Washington State Conservation Commission

Site-Specific Intervention-driven Emissions Reduction Strategies for Climate-Smart Dairy Farming: Research and Demonstration

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Executive Summary

This project developed a practical and economical sensing tool to help dairy farmers quantify greenhouse gas (GHG) emissions, particularly methane (CH_4), carbon dioxide (CO_2), and ammonia (NH_3) at the farm level. Project also explored ways to mitigate the emissions using feed additives to the milking cows as well as biochar addition to dairy manure.

Dairy operations are a significant source of GHG emissions, primarily from enteric fermentation in cows and manure decomposition. To quantify these emissions, Washington State University team developed and deployed a cost-effective, durable GHG and weather sensing network on the commercial dairy farms. The custom developed sensing nodes are capable of continuously monitoring GHG levels alongside local weather conditions such as temperature, humidity, wind speed, and direction. Each node has wireless data transmission and solar-powered energy harvesting capability. These sensing nodes were validated at Cornell University using gold-standard open-circuit respiration chambers housing Holstein dairy cows. The comparison revealed a high level of accuracy, especially for carbon dioxide ($r = 0.97$), and good agreement for methane ($r = 0.75$), indicating that these affordable devices are ready for field deployment.

Following successful validation, 19 sensing nodes were deployed across key locations at our commercial dairy cooperator farm, Royal Family Farming in Royal City, Washington. These locations included the milking parlor, two free-stall barns, a composting area, and a vermiculture (worm farming) facility. The real-time emissions data revealed clear spatial differences in emission concentrations, with the highest levels of CH_4 and CO_2 in the milking parlor, likely due to limited airflow and high animal occupancy. Lower emissions were observed at the composting and worm farm areas, which had better natural ventilation. Weather and emissions data were also analyzed to understand how environmental conditions influence animal GHG patterns throughout the day and across seasons.

As localized emission quantification became feasible, two emission reduction strategies are now actively being evaluated through this project and work will continue post the project term. First, in-vitro biochar experiments are underway to examine the potential of biochar amendments in manure storage for reducing CH_4 and CO_2 emissions. The trials involve dairy manure collected from Cornell's Teaching Dairy Barn and biochar sourced from a partnering dairy. Samples are incubated in climate-controlled chambers, with emissions monitored using our GHG sensing technology. Early trends suggest that biochar may suppress methane generation by altering microbial activity and improving aeration within stored manure. Second, an ongoing feed additive trial is investigating the impact of 3-nitrooxypropanol (3-NOP), a compound known to inhibit methane formation in the rumen. The trial involves Holstein cows housed at Cornell's Large Animal Research and Teaching Unit, with one pen receiving the additive and the other serving as a control. Both enteric emissions and animal performance metrics, such as milk yield and feed intake, are being recorded. Preliminary data collection is still in progress, but the setup promises valuable insight into methane mitigation from the inside out. Similar on-farm experiments are being conducted at our commercial cooperator dairy site.

To connect research with practice, we organized in-person (& Virtual via YouTube live) "Climate-Smart Dairy Farming: Research & Demonstration Field Day 2025" at Royal Dairy, drawing producers, extension educators, and researchers from across the region. Attendees participated in hands-on sensor demonstrations, farm tours, and web-dashboard and mobile application driven live data visualization sessions. This project represents a significant step forward in equipping dairy farms with scalable, site-specific, and science-backed tools to monitor emissions, adopt mitigation practices, and comply with evolving environmental regulations, as well as benefit from carbon credit market, while safeguarding the sustainability and profitability of the dairy industry.

Introduction

Background

Milk is one of the most traded agricultural commodities worldwide (OECD-FAO Agricultural Outlook 2022-2031, 2022), and it is the second largest agricultural commodity in the Northwestern U.S. However, the cost of milk production continues to rise, affecting numerous families' income and food security. Additionally, consumer perception affects the demand for fluid milk due to GHG emissions and natural resource use (Christopher A. Wolf and Glynn T. Tonsor, 2017; Clark et al., 2019; Ly et al., 2021). Moreover, the Pacific Northwest is facing unprecedented weather-related changes/events (e.g., 2021 summer heat and wildfire smoke), exposing thousands of dairy animals to dangerous environmental conditions, i.e., heat and air quality stress. Over the years, the dairy industry has made advancements in enhancing production efficiency and reducing natural resource utilization (Thoma et al., 2013). However, the dairy industry's GHG emission contribution is significantly higher (2X or more) than other agricultural commodities, such as wheat, peas, fruit, and root crops. Around 80% of the emissions from dairy farms come from enteric emissions or manure decomposition, prompting legislation to set emission limits. The dairy industry's sustainability could be put at risk by this legislation. Indeed, Washington's cap-and-invest program sets a limit, or cap, on overall carbon emissions in the state and requires businesses to obtain allowances equal to their covered greenhouse gas emissions (Washington’s Cap-and-Invest Program; Wongpiyabovorn et al., 2023). With accurate and continuous emission estimation, dairy farmers can reduce their greenhouse gas (GHG) footprint, benefiting from challenges that persist in two main areas: 1) quantifying the contribution of enteric GHG emissions from dairy cattle, manure storage, and its association with localized weather, seasonal weather changes; and 2) lack of research driven guidelines on use of site specific interventions to reduce emission (e.g., animal feed additives, biochar additives to solid manure during storage).

There is a lack of rugged and affordable localized weather/GHG emissions monitoring technologies, inhibiting dairy producers from estimating their operation's GHG emissions and implementing site-specific mitigation strategies. Available off-the-shelf GHG emissions sensing technologies are costly, impractical, and inaccessible to many commodities, including cattle and dairy farming (Hill et al., 2016). Recently, some efforts have been focused on monitoring GHG emissions from dairy cattle operations. However, technology adoption and applicability have been limited due to a lack of miniaturized, rugged sensing payload; associated integration and deployment challenges (i.e., robustness, cost, and accessibility at large); ease of unifying data in an ecosystem; and overall scalability to relevant daily operations (Bang et al., 2022; Cantor et al., 2022). In this context, there is a clear need for low-cost, durable, and site-adaptable sensor systems that enable real-time monitoring of GHG emissions and weather parameters. Enabling producers with such tools could facilitate data-driven decisions to adopt mitigation strategies tailored to their unique farm systems—such as optimized feed additives or manure amendments.

Objectives

To address these challenges, the project focuses on four key objectives.

1. Integrate, validate, and deploy rugged localized weather and greenhouse gas emissions sensing network on a commercial dairy farm to monitor and map emissions,
2. Test efficacy of biochar treatments (in-vitro and on-farm) to mitigate emissions from dairy manure storage facilities,

3. Study cattle feed additive (e.g., 3-nitrooxypropanol) role in enteric methane emissions reduction from dairy cattle, and
4. Demonstrate the piloted technology and extension education.

