USB-UART bridge in Rev A
Top fan	Container air	Mechanical ventilation	Used only after measurement; no pump or flow-control interface

2.2 Subsystem Overview

Sampling subsystem. One container will hold the fruit, sensors, and shared headspace. Repeatability will be controlled by container volume, fruit mass and position, sensor distance, equilibration time, exposure window, ventilation time, temperature, humidity, and the baseline-recovery threshold. The user will keep the external fan off and the vent closed throughout accumulation and measurement.

Sensor and analog subsystem. Each heated MQ sensor will form a resistance-dependent voltage with a 10 k Ω load resistor. A 100 k Ω upper resistor and 150 k Ω lower resistor will scale the 0 to 5.1 V design range before a unity-gain MCP6004 buffer and 100 Ω ADC series resistor. GAS_ADC1 through GAS_ADC4 will connect to STM32 pins PA0 through PA3, with a test point on each buffered channel.

Power and control subsystem. The proposed Rev A schematic will include USB-C power entry, a resettable fuse, TVS protection, ferrite filtering, LD1117 3.3 V regulation, and four PMV16XN low-side heater switches. The STM32 will sample four analog channels, read the SHT31 through I2C, and stream data over UART. Rev A will not include a pump driver or an electrically controlled fan driver; the ventilation fan will use a separate manual power source.

2.3 Sampling and Ventilation Subsystem

The nominal experiment will use one cleanable container of fixed internal volume. A written run sheet will record container volume; fruit species, identifier, mass, and position; sensor-lid geometry and sensor distance; sensor warm-up state; equilibration time; exposure time; ventilation time; temperature; humidity; and recovery result. A consistent fixture will prevent the fruit position from changing relative to the sensor lid, while a rigid perforated guard and drip shield will physically separate the heated sensors from the fruit without creating a second gas chamber.

- **SAMP 1:** The container volume, fruit mass range, fruit position, sensor distance, equilibration time, exposure time, and ventilation procedure must remain fixed within one validation dataset.
- **SAMP 2:** The user must keep the external fan off and the vent closed during equilibration and exposure. The fan may be activated only after the fruit has been removed and the sampling window has ended.
- **SAMP 3:** Before the next sample, the user must remove the fruit, open the vent, activate the external fan, and record clean-air recovery. If any usable channel remains more than 10 percent from baseline at the cycle timeout, the system must report an invalid result rather than begin another measurement.
- **SAMP 4:** Heated sensors and electronics must remain physically isolated from fruit, liquid, condensate, and flammable residues. The lid and container must be removable for cleaning.

2.4 Sensor and Analog Front End Subsystem

The proposed analog front end will contain four distinct sensor channels U2 through U5. Each channel will use a 10 k Ω load resistor, a 100 k Ω /150 k Ω divider (R7/R11 through R10/R14), a 100 nF divider-node capacitor (C16 through C19), an MCP6004 unity-gain buffer, and a 100 Ω series resistor into the MCU ADC. The divider nominal factor is 0.600. With 1 percent resistor tolerance and a 5.1 V raw input, the maximum factor is 0.6048 and the maximum ADC-facing voltage is 3.084 V.

- **SENS 1:** For a 0 to 5.1 V raw sensor input and all specified supply and resistor tolerances, GAS_ADC1 through GAS_ADC4 must remain between 0 V and VDDA at the STM32 pins, and the MCP6004 output must remain outside saturation.
- **SENS 2:** The STM32 must sample all four channels at no less than 5 samples/s and preserve one-second averages with timestamps.

- **SENS 3:** The SHT31 must report temperature and relative humidity at least once per second over a 100 kHz I2C bus with 4.7 k Ω pull-ups.
- **SENS 4:** Channels that saturate, disconnect, or fail recovery must be flagged and excluded from classification rather than silently accepted.

2.5 Power and Actuation Subsystem

The proposed 5 V heater rail will power the four MQ heaters. The cited maximum heater power of approximately 0.9 to 0.95 W per sensor gives an upper estimate near 3.8 W, or 0.76 A at 5 V [4]. The 3.3 V MCU, op-amp, SHT31, LED, and UART-interface loads are comparatively small but will be measured during bring-up. The proposed Rev A PCB will power neither a pump nor the external fan.

