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# Smart Micropantry: Enhancing Food Accessibility through Embedded Sensing and Automation

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**Abstract**

Smart Micropantry: Enhancing Food Accessibility through Embedded Sensing and Automation

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Community micro-pantries provide critical access to food for individuals experiencing food insecurity, but their distributed and volunteer-managed nature makes it difficult to monitor usage, food safety, and inventory. In this work, we present Smart Micropantry, an embedded sensing system designed to enhance accessibility and reliability of community pantries. Our system integrates weight, environmental, and access sensors with a low-power microcontroller, enabling continuous monitoring while remaining energy-efficient. The design supports wireless data transmission for real-time updates while maintaining robustness in outdoor environments.

We implemented and deployed the Smart Micropantry system in a real-world setting, demonstrating its ability to track pantry usage patterns, detect changes in inventory, and monitor environmental conditions relevant to food safety. Our evaluation shows that the system can provide accurate, reliable measurements at low power cost, making it sustainable for long-term operation. Insights from deployment highlight both technical performance and opportunities for community engagement, as the system can inform restocking schedules, identify potential food safety risks, and improve equitable access.

This work demonstrates how embedded sensing and ubiquitous computing can extend beyond traditional laboratory settings into grassroots community infrastructure. Smart

Micropantry offers a scalable model for integrating low-cost, low-power sensing into public resources, ultimately contributing to improved food accessibility and community well-being.

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## GLOSSARY

ESP32-S3: Low-power microcontroller by Espressif, used in this project for sensor integration, Wi-Fi communication, and low-power operation.

BME688: Environmental sensor by Bosch capable of measuring temperature, humidity, pressure, and Volatile Organic Compounds (VOCs).

VOC: Volatile Organic Compounds; gases emitted from certain solids or liquids, monitored here to detect potential food spoilage.

HX711: 24-bit analog-to-digital converter used to interface load cells for precise weight measurements.

LOAD CELL: A transducer that converts applied force (weight) into an electrical signal for weight measurement.

REED SWITCH: Magnetic switch used to detect the opening and closing of the pantry door.

LIPO BATTERY: Lithium Polymer battery; rechargeable battery technology used to power the microcontroller and sensors.

SOLAR CHARGER: Module that regulates charging of the LiPo battery from the solar panel input.

DEEP SLEEP: Low-power operating mode of the ESP32-S3 that minimizes energy consumption between measurement cycles.

WI-FI: Wireless communication protocol used by the ESP32-S3 to send data to the Adafruit IO cloud platform.

ADAFRUIT IO: Cloud platform used for storing, visualizing, and analyzing sensor data from the micropantry.

CALIBRATION: Process of adjusting load cell measurements to match known reference weights for accuracy.

IP65 ENCLOSURE: Weatherproof enclosure standard providing protection against dust and water for electronics.

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## DEDICATION

To my family, for their endless love and support.

## Chapter 1

### INTRODUCTION

Access to safe, sufficient, and nutritious food is essential for health and well-being. Yet, despite the abundance of food resources in the United States, food insecurity remains a persistent challenge. Millions of households face uncertainty about where their next meal will come from, with particularly high rates among households with children, older adults, and marginalized communities. In parallel, food waste continues to be a pressing environmental and economic issue, with large quantities of surplus food ending up in landfills and contributing to greenhouse gas emissions.

In metropolitan regions such as Seattle, community-based food assistance plays a key role in mitigating hunger. Hunger Relief Organizations (HROs)—including food banks, meal programs, and centralized food distribution hubs—serve as critical infrastructure for food redistribution. However, their centralized nature can limit accessibility for people with transportation or mobility constraints. Operating hours, resource limitations, and growing demand add further strain to these systems. At the same time, food waste at the neighborhood scale, from households and small businesses, often goes unaddressed.

In recent years, shared micro-pantries have emerged as a grassroots approach to address both food insecurity and food waste. These small, community-run food storage units, often located on sidewalks or outside community spaces, operate on an informal “take what you need, leave what you can” model. Their distributed nature brings food resources closer to people in need, reducing travel barriers. In Seattle alone, hundreds of micro-pantries are in operation, collectively providing significant food redistribution capacity. However, the very features that make micro-pantries accessible—their decentralized management, open access, and variability—also create challenges. Inventory is unpredictable, food safety is difficult to monitor, and coordination between pantries is limited.

This thesis investigates whether connecting micro-pantries through a cyber-physical net-



Figure 1.1: Micropantry installed in the Seattle area.

work can improve their effectiveness. By equipping pantries with low-cost wireless sensors and linking them through an online information platform, the system aims to provide real-time visibility into inventory, usage patterns, and environmental conditions. These data, combined with community engagement, can support better coordination among donors, receivers, and pantry managers, while also improving food safety and reducing waste.

The work builds on a preliminary phase that mapped existing micro-pantries and engaged stakeholders to identify needs and priorities. In the current phase, a prototype sensing platform is being deployed and tested on a single micro-pantry to evaluate its feasibility and performance. The focus is on assessing potential impacts on food distribution monitoring, user interactions, and food safety outcomes, while identifying challenges that may arise in real-world use.

The overarching objective is to establish a proof-of-concept model for connected micro-pantries that can eventually operate alongside traditional hunger relief infrastructure, thereby increasing resilience in local food systems. While this study centers on a single micro-pantry

in Seattle as a case study, the findings have broader relevance for other urban areas where hyper-local, community-driven food access initiatives are active. tive.

## Chapter 2

**BACKGROUND AND LITERATURE REVIEW****2.1 Food Insecurity and Food Waste**

Food insecurity—limited or uncertain access to adequate food—remains widespread in the United States. In 2022, **12.8%** of U.S. households (about **17 million**) experienced food insecurity [7]. Locally, roughly **13%** of adults in the Seattle metro reported food insecurity [4]. Food insecurity is associated with poorer health outcomes, impaired child development, and reduced quality of life.

In parallel, the scale of surplus food is substantial. The U.S. generated approximately **91 million tons** of surplus food in 2021, with about **36%** ultimately landfilled [6]. In urban contexts, **households and small businesses account for more than 70%** of food waste, highlighting the need for interventions close to the point of consumption [1].