This project builds on Washington State University's ongoing efforts to develop cost-effective, site-specific monitoring tools for GHG emissions in dairy systems. Our sensing network and real-time data acquisition portal are designed to quantify GHG emissions from enteric sources under varying environmental conditions. These data will serve as a foundation for evaluating targeted interventions—such as dietary 3-NOP supplementation and biochar amendments—to reduce emissions. The feasibility and impact of these strategies will be demonstrated through field trials and stakeholder engagement at a collaborating commercial dairy farm, ultimately supporting informed adoption of climate-smart practices in dairy production systems.

Methods

Study Site

The sensing nodes manufacturing happened at Washington State University. Sensor validation against gold standard and in-vitro trials happened at Cornell University. The on-farm trials are being conducted at Royal Family Farming, a commercial dairy farm located in Royal City, Washington. The site houses over 6,800 dairy cows and includes multiple emission hotspots such as feed bunks, composting zones, a milking parlor, and a vermiculture facility.

Integration and Testing of Weather/GHG Emissions Sensing Network

System Integration

The wireless sensing network (WSN) is composed of weather/GHG sensing nodes and a supporting Long Range (LoRa) communication infrastructure. Our team has successfully developed the active GHG sensing node (Figure 1.a), which builds upon the prior passive sampling design. The sensing node (Figure 1.b) consists of a microcontroller unit (MCU), designed to acquire and process data from various sensors. The GHG sensing capabilities of the node include two factory-calibrated non-dispersive infrared (NDIR) sensors for methane (CH_4; range: 0-50,000 ppm), and carbon dioxide (CO_2; range: 0-40,000 ppm), and factory factory-calibrated electrochemical gas sensor for ammonia (NH_3; range: 0-100 ppm). These sensors are housed in a custom-designed gas chamber made from Polyethylene Terephthalate Glycol (PTEG) material, known for its durability and chemical resistance, and are connected to a miniature diaphragm gas pump. The pump ensures continuous airflow at 500 cc/min, critical for maintaining accurate and consistent gas sampling within the chamber. The diaphragm gas pump operation is regulated by a pump controller, ensuring precise airflow control. The sensor node is equipped with multiple communication interfaces, including SD card storage, Wi-Fi, Bluetooth, and Long-Range (LoRa), enabling flexible data transmission and remote monitoring capabilities. Additionally, the node features an integrated low-power Global Navigation Satellite System (GNSS) receiver for precise geolocation and an OLED display for real-time data visualization. The system is powered by two 1S3P Li-ion batteries, with backup support provided by a 6V 2W solar panel to ensure uninterrupted operation in remote environments. A charge controller and battery management system (BMS) oversee power management, optimizing energy efficiency, and safeguarding the batteries from overcharging or excessive discharge, thereby enhancing system reliability and longevity. Our team is now pursing commercialization of these sensing nodes.

An all-in-one weather sensor (model: ATMOS41, Meter Group Inc., USA) is integrated into the system to provide real-time environmental data. This sensor measures air temperature (range: -50°C to 60°C), relative humidity (range: 0 – 100%), wind speed (range: 0 – 60 m/s), barometric pressure (range: 1 – 120 kPa), wind gust (range: 0 – 60 m/s), and solar radiation (range: 0 – 1750 W/m^2). In addition, the sensing node includes provisions for an air quality sensor (model: PA-II, PurpleAir Inc., USA) to monitor particulate matter (PM) air pollution.

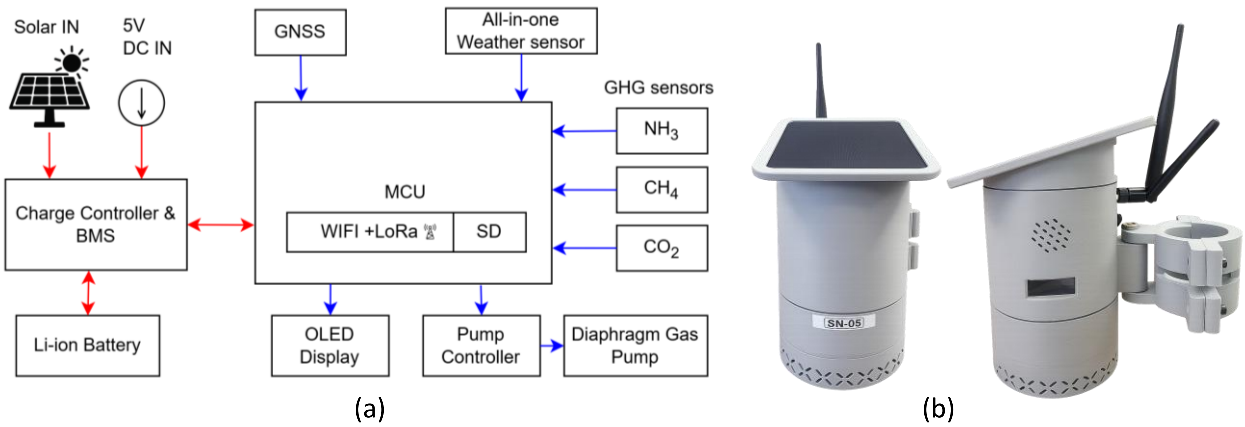


Figure 1: (a) Schematic diagram of the integrated weather/GHG sensing node (b) Physical implementation of the sensing node for field deployment.

GHG Sensor Calibration

All sensing nodes were programmed, validated, and calibrated to ensure accurate performance within the WSN at the study site before deployment. Calibration was essential to establish a reliable relationship between sensor output and true gas concentrations. For CH_4 sensors, pre-calibration techniques were employed using the manufacturer's calibration tool (Figure 2.a) to fine-tune the sensors and minimize systematic error. For CO_2 sensors, a Forced Re-Calibration (FRC) was carried out at 5000 ppm using an inbuilt Arduino function to adjust the baseline. Following pre-calibration, sensors underwent span and zero calibration processes (Figure 2.b). Zero calibration was performed using standardized calibration gases (models: J1002, F1005, H1013, MESA International Technologies, CA, USA) to determine baseline readings in the absence of target gases (zero air, gas composition: Oxygen 20.9%, Total Hydrocarbons < 1 ppm, Nitrogen ~79.1%), compensating for inherent sensor biases. Then, span calibration was conducted to align the sensor's sensitivity with standardized gas concentrations (CH_4: 50 ppm and 600 ppm; CO_2: 400 ppm, 5000 ppm; NH_3: 5 ppm and 25 ppm), ensuring precise measurements within the operational ranges of each sensor. Additionally, temperature compensation features were enabled in the sensor firmware to maintain accuracy under varying environmental conditions.