- **PWR 1:** The heater rail must remain at $5.0\text{ V} \pm 0.1\text{ V}$ while four heaters operate.
- **PWR 2:** The 3.3 V rail must remain within $3.3\text{ V} \pm 5\%$ during ADC, I2C, UART, and heater-switch operation.
- **PWR 3:** Measured steady-state input current must remain below 1.0 A for the proposed Rev A PCB, which will contain neither a pump nor a PCB-powered fan.
- **PWR 4:** Each heater MOSFET gate must default low during reset through its hardware pulldown.

2.6 Embedded Control and Data Subsystem

The control state machine will implement OFF, WARMUP, BASELINE, LOAD SAMPLE, EQUILIBRATE, EXPOSE, VENTILATE/RECOVER, RESULT, and FAULT. VENTILATE/RECOVER will be a monitored state rather than a fan-control state: the interface will prompt the user to remove the fruit, open the vent, and manually operate the external fan while the STM32 monitors baseline recovery. Data records will contain sequence number, elapsed time, four ADC averages, four normalized values, temperature, humidity, state, and fault flags. The proposed Rev A PCB will expose data through a 3.3 V UART header on PA9/PA10; USB-C will provide power only, and an external USB-UART bridge will connect the board to the computer.

- **CTRL 1:** The controller must acquire four ADC channels, temperature, and humidity without missing more than one one-second record in a cycle.
- **CTRL 2:** UART must operate at 115200 bit/s with a parseable delimiter or checksum.
- **CTRL 3:** Classification must remain blocked until warm-up, baseline, exposure, and recovery criteria are satisfied. ADC saturation, sensor disconnection, or recovery timeout must produce an invalid result and enter FAULT.
- **CTRL 4:** The final result must appear within one second after the baseline-recovery criterion is satisfied or the recovery timeout is reached.

2.7 Classification and User Interface Subsystem

The model will use repeated measurements of multiple physical apples and bananas. Measurements from the same fruit specimen must not appear in both training and test partitions. Before viewing sensor data, the team will assign freshness labels using a written rubric based on storage duration and conditions, firmness, visible decay, and odor observed before sealing the container. Features will include normalized analog response, peak, slope, recovery behavior, temperature, and humidity. The interface will store the complete record and display fruit class, freshness class, confidence, cycle state, and invalid or fault conditions.

- **ALG 1:** The report must include fruit-level sample counts, separate confusion matrices for fruit type and freshness, and both held-out accuracies.
- **ALG 2:** Each trial must be normalized using only its own clean-air baseline and calibration parameters derived from the training set.
- **ALG 3:** The classifier must output Invalid when a required channel is saturated, missing, or unrecovered.

2.8 Tolerance Analysis

For each channel, $k = 150/(100 + 150) = 0.6000$. With 1 percent resistors, $k_{\min} = 148.5/(101 + 148.5) = 0.5952$ and $k_{\max} = 151.5/(99 + 151.5) = 0.6048$. A 5.1 V conservative raw-input limit therefore produces 3.060 V nominally and 3.084 V in the worst divider case. Because PWR 2 permits the 3.3 V rail to fall to 3.135 V, the worst-case rail margin is only 51 mV, not 216 mV. Pre-fabrication simulation and bench testing must verify the MCP6004 output swing, STM32

VDDA-dependent ADC range, and settling behavior. If this margin is inadequate, the upper divider resistors will be increased before fabrication to reduce the ADC-facing voltage.

Table 2 Analog scaling tolerance results

Case	High	Rlow	Scale factor	Output at 5.1 V
Nominal	100.0 k Ω	150.0 k Ω	0.6000	3.060 V
Minimum scale	101.0 k Ω	148.5 k Ω	0.5952	3.036 V
Maximum scale	99.0 k Ω	151.5 k Ω	0.6048	3.084 V

2.9 Pre-Fabrication Verification

SPICE verification will model the sensor interface as a variable-resistance or equivalent voltage-source/load-resistor circuit, followed by the proposed divider, C16 through C19 filtering, MCP6004 voltage follower, 100 Ω ADC series resistor, and a representative STM32 ADC input model. A manufacturer-provided MCP6004 macro-model will be used where available. DC sweeps will cover raw sensor voltage from 0 to 5.1 V; transient tests will evaluate slow sensor changes and ADC sampling; and tolerance/corner sweeps will include divider tolerance, supply limits, capacitor tolerance, sensor-equivalent resistance, and MCP6004 output swing. Acceptance requires an ADC-facing voltage between 0 V and the minimum simulated VDDA, stable buffer operation without clipping or oscillation, and adequate settling before each scheduled ADC conversion. SPICE will model electrical behavior only; it will not predict MQ chemical selectivity or fruit VOC response.