Traditional food assistance systems, primarily operated by hunger-relief organizations (HROs) such as food banks and meal programs, mitigate food insecurity by redistributing surplus food [2]. However, these centralized systems are constrained by *limited hours, locations, and resources*. Many recipients also face *mobility barriers* that make scheduled, hub-and-spoke distribution difficult to access, leaving pockets of unmet demand even when aggregate supply is sufficient.

**2.2 Emergence of Shared Micro-Pantries**

In response to these limitations, shared micro-pantries—small, often volunteer-managed food storage units—have emerged as a form of grassroots, hyper-local food assistance. Often placed in accessible public or community spaces, micro-pantries operate on an open-access model where anyone may donate or take food. These installations gained visibility during the COVID-19 pandemic [3], when disruptions to formal food assistance systems underscored the value of decentralized community resources.

Micro-pantries address some of the spatial and logistical challenges of centralized HROs. Their distributed nature allows more frequent access, reduces transportation barriers, and enables rapid, informal redistribution of surplus food. However, the informal nature of micro-pantries presents its own set of challenges. Inventory levels are inconsistent, quality varies, and food safety monitoring is limited. In addition, the lack of coordination between individual pantries can lead to localized oversupply in some areas and shortages in others.

### **2.3 Technology-Enabled Food Redistribution**

Recent advances in low-cost sensors and wireless communication systems have created new opportunities to enhance the **visibility, coordination, and safety** of community food systems. Cyber-physical systems that integrate sensing platforms with information-sharing tools have been successfully implemented in other domains, such as cold-chain logistics, shared mobility systems, and public infrastructure monitoring.

In food systems, similar sensor deployments have been applied to:

- Monitor environmental conditions,
- Track inventory levels, and
- Optimize routing for food distribution.

For micro-pantries, a **modular sensing platform** can capture key operational data, such as:

- **Inventory weight** – to monitor donations and withdrawals,
- **Temperature and humidity** – to ensure food safety,
- **Door activity** – to estimate usage patterns,
- **Volatile Organic Compounds (VOCs)** – to detect potential spoilage.

When coupled with a **digital information platform**, these data streams can inform donors, receivers, and managers in near real time:

- **Donors** can direct contributions to locations with low stock,
- **Receivers** can more easily locate available food, and
- **Managers** can quickly identify and address safety concerns.

This integrated approach supports micro-pantries in remaining well-stocked, safe, and responsive to community needs.

## 2.4 Research Gap

While micro-pantries have expanded rapidly across urban areas, there is limited research on systematic methods to connect and coordinate them using technology. Existing studies primarily document their proliferation and social value, but few explore large-scale integration through sensing platforms and real-time information systems.

In particular, there is a lack of research on:

- The effectiveness of **connected micro-pantries** in improving food availability and safety,
- Potential **behavioral changes** among donors, receivers, and managers when real-time inventory and condition data are available,
- The **scalability and sustainability** of cyber-physical systems for community food assistance.

In addition to these system-level questions, there is a notable absence of **quantitative data on food spoilage in micro-pantries**. While anecdotal reports and community discussions have raised concerns about expired or unsafe food, no systematic monitoring has been conducted to measure spoilage rates or environmental conditions in these installations. This lack of data limits the ability to assess safety risks and design evidence-based interventions.

This thesis addresses these gaps by designing, deploying, and evaluating a network of **sensor-enabled shared micro-pantries**. The system integrates:

- A **modular sensing platform** to monitor inventory weight, environmental conditions, and food spoilage indicators,
- A **cloud-based information system** for real-time data aggregation and visualization,
- **Community engagement** strategies to ensure adoption and effective use.

The Seattle metropolitan area serves as the pilot site, providing a case study for assessing impacts on food distribution efficiency, safety, and waste reduction, with potential for replication in other urban contexts.

## Chapter 3

### RESEARCH OBJECTIVES AND QUESTIONS

The primary goal of this research is to design and deploy a **low-power, sensor-enabled monitoring system** for a shared micro-pantry, capable of tracking inventory, usage patterns, environmental conditions, and potential spoilage indicators. The system integrates a modular sensing platform with a cloud-based information architecture to demonstrate how real-time and predictive information can support donors, receivers, and micro-pantry managers.

While this work focuses on the design, implementation, and evaluation of the sensing platform on a pilot micro-pantry, the long-term vision is to scale this approach into a **cyber-physical network** of connected micro-pantries, which could enhance efficiency, safety, and equity in hyper-local food redistribution across multiple urban locations.

#### *3.1 Research Objectives*

The specific objectives of this research are to:

1. **Design and implement** a low-power, sensor-enabled monitoring platform on a pilot micro-pantry, integrating wireless sensors to track inventory, usage patterns, environmental conditions, and spoilage indicators.
2. **Optimize power efficiency** of the sensing platform to enable long-term deployment with minimal maintenance.
3. **Evaluate system performance** by assessing the reliability, accuracy, and usefulness of collected data for pantry monitoring and management.
4. **Assess food safety and usage patterns** in the pilot pantry, and explore how real-time monitoring could inform training, stocking strategies, and operational guidelines for pantry managers.
5. **Model the potential scalability and sustainability** of expanding the sensing

platform into a connected micro-pantry network for other urban contexts.

### **3.2 Research Questions**

These objectives are addressed through the following research questions.

#### *Primary Research Question*

Can a low-power, sensor-enabled monitoring system for a shared micro-pantry provide reliable and actionable information that improves food safety, availability, usage efficiency, and waste reduction?

#### *Supporting Research Questions*

1. How can low-cost, low-power sensing technology be leveraged to provide reliable, real-time information about pantry inventory, usage activity, and environmental conditions?
2. To what extent can real-time and predictive information influence stocking decisions, user behavior, and community engagement?
3. What protocols and information tools are effective in supporting food safety, optimal usage, and energy-efficient operation in shared micro-pantries?
4. What are the practical considerations and barriers to scaling a low-power connected micro-pantry system to other metropolitan regions?

## Chapter 4

# SYSTEM DESIGN AND METHODOLOGY

### 4.1 *System Overview*

The research objectives and questions are addressed through the design, deployment, and evaluation of a **low-power, sensor-enabled monitoring platform** for a pilot micro-pantry. The system is designed to:

- Continuously monitor **inventory levels, usage activity, and environmental conditions**,
- Operate on **low power** to enable long-term unattended deployment,
- Transmit data to a **cloud-based backend** for real-time monitoring and analysis,
- Provide a foundation for **scaling to multiple connected micro-pantries** in the future.