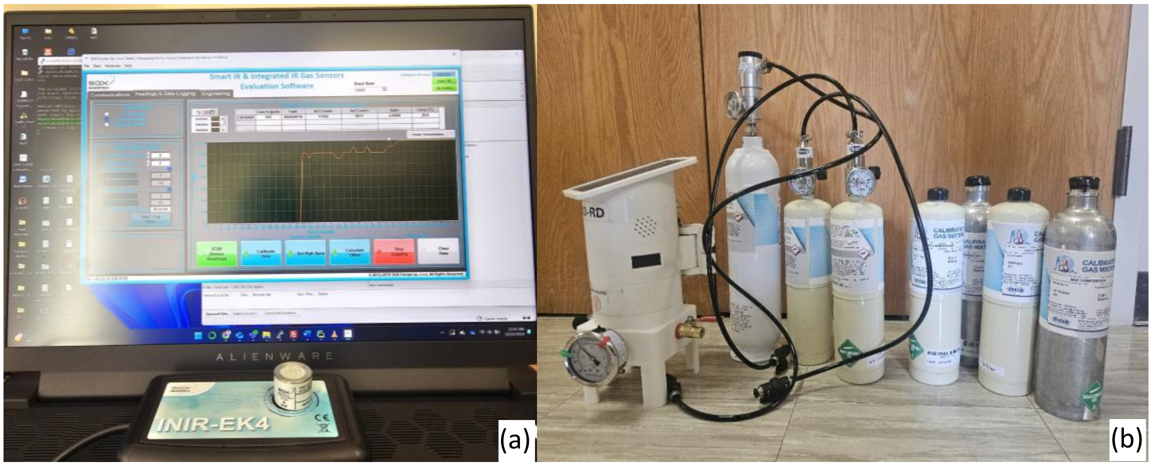


Figure 2: (a) Pre-calibration of CH_4 sensors, (b) Field-ready sensing node undergoing zero and span calibration using certified calibration gases.

Sensing Node Validation and Laboratory Testing

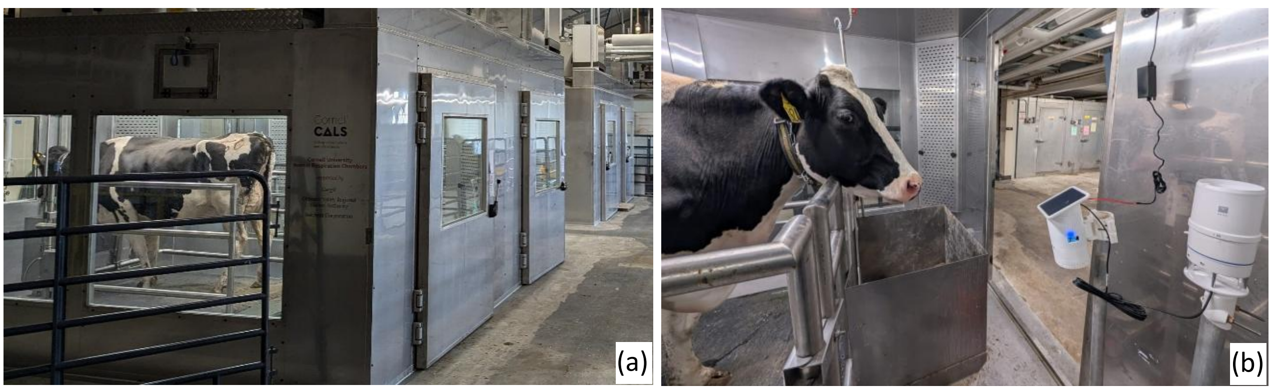


Figure 3: (a) Four open-circuit respiration chambers at LARTU, Cornell University, used for validating greenhouse gas emissions from dairy cows (b) Sensing node with integrated weather sensors installed inside a respiration chamber for comparative validation.

Prior to full-scale field deployment, the sensing network was validated under controlled conditions in open-circuit respiration chambers at the Large Animal Research and Teaching Unit (LARTU) at Cornell University (Ithaca, NY), which served as the gold standard for gas emissions measurement from cattle (Figure 3a). The objective of this validation phase was to assess the accuracy, stability, and response behavior of the developed sensing nodes relative to the gold standards. Four prototype sensing nodes were installed—one per respiration chamber (RC) to simultaneously monitor emissions alongside the chamber's integrated gas analyzers (Figure 3b).

Animal Enrollment

All procedures involving animals were approved by the Cornell University Institutional Animal Care and Use Committee (IACUC), protocol #2024-0143. Holstein cows (n = 16) entering second or greater lactation, between 215 to 280 days in milk (DIM), and between 62 to 121 days carried calf (DCC), were enrolled from the Cornell University Ruminant Center (CURC; Harford, NY; Figure 4) and transported to LARTU (Figure 5). Cows immediately moved into tie stalls in Monitor Rooms (MR) for 24-36 h. On the 3rd day of enrollment, cows were temporarily moved to RC at LARTU, 1 cow per RC, for a 4 h observed acclimation period and then returned to MR.

On day 4 of enrollment, cows were moved to the same RC they were assigned at acclimation, where they remained for up to 14 d. After the 14-d testing period, cows were moved back to the MR for 12 – 24 h and then transported back to CURC.

Figure 4: Cornell University Ruminant Center (CURC; Harford, NY).

Individual Animal Sampling

Cows were monitored with cameras for the duration of the study using Reolink 4K wired outdoor security cameras (ReolinkDirect; Wilmington, DE). Cows were also observed daily between 0530 and 0800 by research staff for health disorders. Observations and physical exams included temperature, respiration rate, heart rate, rumination rate, mastitis scoring, and β-hydroxybutyrate (BHB). Intravaginal temperatures were monitored every 10 minutes via HOBO MX2304 Data Logger (LI-COR; Bourne, MA), and then recorded 1 x d (Figure 6).

Figure 5: Large Animal Testing Unit (LARTU; Ithaca, NY) monitor rooms.

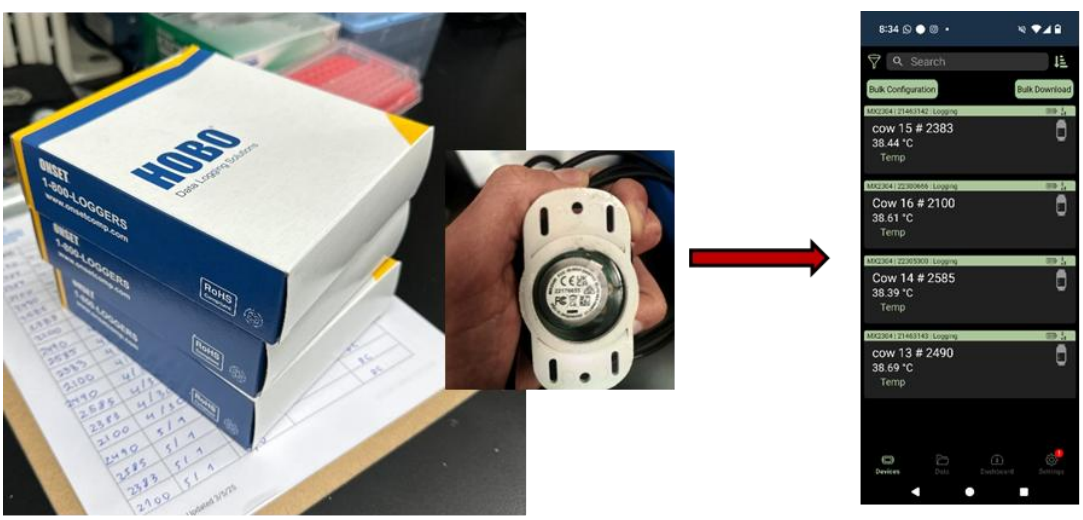


Figure 6: Left to Right: HOBO temperature data logger boxes, logger, and an example of the application monitoring intravaginal temperature.