I2C signal-integrity verification will use manufacturer-provided IBIS models for the STM32 and SHT31 where available. The model will include the proposed 4.7 k Ω pull-ups, 3.3 V rail, estimated trace and interconnect parasitics, device input loading, and 100 kHz bus speed. Simulations will check SDA/SCL rise and fall times, logic thresholds, overshoot, undershoot, and sensitivity to line length and loading. If an official IBIS file is unavailable, the study will use an equivalent open-drain I/O model and identify that limitation. IBIS models describe digital I/O and signal integrity; they do not model the sensors' chemical selectivity or analog sensing response.

3 Ethics, Safety, and Societal Impact

3.1 Ethical Responsibilities

The central ethical risk is overclaiming what the prototype measures. The sensor array will respond to a mixed headspace and cannot prove that food is free of pathogens or toxins. The interface and report will describe results as controlled-condition quality classifications, disclose failed tests and limitations, and state that the device is not a sole food-safety decision tool [8].

Apples and bananas vary by cultivar, supplier, storage history, bruising, and humidity. The team will record these conditions, split data by specimen, retain failed trials unless a documented hardware fault justifies exclusion, and report sample counts and confusion matrices. The system will not collect personal information or require human- or animal-subject testing.

3.2 Safety

Four heated sensors will create burn, overheating, and ignition hazards. They will be mounted behind a rigid perforated guard and drip shield, away from fruit, liquid, condensate, heat-sensitive plastic, and flammable residues. The user must keep the external fan off while the container is closed for measurement, and the enclosure must not be opened while heaters are energized. A fuse, default-off MOSFET gates, current-limited bring-up, post-test ventilation, and cool-down before handling will reduce risk.

Chemical reference tests will use only small, TA-approved quantities under applicable course and laboratory rules. Liquids will remain physically separate from heated sensors. No hydrogen sulfide will be generated for MQ136 calibration, and spoiled samples will not be consumed. The team will use appropriate PPE during soldering and mechanical assembly and follow the ECE 445 safety rules and laboratory Chemical Hygiene Plan [9], [10].

3.3 Societal, Environmental, and Economic Impact

A low-cost electronic nose could support repeatable demonstrations of fruit-quality monitoring for households, small retailers, education, and supply-chain research. The simplified shared-headspace design reduces tubing, pumps, and chamber hardware while retaining a documented procedure. It does not replace microbiological testing, chromatography, regulated inspection, or professional judgment.

The project may help reduce unnecessary disposal if it enables better inventory decisions, but the MQ heaters will consume several watts and the PCB and sensors will eventually become electronic waste. The team will use replaceable sensors, avoid disposable sampling cartridges, and route failed electronics through an approved e-waste stream.

References

- [1] United Nations Environment Programme, Food Waste Index Report 2024. Nairobi, Kenya: UNEP, 2024.
- [2] D. R. Rudell et al., “Characterization of volatile production during low-oxygen stress in apple fruit,” *Journal of Agricultural and Food Chemistry*, 2014.
- [3] A. Bhattacharjee et al., “IoT-based cost-effective fruit quality monitoring system using electronic nose,” arXiv:2512.08753, 2025.
- [4] Zhengzhou Winsen Electronics Technology Co., MQ-3B, MQ135, MQ136, and MQ138 technical manuals.
- [5] STMicroelectronics, STM32F072x8 and STM32F072xB Arm Cortex-M0 microcontroller data sheet.
- [6] Microchip Technology Inc., MCP6001/1R/1U/2/4 Low-Power Operational Amplifiers data sheet.
- [7] Sensirion AG, SHT3x-DIS Digital Humidity and Temperature Sensor data sheet.
- [8] IEEE, IEEE Code of Ethics.
- [9] University of Illinois Urbana-Champaign, ECE 445 Safety Guidelines.
- [10] Occupational Safety and Health Administration, 29 CFR 1910.1450, Occupational Exposure to Hazardous Chemicals in Laboratories.