The system consists of three integrated components:

1. **Sensing Module** — hardware sensors for weight, door activity, temperature, humidity, and VOCs.
2. **Processing and Communication Module** — microcontroller unit for sensor integration, low-power operation, and wireless data transmission.
3. **Cloud and Visualization Platform** — data aggregation, storage, and dashboard interface for visualization and analysis.

The following sections describe the detailed hardware, firmware, communication protocols, and cloud infrastructure.

### 4.2 *System Design*

#### 4.2.1 *Hardware Architecture*

The hardware design emphasizes **low power consumption, modularity, and robustness** for deployment in varying pantry configurations. Figure 4.2 shows the overall architecture

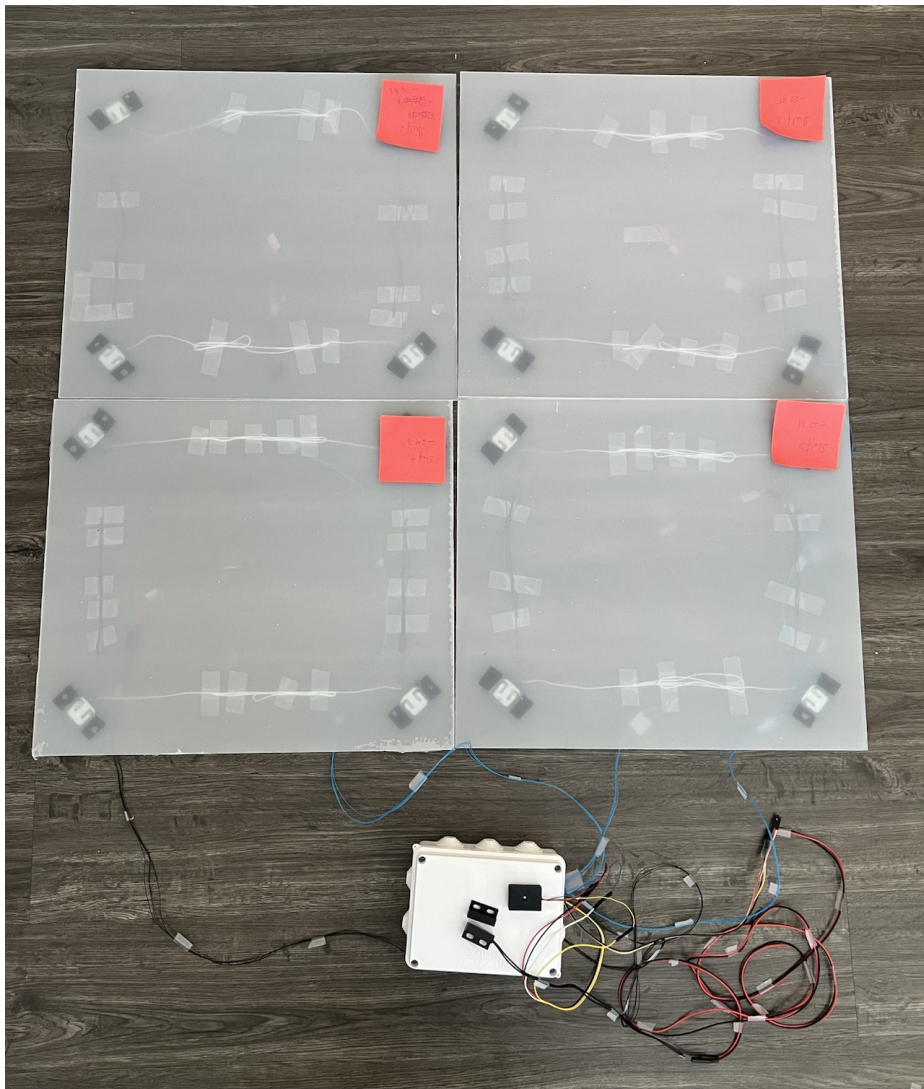


Figure 4.1: Sensor System

of the system, integrating weight, environmental, and usage monitoring sensors with a low-power microcontroller.

#### *Load Cell Assembly*

Inventory weight is measured using four 50 kg load cells arranged in a full-bridge Wheatstone configuration beneath a 1/4-inch acrylic shelf platform. Each load cell is secured inside a

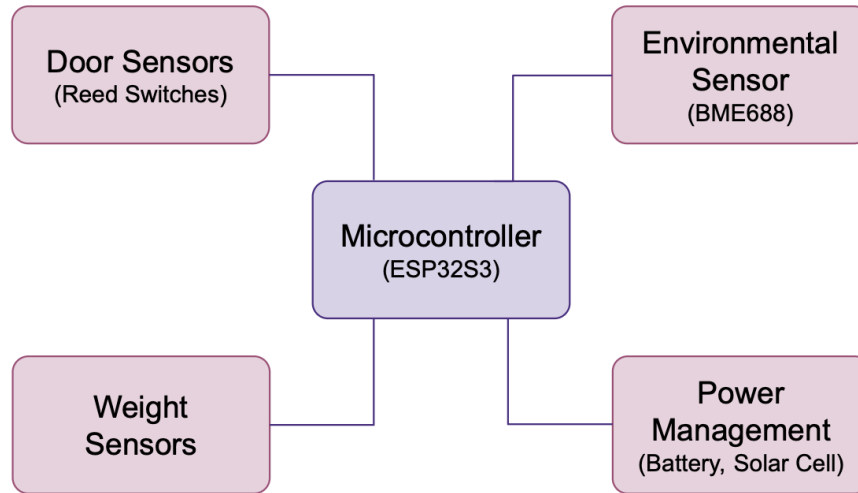


Figure 4.2: Block diagram of the sensor-enabled micro-pantry hardware architecture.

custom **3D-printed mounting case**, designed to ensure mechanical stability, protect the strain gauges from environmental stress, and maintain consistent load distribution.

The load cells interface with HX711 24-bit ADC amplifiers for high-resolution weight measurements. A calibration procedure using standard weights established scaling factors stored in firmware.