Feed and Milk Sampling

Figure 7: a) and b) Collection and storage of total mixed ration (TMR) sampling prior to submission to DairyOne.

Irrespective of location (MR or RC), all cows were individually fed a high cow total mixed ration (TMR) daily between 0800 and 1000 h. Water was available at all times. Cow dry matter intakes (DMI), refusals, and water intakes were weighed and recorded daily. Samples of TMR were collected daily (Figure 7.a). Cows were individually milked 2 x d between 0600 and 0800 or 1800 and 2000. Samples were collected aseptically from each teat for bacteriology (Figure 7.b). After weighing, additional samples were taken from the bucket for fatty acid (FA) and composition analysis. Milk was discarded at each milking.

Blood Sampling. Blood samples were collected daily between 0600 and 0800 h from the coccygeal vein or artery beginning on the day of acclimation to the GHG Chamber through to the day cows exited to the MR. Blood samples were collected using 20-gauge Vacutainer needles (Greiner Bio-One GmbH) into one 10-mL tube containing 158 USP units of lithium heparin (Becton Dickinson) and one plain 10-mL evacuated tube (Becton Dickinson).

Sensors *Data Collection*. The sensing nodes recorded gas concentrations in ppm along with environmental variables (temperature, relative humidity, wind speed, wind gust, and air pressure) at 1-minute intervals for a 14-day period in April 2025, generating high-frequency time-series data for comparative analysis.

This validation phase enabled quantitative assessment of sensor performance characteristics such as detection sensitivity, signal drift, calibration stability, and environmental compensation under a controlled environment. The outcomes demonstrated that the low-cost sensing nodes exhibited performance characteristics comparable to the gold-standard reference system, thereby confirming their suitability for real-world deployment. Additionally, insights gained from this phase informed the refinement of onboard signal processing algorithms and calibration routines to enhance accuracy and reliability under variable field conditions.

Sample Analysis

Feed and Milk Sample Analysis

TMR samples were baked for at least 1 h at 60 ˚C to evaluate dry matter (DM). Dried samples were then composited by week and submitted to DairyOne (Ithaca, NY) for wet chemistry analysis.

All milk samples were plated and incubated to assess bacterial growth and select samples for submission for full bacteriology. Select milk samples were submitted to Cornell University Animal Health and Diagnostic Center (AHDC; Ithaca, NY) for bacteriological analysis. A sample from each milking was composited and analyzed for FA, and an additional sample was submitted for analysis of fat, protein, total solids, lactose, and somatic cell counts at DairyOne (Ithaca, NY).

Blood Sample Analysis

Figure 8: (a) Precision Xtra Meter (Abbott Laboratories; Alameda, CA) (b)Blood gas analyzer and a sample readout (Nova Biomedical, Waltham, MA).

Whole blood samples collected in those collected into tubes containing lithium heparin were transported on ice to the laboratory, then analyzed for BHB using Precision Xtra Blood Ketone Monitoring System (Abbott; Alameda, CA; Figure 8.a) and blood gas analysis with Blood Gas Analyzer Stat Profile Prime Plus (Nova Biomedical, Waltham, MA; Figure 8.b). After analysis of whole blood, lithium heparin and plain evacuated tubes were then processed and stored. Plasma and serum were harvested by centrifugation at 2,000 × g for 20 min at 4℃, split into 2 aliquots, and stored at -80℃ until further analysis.

On-Farm Sensing Node Deployment

A total of 19 sensing nodes were deployed across key operational zones at Royal Dairy Farm to monitor spatial variations in GHG emissions (Figure 9). In the layout, red icons represent sensing nodes equipped with both GHG and weather sensors, while blue icons indicate nodes that monitor only GHG concentrations. Specifically, two nodes were installed in the milking parlor, an area with high animal activity and ventilation variability, to capture emissions associated with animal respiration and cleaning operations. Ten nodes were distributed across two free-stall barns (Barn 2 & Barn 3), providing comprehensive coverage of indoor housing conditions where large herds are maintained. To establish ambient background levels, one node was installed outside the barns and designated as the baseline reference. In addition, two nodes were deployed at the vermiculture (worm farm) facility, targeting emissions from manure processing through biological decomposition. Finally, four nodes were placed in the composting area, where solid manure undergoes aerobic degradation, a known source of GHG emissions.

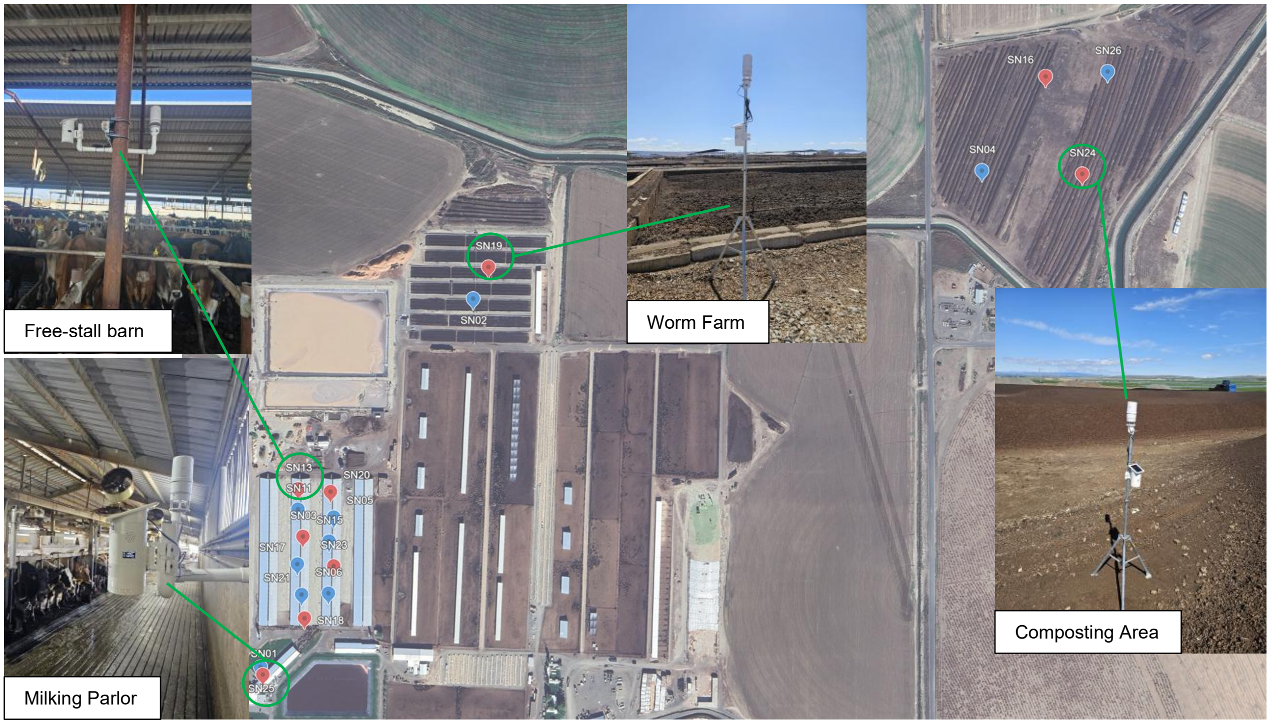


Figure 9: Deployment layout of sensing nodes at Royal Dairy Farm, across key operational areas, including the milking parlor, free stall barns, vermiculture (worm farming) facility, and composting area.

In-vitro Biochar Treatments for Manure Emissions Mitigation

Fresh dairy manure was sourced from the Cornell University Teaching Dairy Barn, and biochar was procured from a collaborating dairy farm. The experimental setup included a total of eight sealed emission chambers (Figure 10), consisting of two control units (0% biochar) and six treatment units, with two replicates each of biochar-amended manure at 15%, 30%, and 50% volumetric inclusion rates, respectively. The manure-biochar mixtures were placed in a sealed anesthesia induction chamber (model: RWD-AICRC-V102, Conduct Science, USA) to maintain a controlled headspace environment. Each chamber was equipped GHG sensing node to monitor real-time concentrations of CH_4, CO_2, and NH_3. Additionally, HOBO temperature loggers (model: MX2203, Onset Computer Corporation, USA) were installed to track internal thermal conditions. Each chamber was equipped with a passive venting mechanism comprising a water trap, which allows gases generated from manure decomposition to escape while preventing ambient air from re-entering. This setup maintains near-atmospheric internal pressure, minimizes disturbance to the internal gas environment,

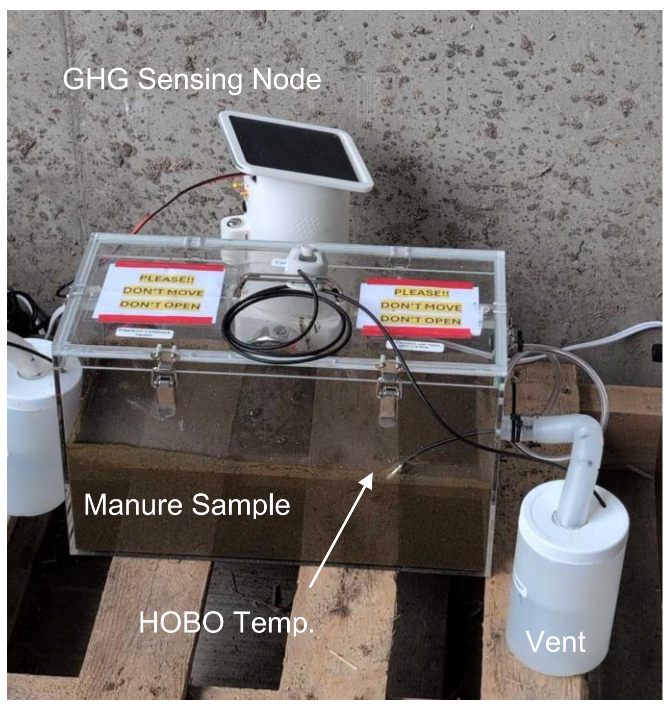


Figure 10: In-vitro emission chamber setup with GHG sensing node, HOBO temperature logger, and passive venting for monitoring manure-biochar treatments under controlled conditions.

and avoids over-pressurization that could affect emission dynamics. The water trap also acts as a barrier against particulate contamination and moisture loss, ensuring consistency across treatments. Sensor nodes recorded emissions continuously, capturing short-term fluctuations during the initial decomposition phase. The methodology closely followed previously validated studies (Harrison et al., 2022), with standardized manure volume (4.0L volume, 14.0% DM) and uniform chamber geometry to ensure comparability across treatments.

The next phase will involve collecting gas concentration data over time, followed by laboratory analysis of chemical and physical properties (e.g., percent solids, organic matter, pH, soluble salts, total nitrogen, total carbon, Carbon: Nitrogen ratio) at the Agricultural Analytical Services Lab, Penn State. Final analysis will conclude after the end of this funding cycle.

On-Farm Feed Additives Trial and Enteric Emissions

Figure 11: Free stall barns at Royal Dairy Farm with GHG sensor nodes and an automated commodity and mixing TMR station under construction to accurately dose the additive Bovaer® (3-nitrooxypropanol, 3-NOP) for pen studies.

A pen-based field experiment is underway at Royal Dairy, Rayol City, WA, to assess the impact of the methane-reducing feed additive Bovaer® (3-nitrooxypropanol, 3-NOP) on enteric emissions and animal performance (Figure 11). The study includes treatment pens where lactating dairy cows receive a daily dietary supplementation of 60 mg 3-NOP per animal mixed into the total mixed ration (TMR), and a control pen with no additive. The pen study includes replicates (n=8) with a wash-out period in between replicates of 21 days. Each pen houses around 400 mature lactating cows and has a network of GHG sensors, as noted in Figures 9 and 11. In this specific study, experimental unit is the pen, and replicates to account for pen effect, treatment effect, and interactions. The cooperator is collecting health/disease indicators, monthly milk dairy herd information (DHI), weekly total mix ration samples responses, to evaluate physiological and metabolic changes. Additionally, total mixed ration (TMR) samples are being collected regularly to ensure dosing accuracy and nutrient consistency. Royal Dairy is one of the few commercial dairy farms in the country feeding Bovaer® (3-nitrooxypropanol, 3-NOP), and the farm is currently finishing its automated commodity and mixing to prepare TMR for their cows. This facility will allow us to complete this study objective.

Technology Demonstration and Extension Outreach

The project team conducted a targeted extension and demonstration to support stakeholder engagement and knowledge dissemination. As part of Objective 4, we organized the Climate-Smart Dairy Farming: Research & Demonstration Field Day-2025 event on May 30, 2025, at Royal Dairy Farm in Royal City, WA. Planning and promotion of the event involved a coordinated digital marketing campaign, including posts and event flyers (Figure 12) circulated through Facebook, LinkedIn, and X, as well as through the WSU AgWeatherNet weather portal. These efforts were aimed at attracting a diverse group of participants from academia, industry, government, and the farming community.