The load cell arrangement and mounting details are illustrated in Figure 4.3, showing both the Wheatstone bridge configuration beneath the acrylic shelf and the protective 3D-printed cases. The integration of calibrated acrylic shelves with the load cell sensors into the micro-pantry enclosure is shown in Figure 4.4, demonstrating partial installation, final placement, and the completed sensor-equipped pantry ready for deployment.

#### *Door Activity Monitoring*

Door activity is detected using **magnetic reed switches** mounted to the pantry frame. The reed switch (Figure 4.5a) is aligned with a magnet so that when the pantry door is closed, the circuit is completed, and when opened, the circuit is broken. Each opening



(a) Arrangement of load cells in Wheatstone bridge configuration beneath acrylic shelf. (b) Close-up of load cell mounted in 3D-printed case.

Figure 4.3: Load cell assembly and mounting for the micro-pantry platform

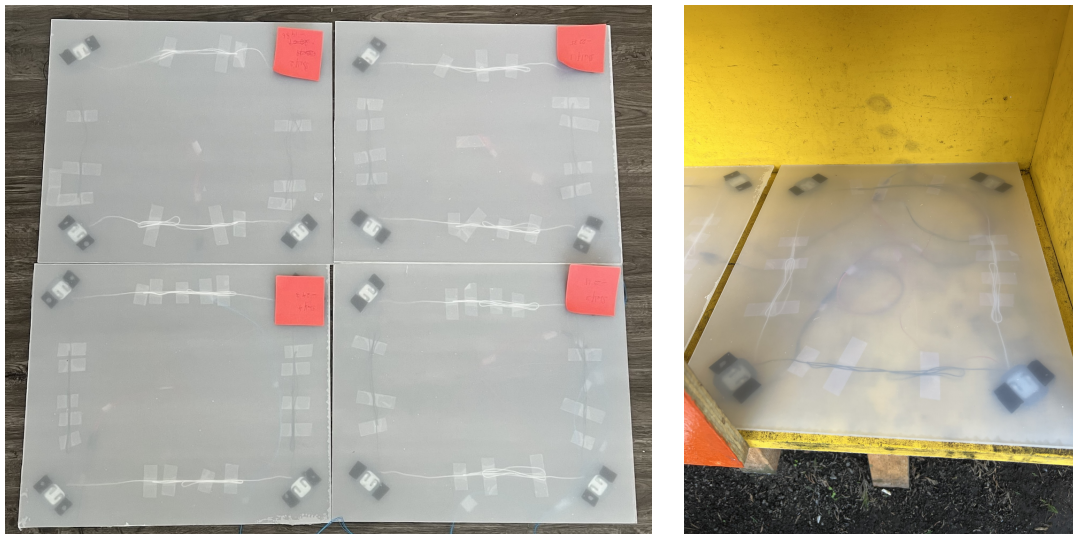
or closing event is logged with a timestamp, enabling estimation of usage frequency and correlation with inventory changes recorded by the load cells.

The installed reed switch setup (Figure 4.5b) shows the placement of the sensor within the micro-pantry, ensuring minimal obstruction while providing reliable door status monitoring.

### *Environmental Sensing*

An **Adafruit BME688 environmental sensor module** is used to monitor **temperature, humidity, pressure, and Volatile Organic Compounds (VOCs)** inside the micro-pantry. The BME688 is mounted inside a custom **3D-printed enclosure** (Figure 4.6) to protect it from dust, debris, and accidental mechanical damage, while keeping the sensing port exposed for accurate measurements.

VOC resistance values are processed using the onboard Bosch gas scanner algorithms to produce an **Air Quality Index (AQI)** relevant to food freshness. Temperature and hu-



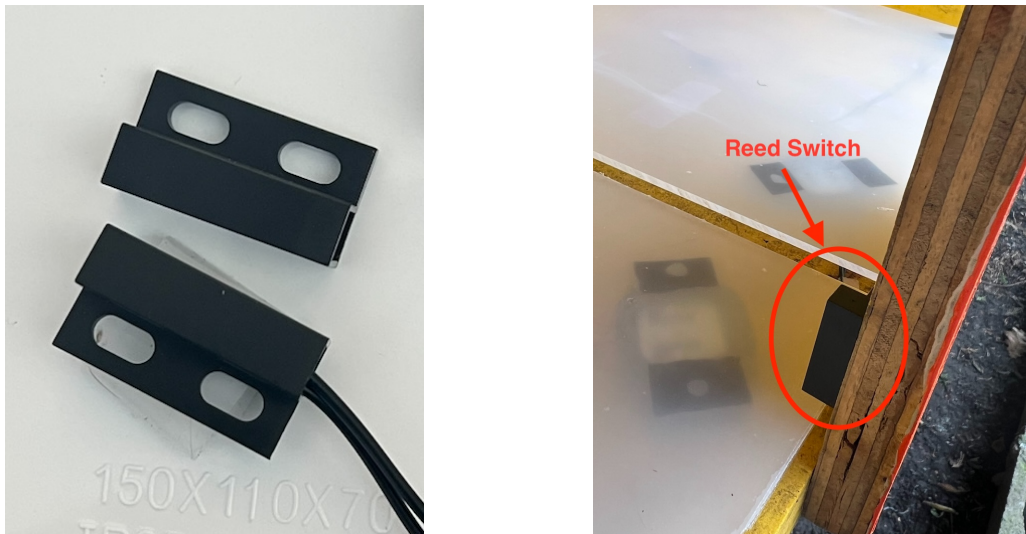
(a) Calibrated acrylic shelves with integrated weight sensors

(b) Micro-pantry with shelves and weight sensors partially installed



(c) Fully installed micro-pantry with shelves and weight sensors

Figure 4.4: Installation of calibrated shelves with load cell sensors into the micro-pantry structure.



(a) Magnetic reed switch used for door activity detection

(b) Reed switch installed in the micro-pantry for door status monitoring

Figure 4.5: Door activity detection using magnetic reed switches in the micro-pantry system

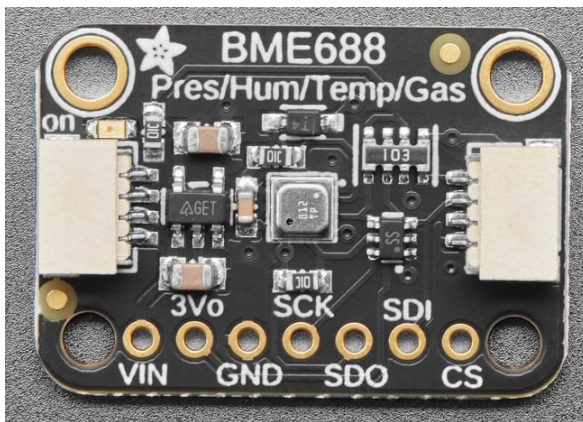
midity readings are compared against recommended thresholds for perishable food, enabling alerts when unsafe storage conditions are detected.

#### *Microcontroller and Power Management*

The **Seeed Studio XIAO ESP32-S3 microcontroller** (Figure 4.7) was selected for its integrated Wi-Fi, low-power modes, and sufficient GPIO for sensor integration. It coordinates weight, environmental, and door activity sensing, while managing low-power operation.

Energy efficiency is achieved through:

- **Deep sleep mode** between measurements to minimize idle power draw,
- **Interrupt-driven dynamic polling** of sensors based on pantry activity (e.g., increased sampling rate after door events),
- **Batch Wi-Fi transmissions** instead of continuous operation to reduce radio energy use.



(a) Adafruit BME688 sensor module



(b) BME688 installed in a 3D-printed enclosure for protection

Figure 4.6: Adafruit BME688 environmental sensing module and its 3D-printed enclosure

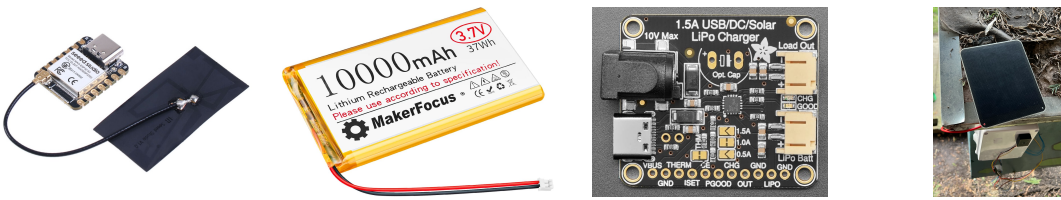
**Power Circuit:** Power is supplied by a rechargeable **Lithium-Polymer battery pack**, which is connected to an **Adafruit Solar LiPo Charger** (Figure 4.7). The solar charger manages both battery charging and regulated output to the ESP32-S3. A **6V solar panel** is connected to the charger's input, allowing for sustainable operation in future large-scale deployments.

The charger circuit works as follows:

- The **solar panel** supplies power when sunlight is available.
- The **charger module** prioritizes charging the LiPo battery while supplying regulated output to the ESP32-S3.
- When solar input is insufficient, the ESP32-S3 runs from the **LiPo battery**.
- Built-in power path management ensures uninterrupted operation during charge/discharge transitions.

#### *Enclosure and Mounting*

All core electronics for the micro-pantry system are housed in an **IP65-rated enclosure** (Figure 4.9) mounted inside the pantry. This enclosure protects sensitive electronics from



(a) Seeed Studio XIAO ESP32-S3 microcontroller (b) Lithium-Polymer battery pack (c) Adafruit Solar LiPo charger (d) Solar panel connected to charger

Figure 4.7: ESP32-S3 and power management components: (a) microcontroller, (b) LiPo battery, (c) solar charger, and (d) solar panel

**rain, humidity, dust, and temperature fluctuations**, enabling continuous outdoor operation.

Inside the enclosure (Figure 4.9a), the following components are installed:

- **Seeed Studio XIAO ESP32-S3 microcontroller** for sensing and communication,
- **Adafruit Solar LiPo charger** for power regulation,
- **10,000 mAh LiPo battery** for energy storage,
- **HX711 load cell amplifiers** for weight measurement,

Cable glands are used at sensor wire entry points to maintain waterproofing. The **Adafruit BME688 environmental sensor** is mounted externally on the enclosure (Figure 4.9b) to ensure accurate air quality and temperature readings while still being protected from direct weather exposure.

#### 4.2.2 Firmware and Software Architecture

The firmware running on the **Seeed Studio XIAO ESP32-S3** manages all sensing, power management, and data communication tasks. The system is optimized for **low power operation, robust data handling, and real-time monitoring**.

The overall data flow and system operation are summarized in Figure 4.10, which illustrates how sensor data is collected, processed, and transmitted to the cloud.

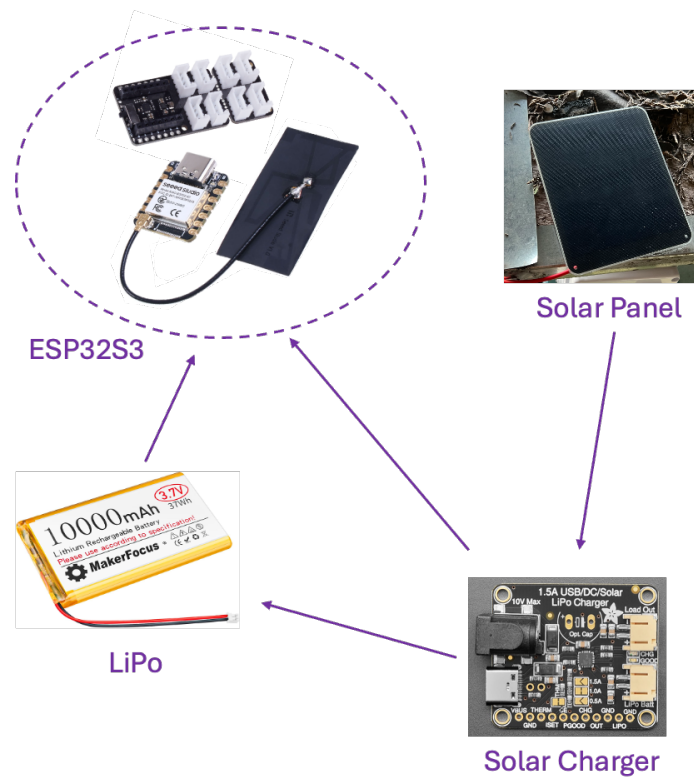
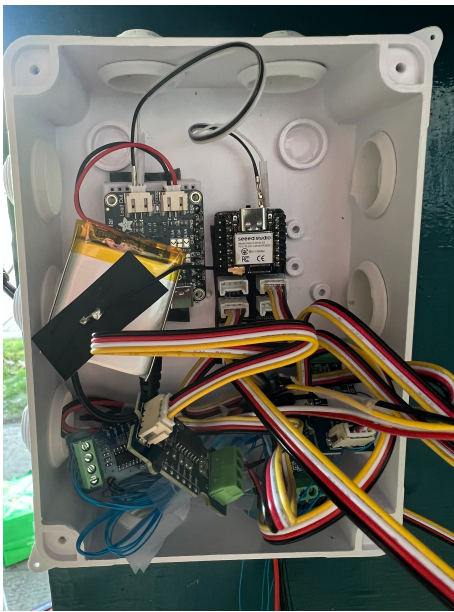