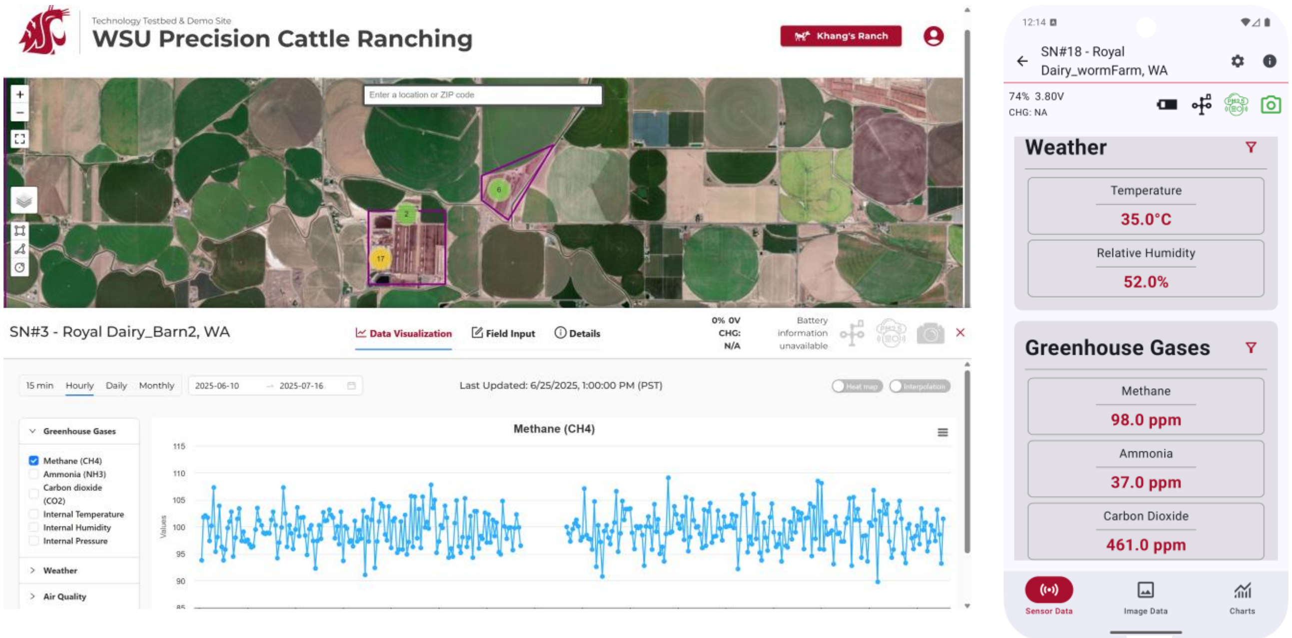
The event featured live demonstrations of the integrated GHG-weather sensor nodes, field deployments in key locations such as the composting area, worm farm, and milking parlor, and real-time visualization of environmental data through a custom-built dashboard. Guided farm tours and interactive discussions were organized to highlight the integration of sensing technologies with practical emission mitigation strategies like biochar amendments and feed additives. Additionally, the event was live streamed via YouTube to increase accessibility and allow remote participation.

Figure 12: Promotional flyer for the Climate-Smart Dairy Farming: Research & Demonstration Field Day 2025, held at Royal Dairy Farm, WA

As part of its outreach and dissemination strategy, the project team actively engaged with regional stakeholders through conference participation. One key effort included presenting at the 2024 Northwest Bioenergy Summit, held October 15–16 in Spokane, WA. This annual summit brings together researchers, policymakers, and industry leaders to explore renewable energy and climate-smart agriculture innovations. The team presented a research poster titled “Greenhouse gas emission and weather indicators sensing network for improved cattle health,” which focused on the development and field validation of a low-cost GHG and weather sensing network.

Data Collection, Curation and Management

Gas concentration values (in parts per million, ppm) and weather parameters are recorded along with associated metadata, including device ID, device name, battery status, connectivity status, and SD card storage health. The data are initially logged locally on the SD card and then transmitted wirelessly via Bluetooth and the LoRa Wide Area Network (LoRa WAN) to a remote cloud server. This infrastructure supports advanced analytics and enables real-time monitoring and decision-making.



(a) (b)

Figure 13:(a) Web-based dashboard interface showing geospatial deployment and real-time data visualization for sensing nodes across the dairy farm (b) Android mobile application interface enabling local monitoring and configuration of individual sensing nodes via Bluetooth connectivity.

To support real-time monitoring and decision-making, a dual-platform system comprising a web-based dashboard (Figure 13a) and an Android mobile application (Figure 13b) have been developed. The web dashboard provides centralized access to all sensing nodes integrated within the WSN via LoRaWAN. It enables remote visualization, monitoring, and analysis of real-time greenhouse gas and weather data from each deployed node. The backend infrastructure is hosted on a CAHNRS virtual machine (VM) cloud server at Washington State University, provisioned with 8 vCPUs, 64 GB RAM, and 500 GB storage. This server facilitates data storage, preprocessing, and dynamic visualization for the web interface. The portal is built with a React-based JavaScript frontend for interactive and intuitive user experience, and a Flask-based Python backend for efficient data processing and Application Programming Interfaces (APIs) integration. All field deployed nodes transmitted data is stored in a structured database, allowing secure and organized access.

In parallel, an Android mobile application, developed using Kotlin in Android Studio, serves as a flexible interface for nodes operating outside the LoRaWAN coverage. These nodes connect directly to the mobile app via Bluetooth for real-time data monitoring and configuration. When internet connectivity is available, the mobile app can also retrieve data from WSN-connected nodes using APIs provided by the backend server. Both the web portal and mobile application feature dynamic graphing capabilities and support data export in multiple file formats, enabling users to conduct advanced analysis and share information efficiently. This integrated system enhances data accessibility, promotes field-level usability, and supports comprehensive monitoring across diverse deployment scenarios, as a scalable system if additional farmers deploy GHG/Weather sensing network on their farms.

Results

GHG Sensors Performance Validation

The sensing nodes data were compared against gold-standard measurements for both CO_2 and CH_4 concentrations. The sensing nodes showed slightly elevated readings compared to the gold standard. For CO_2, the average concentration measured by the sensing nodes was 3,036.86 ± 506.11 ppm, while the gold standard measured 2,851.76 ± 526.97 ppm. For CH_4, the sensing nodes reported an average of 217.93 ± 76.92 ppm compared to 173.41 ± 47.22 ppm from the gold standard.

A typical sensing node and respiration chamber captured consistent daily emission patterns, with synchronized peaks and troughs (Figure 14). The shaded regions surrounding the sensing node lines represent the 95% confidence intervals, reflecting variability across the sampling window. Pearson correlation analysis indicated a strong correlation for CO_2 measurements ($r = 0.97$, $P < 0.0001$) and a moderate correlation for CH_4 ($r = 0.75$, $P < 0.0001$), demonstrating alignment in concentration dynamics between the low-cost sensing nodes and the gold standard benchmark.