Figure 4.8: Power management system showing the interconnection of ESP32-S3, LiPo battery, solar charger, and solar panel for sustained outdoor operation

**Sensor Data Acquisition:** Each sensor is polled at a defined interval:

- **Weight sensing:** Each shelf is read individually through its dedicated load cell channel. This enables identification of shelves that require restocking and estimation of inventory distribution.
- **Environmental sensing:** Temperature, humidity, pressure, and VOCs are read from the BME688 to monitor conditions relevant to food safety.
- **Door activity:** Reed switches generate an interrupt on door open/close events, triggering immediate wakeup from deep sleep to log usage.

**Data Handling:** Sensor readings are processed and stored in a **queue buffer** within the ESP32-S3 before transmission. This ensures:



(a) Enclosure with cover removed, showing internal components: ESP32-S3, battery, solar charger, HX711 modules, and wiring



(b) Enclosure mounted inside pantry with BME688 sensor installed externally for environmental monitoring.

Figure 4.9: Electronics enclosure for the micro-pantry system: (a) internal electronics layout, (b) closed installation with external BME688 sensor

- Reliable storage of multiple readings in case of network unavailability,
- Aggregation of weight, environmental, and door activity data into a single transmission cycle to conserve energy.

**Power Management:** The ESP32-S3 spends the majority of its time in **deep sleep mode**, waking only for:

- Scheduled measurement intervals,
- Door activity interrupts,
- Critical alerts (e.g., abnormal temperature or rapid weight loss).

Wake durations are minimized to reduce power draw, with sensor polling, data packaging, and transmission optimized for rapid execution.

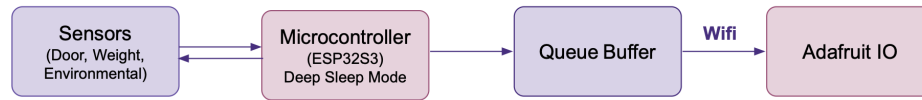


Figure 4.10: Firmware and software data flow: sensor inputs are processed by the ESP32-S3 microcontroller, queued for buffering, and transmitted via Wi-Fi to Adafruit IO for cloud storage and visualization.

**Cloud Integration:** All processed sensor readings are transmitted to the **Adafruit IO cloud platform** over **Wi-Fi** using the Adafruit IO REST API. The firmware packages readings into lightweight HTTP requests for efficient transmission. Data is organized as:

- **Feed structure:** Each pantry shelf and sensor type has a dedicated Adafruit IO feed, allowing modular expansion for multiple pantries.
- **Data payload:** Timestamped measurements include individual shelf weights, total weight, temperature, humidity, VOC levels, and door activity status.

This integration enables real-time dashboards, historical logging, and automatic alerts within the Adafruit IO ecosystem, giving pantry managers actionable insights for stocking and safety.

## Chapter 5

**EVALUATION AND RESULTS**

The pilot deployment of the sensor-enabled micro-pantry system (Figure 5.1) was evaluated to assess data reliability, power efficiency, and overall system utility. The evaluation was conducted over a continuous field deployment period at the Seattle pilot site.

**5.1 Data Reliability**

Prior to deployment, each load cell was calibrated using a one-time reference weight procedure to establish its scaling factor. The calibration was performed by placing known standard weights on the shelf platform and adjusting the offset and gain values in firmware.

Once deployed, the system directly applied these calibration parameters during operation. Weight readings were periodically verified against manual measurements using known food packages placed in the pantry.

The system consistently measured weights within approximately  $\pm 50$  g of the reference values over the two-week deployment period. Although a full calibration curve was not generated, operational checks confirmed the stability and accuracy of the measurements for practical pantry use.

Observed trends in weight readings from two shelves during deployment are shown in Figure 5.2. The plots demonstrate clear step changes in weight corresponding to pantry stocking and food withdrawals, validating the reliability of the sensing system.

Door activity readings from the magnetic reed switches matched visual observations during test openings. Environmental readings from the BME688 correlated closely with a calibrated reference sensor placed in the pantry, with temperature deviations under  $0.5^{\circ}\text{C}$ .

As shown in Figure 5.3, temperature and humidity readings remained stable throughout the deployment period, validating the environmental sensing accuracy.



Figure 5.1: Deployed micro-pantry at the Seattle pilot site with real-time monitoring displayed on a mobile device via Adafruit IO dashboard

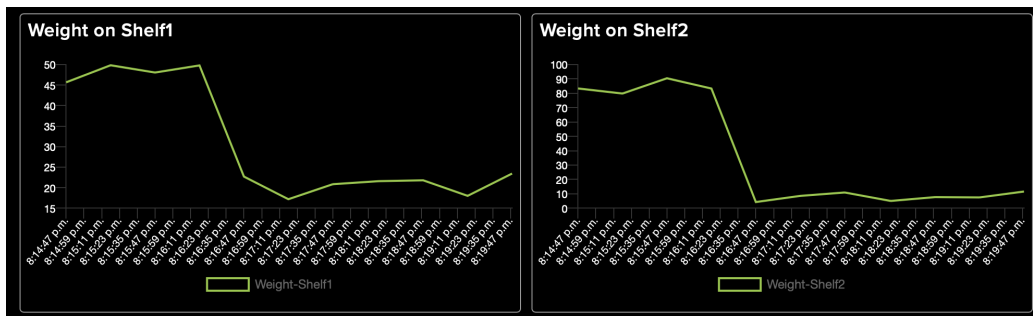


Figure 5.2: Weight measurements from Shelf1 and Shelf2 during pilot deployment, showing characteristic step changes corresponding to pantry use events

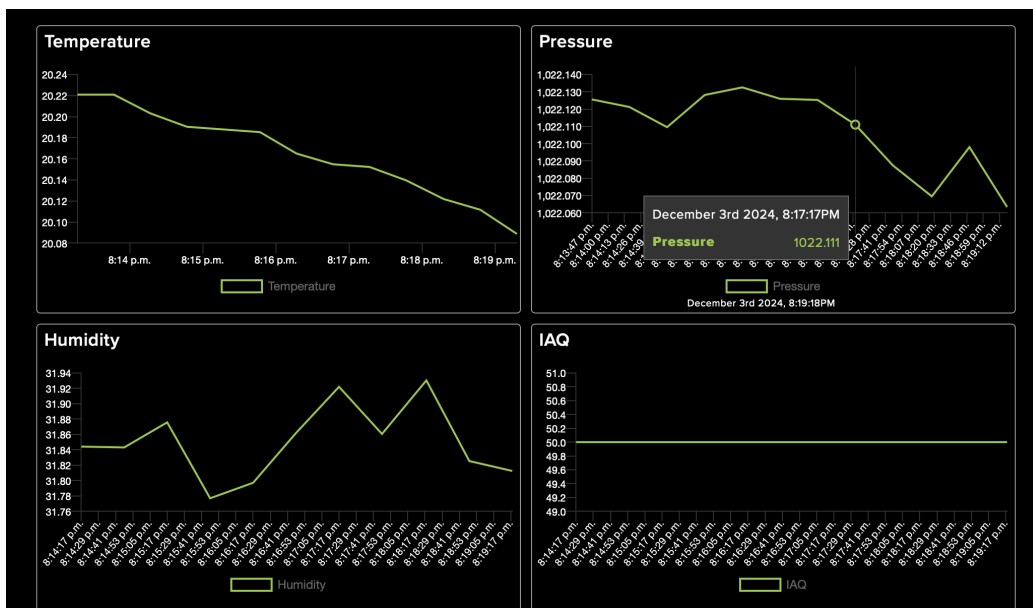


Figure 5.3: Temperature and humidity measurements from the BME688 sensor during pilot deployment, showing stable trends and close correlation with a calibrated reference sensor

## 5.2 Power Performance

The Seed Studio XIAO ESP32-S3 microcontroller, combined with deep sleep operation and solar-assisted charging, was configured for continuous low-power operation throughout the deployment. While direct battery voltage profiling was not recorded, the system operated

uninterrupted for the 15-day period without manual recharging. Average deep sleep current draw (based on manufacturer specifications and bench testing prior to deployment) is approximately 120  $\mu$ A, with active sampling and Wi-Fi upload peaks reaching 150 mA for short bursts.

### 5.3 System Utility

Data collected during deployment was visualized in real-time using the Adafruit IO cloud dashboard. Figure 5.4 shows an example time series plot of shelf weight, door activity, and temperature readings.



Figure 5.4: Example Adafruit IO dashboard visualization of shelf weight, door activity, and temperature during lab test

#### 5.4 Pantry Usage (Beacon Hill Pilot)

We analyzed everyday use over a four-day window (Jan 25–28) at the Beacon Hill site. Activities were inferred by pairing door-open events with step changes in shelf weight: consecutive door events within a short window were merged into a single user action, and clusters with  $|\Delta w| < 50$  g were ignored as noise (calibration accuracy).

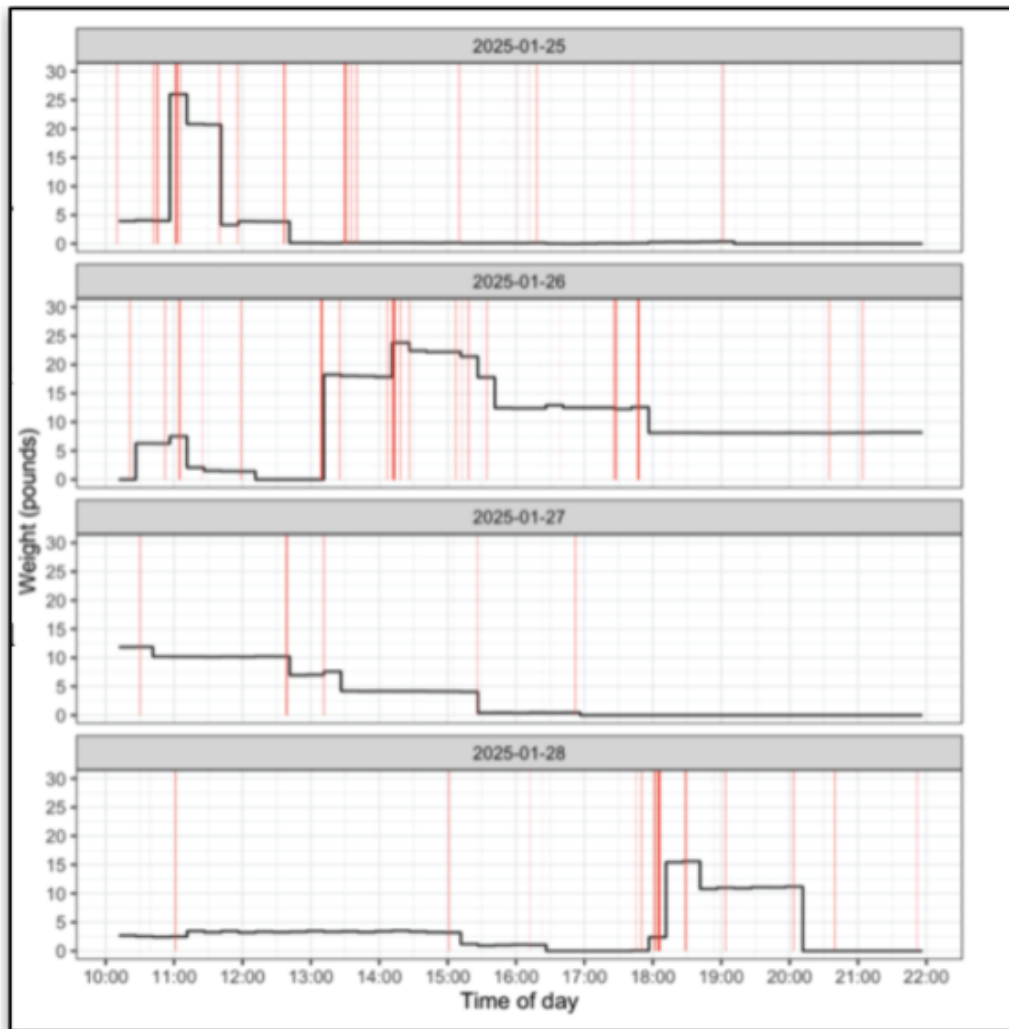


Figure 5.5: Four-day time series of shelf weight (black) with door events (red). Shaded regions indicate clustered activities (donations/receptions).