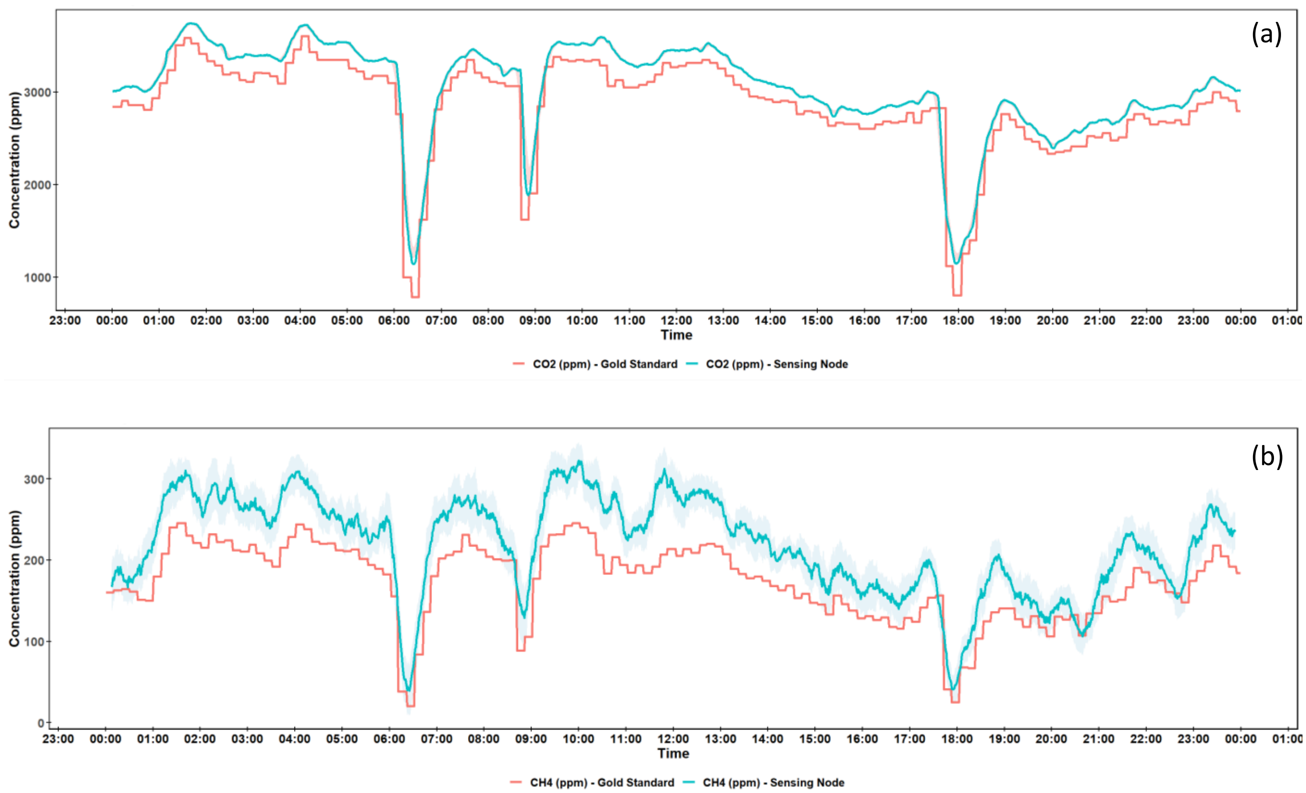


Figure 14: Comparison of (a) CO_2 and (b) CH_4 concentrations measured by the sensing nodes and the respiration chamber (gold standard) over 24 hours. Shaded bands represent the 95% confidence interval for measurements.

On-Farm Emission Trends

The distribution of CH_4, NH_3, and CO_2 concentrations was assessed across five key zones at Royal Dairy Farm, highlighting spatial variability in gas emissions (Figure 15). CH_4 concentrations were highest at the milking parlor (239.74 ± 80.62 ppm), followed by the worm farm (159.61 ± 91.92 ppm), Barn 2 (125.76 ± 85.67 ppm), and Barn 3 (125.68 ± 74.65 ppm), with the lowest observed at the composting area (70.53 ± 48.85 ppm). CO_2 levels followed a similar spatial trend, peaking at the milking parlor (764.36 ± 231.17 ppm), then the worm farm (658.50 ± 24.25 ppm), Barn 2 (541.38 ± 50.44 ppm), Barn 3 (518.24 ± 43.36 ppm), and the Composting area (425.09 ± 13.53 ppm). NH_3 concentrations were comparatively lower across all sites but showed a marked elevation in the milking parlor (0.60 ± 0.31 ppm), followed by the worm farm (0.43 ± 0.15 ppm). NH_3 levels remained minimal at Barn 2 (0.15 ± 0.18 ppm), Barn 3 (0.43 ± 0.42 ppm), and the composting area (0.13 ± 0.00 ppm).

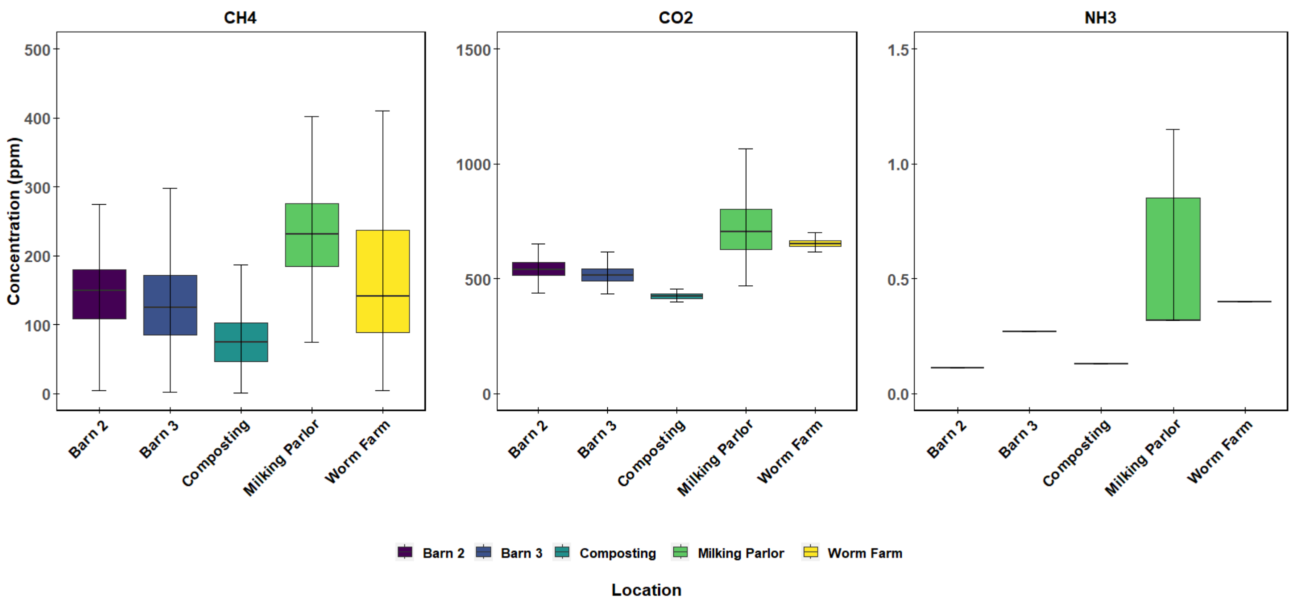


Figure 15: Distribution of CH_4, CO_2, and NH_3 concentrations measured by sensing nodes across five operational zones at Royal Dairy Farm, highlighting spatial differences in emission profiles.