Across the study window, daily totals showed substantial turnover: on average **37.2 lb/day** were donated (min **4**, max **59**), and **31.2 lb/day** were received (min **17**, max **40**), yielding a net increase of approximately **+6 lb/day** in stock. Mean per-event amounts were **5.3 lb** (donation) and **2.4 lb** (reception), corresponding to roughly **7** donation events/day and **13** reception events/day.

Table 5.1: Beacon Hill pilot usage summary (Jan 25–28).

Metric	Mean	Min	Max	4-day total
Donated (lb/day)	37.2	4	59	148.8
Received (lb/day)	31.2	17	40	124.8
Net (lb/day)	+6.0	–	–	+24.0
Per-event (lb)	5.3 (donation), 2.4 (reception)			–

*Interpretation.* Fewer, larger donations and more frequent, smaller receptions indicate high churn with steady restocking.

## Chapter 6

**DISCUSSION AND CONCLUSION****6.1 Discussion**

The pilot deployment (Figure 6.1) demonstrated that a low-cost, solar-assisted sensing platform can provide reliable weight, environmental, and access data for community micro-pantries. Weight sensing remained within approximately  $\pm 50$  g of reference values over two weeks, which is sufficient for monitoring stock changes at the scale of typical pantry donations. Environmental sensing from the BME688 showed strong agreement with a calibrated reference sensor, with temperature deviations under  $0.5^{\circ}\text{C}$ , validating the suitability of this sensor for food safety monitoring in outdoor conditions. Door activity readings from magnetic reed switches correlated well with observed usage, supporting the reliability of event detection.

The power system, while not profiled in detail, sustained uninterrupted operation for 15 days through the combination of deep sleep operation and solar-assisted charging. This confirms the viability of the power design for extended deployments without manual intervention. However, the lack of recorded battery voltage profiles limits detailed analysis of the solar charging efficiency under varying environmental conditions.

Some features, such as automated alerting for environmental threshold violations, were configured but not triggered during the pilot. This means their functional integration is confirmed, but their performance in real-world conditions remains to be validated.

**6.2 Future Work**

Future iterations of the system should include:

- Multi-point load cell calibration to further improve accuracy across the full weight range.



Figure 6.1: Deployed micro-pantry at the Seattle pilot site during field testing

- Integrated battery voltage and current logging to quantitatively evaluate solar charging efficiency.
- Field testing of automated environmental alerts under controlled threshold exceedance events.
- Expansion to multiple micro-pantry sites to assess scalability and performance in diverse conditions.

- Exploration of edge processing for local data aggregation to reduce network transmission and improve energy efficiency.
- Integration with **refrigerated micro-pantries** to monitor and maintain safe storage conditions for perishable food items.
- Incorporation of **low-power camera modules** for inventory monitoring, automated object recognition, and enhanced transparency in stocking and usage patterns.

### 6.2.1 Camera Add-On (Prototype—Bench Tested)

We developed a low-power camera prototype to provide item-level context during pantry use. The module uses a Himax HM01B0 image sensor connected to a Nordic nRF53 over **SPI**, with frames/thumbnails sent to a mobile application over **BLE**. The prototype has been **bench-tested as a standalone system** and is **not yet integrated** into the deployed pantry node (Figure 6.2).

#### Planned integration and evaluation.

- **Install & trigger:** mount inside pantry; wake on door interrupt; capture 1–3 frames per event.
- **Linkage:** attach timestamp, activity ID, and  $\Delta w$  to each image; store alongside weight/door data.
- **Power/latency:** measure added average current, capture-to-upload latency, and success rate of transfers.
- **Privacy:** event-only capture; shelf-only field of view; no continuous video or faces.
- **Roadmap:** basic on-device downsampling/thumbnailing; later, lightweight food-type detection and simple nutrition cues.

### 6.3 Conclusion

The pilot deployment of the sensor-enabled micro-pantry demonstrates the feasibility of continuous, autonomous monitoring of stock, environmental conditions, and access activity

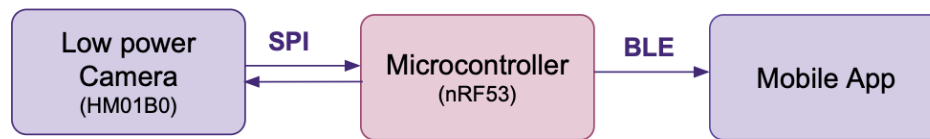


Figure 6.2: Camera pipeline: HM01B0 → nRF53 (SPI) → BLE → mobile app

using a compact, low-power platform. The combination of ESP32-S3 microcontroller, solar-assisted power, and multi-sensor integration provided stable operation over three weeks without maintenance.

While some performance aspects, such as detailed power profiling and alert verification, remain for future work, the system has shown sufficient reliability and energy efficiency to justify broader trials. With targeted improvements in calibration, monitoring, and scalability, this platform can support enhanced transparency, coordination, and food safety in community-based hunger relief networks.

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## VITA

Deeksha Prabhu received her Bachelor of Engineering degree in Electronics and Communication from Manipal Institute of Technology, India, with a concentration in Embedded Systems. Following graduation, she worked as a Senior Embedded Software Engineer at GE Healthcare, where she developed firmware and embedded software for safety-critical medical diagnostic equipment.

She is currently pursuing a Master's degree in Electrical and Computer Engineering at the University of Washington, specializing in Embedded Systems and Machine Learning. Her research focuses on ubiquitous computing, low-power wireless communication, and secure wireless sensing. During her Master's program, she has contributed to projects involving low-power camera systems, smart pantry solutions for food accessibility, and secure wireless sensing platforms.

Her long-term goal is to design next-generation embedded systems that seamlessly integrate into everyday life to improve community well-being.