Weather parameters revealed significant site-specific variation. The milking parlor exhibited the lowest average wind speed (0.20 ± 0.04 m/s) and gust speed (0.45 ± 0.13 m/s), alongside the highest temperature (17.63 ± 2.30 °C) and humidity (0.59 ± 0.10). In contrast, the composting area and worm farm recorded higher ventilation (2.54 ± 1.04 m/s and 2.56 ± 1.03 m/s, respectively) and lower temperatures (12.81 ± 4.56 °C and 13.08 ± 4.49 °C), aligning with their reduced GHG accumulation. Our future efforts will focus on relating weather data to the node specific emissions.

In-Vitro Biochar Treatments Impact on Enteric Emissions

Preliminary in-vitro trials have been launched to evaluate the influence of biochar amendments on enteric methane emissions. These experiments are designed to simulate ruminal fermentation using standardized procedures to observe how biochar incorporation affects gas production, fermentation dynamics, and microbial behavior. As the trials are still ongoing, no results are currently available. Findings from this study are anticipated to inform future mitigation strategies using sustainable carbon-based materials.

Feed Additive (3-NOP) Impact on Enteric Emissions

Concurrent laboratory experiments are underway to investigate the effect of the methane-inhibiting feed additive on enteric emissions. While the experiments are actively progressing, no conclusive results have been generated thus far. Results will be reported upon the completion of experimental phases.

Field Demonstration and Stakeholder Engagement

The Climate-Smart Dairy Farming: Research & Demonstration Field Day 2025 successfully facilitated direct interaction between the research team and key stakeholders (Figure 16). The in-person event brought together > 30 dairy producers, agricultural professionals, extension agents, and researchers, creating a collaborative environment to share insights on climate-smart technologies. Live demonstrations and guided tours provided attendees with first-hand exposure to the deployed sensing systems and the data collection workflow. The YouTube live stream attracted 12 virtual attendees, with positive feedback received from both in-person and online participants. This link is still active with recorded event for asynchronous watch in the future.

Figure 16: Field Day demonstrations during the Climate-Smart Dairy Farming: Research & Demonstration Field Day 2025 at Royal Dairy, WA. Activities included hands-on demonstrations of the GHG sensing network, interactive discussions, and a guided farm tour highlighting key facilities such as the farm kitchen and the vermiculture (worm farm) site.

Field demonstrations highlighted sensor deployment locations, hardware configurations, and the capabilities of both the web-based dashboard and the Android mobile application. Live data from deployed sensing nodes were visualized to illustrate emissions variability across the farm environment, underscoring the value of site-specific monitoring. In addition to in-person outreach, the Field Day event was also live-streamed on the YouTube platform, enabling broader virtual participation. To further amplify the outreach, project summaries and flyers were developed and distributed, encouraging future collaborations and adoption of the sensing technology. These extension activities played a critical role in validating system usability in real-world settings, gathering stakeholder feedback, and fostering continued interest in scalable GHG mitigation technologies for the dairy industry.

The poster presentation (Figure 17) at the Northwest Bioenergy Summit attracted attention from a diverse audience of approximately 100 participants. Attendees included researchers, extension agents, and agricultural stakeholders interested in the intersection of livestock production and environmental sustainability. Positive feedback was received regarding the sensing system's applicability and data accuracy. The poster detailed the integration process, deployment at dairy sites, and benchmarking against gold-standard respiration chamber data. The summit provided a platform to introduce the sensing framework's potential to support decision-making and emissions mitigation across dairy operations.

Figure 17: The project team presenting at the 2024 Northwest Bioenergy Summit in Spokane, WA.

Conclusions & Discussion

The sensing nodes consistently captured daily emission trends for both CO_2 and CH_4 with high temporal fidelity. The observed agreement with gold standard values, particularly the strong correlation for CO_2 (r = 0.97), underscores the reliability of the sensing nodes in quantifying concentration changes. Although CH_4 correlation was moderate (r = 0.75), it remains within acceptable bounds when compared to commercial alternatives, such as the GreenFeed system (r = 0.68; Ma et al., 2024). Slightly higher average values reported by the sensing nodes, especially for CH_4, may reflect localized gas accumulation near sensor inlets or differences in ventilation and sampling locations. These deviations are consistent with known challenges in comparing fixed-point sensors with integrated chamber systems. Importantly, the close tracking of diurnal patterns and the similar interquartile ranges suggest that the sensing system is sufficiently accurate for deployment in dynamic farm environments. Overall, the validation confirms the system's potential for real-time GHG monitoring in commercial dairy operations, providing a practical and cost-effective alternative to existing measurement platforms.

The spatial GHG emissions patterns underscore how microclimatic conditions and operational activities shape emission dynamics within a dairy farm setting. The Milking Parlor consistently emerged as the highest-emitting zone for CH_4, NH_3, and CO_2, which can be attributed to direct animal presence, high manure turnover, and restricted airflow—as indicated by the low wind speed and gust data. The moderate to low gas concentrations observed at the Composting Area and Worm Farm, despite their exposure to decomposing organic matter, may reflect enhanced natural ventilation and lower animal density. Higher wind speeds likely promoted gas dispersion, while lower temperatures may have reduced microbial and volatilization activity. These spatial trends highlight the importance of deploying distributed sensing to capture localized emission profiles. The integration of GHG and meteorological data reveals not only emission hotspots but also contextual environmental drivers, crucial for informing site-specific mitigation strategies. Future mitigation could target high-emission areas like the Milking Parlor with solutions such as improved ventilation, biofiltering, or feed-based CH_4 reduction strategies.

The ongoing trials on feed additive (to cattle) and biochar treatments (in manure storage/treatment facilities) towards enteric emissions reduction and due quantification by GHG emission sensing nodes will continue this final reporting timeline. Pertinent results will be published in peer-reviewed journal as well as extension articles through WSU and Cornell University Extension outlets.

Expected Products and Publications:

- Invention Disclosure: Rugged and scalable GHG sensing nodes.
- Publication 1: Sensor GHG validation in respiration chambers
- Publication 2: Measurements of GHG emissions in different facilities at Royal Dairy farm, Royal City WA.
- Publication 3: Comparison of GHG sensor nodes and satellite methane measurements at Royal Dairy farm, Royal City, WA.
- Publication 4: Pen study 3-NOP efficacy at a commercial dairy farm in Washington State (Royal Dairy).
- Publication 5: Efficacy of Biochar to reduce GHG emissions from dairy cattle manure (in vitro and field testing).
- Publications 6-7: WSU and Cornell University lead extension articles.

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