A Sensing System is More than its Electronics: Towards addressing environmental challenges on outdoor data collection platforms

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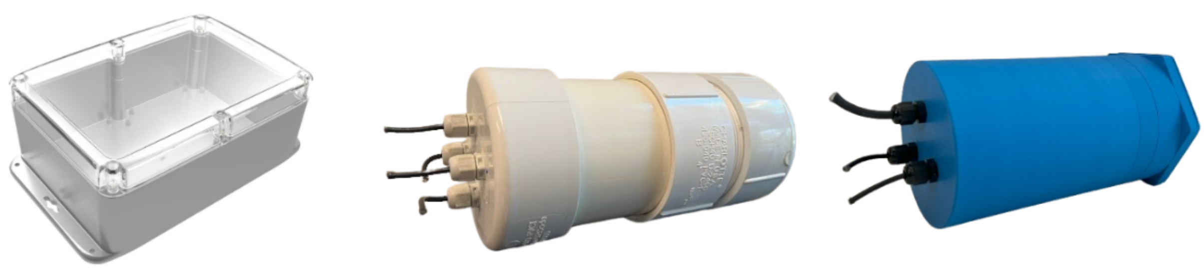


Figure 1: Three different environmental enclosure options for sensing platforms. From left to right: an industry standard, commercial-off-the-shelf IP68 box, our custom PVC enclosure, and our custom 3D printed enclosure.

Abstract

In-situ environmental sensing has driven significant advancements in energy-efficient, accurate, and modular sensing platforms. However, less attention has been given to improving their resilience to harsh outdoor conditions. Electrical components in these platforms are sensitive to heat, moisture, and physical stress, making enclosure design a critical but often overlooked factor in long-term deployment. In this paper, we present a scientific approach to developing a robust, cost-effective enclosure for an open-source outdoor sensing platform. We explore iterative design processes using widely available materials—PLA and PVC—and evaluate their durability, waterproofing, and ease of assembly in both lab and field conditions. By open-sourcing our designs, we aim to highlight the need for greater focus on enclosure robustness as a key challenge in environmental sensing research.

ENSsys '25, Irvine, CA, USA

ACM ISBN 979-8-4007-1606-5/2025/05
https://doi.org/10.1145/3722572.3727933

CCS Concepts

• **Computer systems organization** → **Embedded and cyber-physical systems**; **Sensor networks**.

Keywords

Environmental sensing, In-situ monitoring, Outdoor enclosures, Open-source hardware

ACM Reference Format:
Stephen Taylor, Fayza Elshafie, David Fisher, Michael Gonzalez, Benny La, Yaman Sangar, Elliot Snyder, and Pat Pannuto. 2025. A Sensing System is More than its Electronics: Towards addressing environmental challenges on outdoor data collection platforms. In *The 13th International Workshop on Energy Harvesting and Energy-Neutral Sensing Systems (ENSsys '25), May 6–9, 2025, Irvine, CA, USA.* ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/3722572.3727933

1 Introduction

Environmental sensing has long been a crucial area of scientific research, with applications ranging from precision agriculture to wildfire prevention and ocean monitoring [5]. Recent advances have led to the development of more energy-efficient, accurate, and cost-effective sensors [3]. As a result, there has been growing interest in designing integrated systems that power and collect data from environmental sensors [2, 4, 8]. These platforms vary in complexity, from simple configurations like a soil moisture sensor connected to an Arduino to more sophisticated, multi-sensor networks.

Despite these advances, low-power sophisticated sensing technology has been slow to translate into practical commercial systems. We suggest that one understudied limitation impeding adoption at-scale is the robustness of these platforms in real-world conditions. Outdoor sensing platforms are exposed to extreme temperatures, moisture, UV radiation, and physical stress, all of which can compromise long-term operation. Although off-the-shelf enclosures exist, they are often cost prohibitive and are not designed for environmental data logging (and thus demand boutique and ad-hoc customizations). For sustainable, long-term deployments, enclosure durability is just as critical as sensor accuracy and energy efficiency.

In this work, we present a design process to develop robust enclosures for sensing systems. We aim to provide an example for researchers and domain scientists (who may not have deep expertise in mechanical engineering or design) to help get their novel measurement technologies out of the lab and into real-world settings. We demonstrate the design process by walking through our experience prototyping enclosures for the open-hardware Environmentally NeTworked Sensing (ENTS) platform nodes [7].

A key consideration is accessibility, which encompasses both the cost of raw materials and the complexity and robustness of the manufacturing process. We consider two fundamental approaches: additive manufacturing (i.e. 3D printing) and machining / assembly of standard construction materials. One particular usability challenge that we explore in depth is the robust installation of largely flat, rectangular PCBs and electronic components into the round cylinders which typify stock construction materials that are most-readily waterproofed (such as the PVC pipe we use).

We evaluate our custom enclosures for their performance in waterproofing, UV resistance, and ease of use. Both designs are tested in controlled lab conditions and then deployed in a saltwater marsh. The prototypes kept stable moisture levels in both the controlled lab experiments as well as a full tide cycle in the marsh. We publish these designs as an open-source resource [6].

2 A Sensing System is More than its Electronics

We begin with a brief background of the Environmentally NeTworked Sensing (ENTS) platform, which motivates our work.

ENTS is an open-source platform designed for measuring sensitive analog signals in environmental contexts, both in laboratory and field settings [7]. The first, driving application for the ENTS platform was the capability to measure performance of soil microbial fuel cells (SMFCs) [8]. An SMFC is a bioelectrochemical cell that harvests small amounts of power (order µW) from natural metabolic processes of soil bacteria. The output of an SMFC is highly dependent on a variety of environmental conditions.

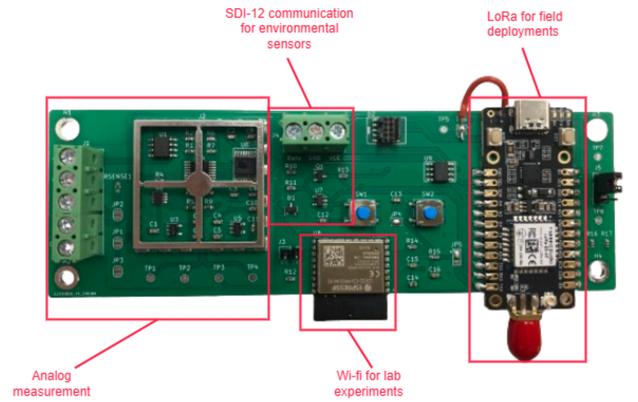


Figure 2: An ENTS node. A typical deployment might involve dozens of ENTS nodes collecting SMFC data in laboratory settings over WiFi before being transitioned to outdoor deployments, where data transmission occurs via LoRa.

While there are lab-based studies with SMFCs, there is a paucity of literature on their real-world performance. The ENTS platform hypothesizes that a major hindrance to repeatable SMFC research in real-world settings is the lack of accurate, cheap, scalable, and reliable infrastructure capable of in-situ measures of SMFC performance [11]. Thus the ENTS board, seen in Figure 2, was developed to provide affordable and easily field-deployable low-power measurement. The ENTS electronics meet their goals: the boards are $20 - 100\times$ less expensive than benchtop lab equipment with equivalent capability, are far more portable, are able to transition across local WLAN and long-range LPWAN connectivity, and are sufficiently low-power to achieve steady-state, energy neutral operation from e.g. modest solar panels. Yet, in practice, ENTS is not an 'affordable and easily field deployable' instrument because these highly capable electronics lack affordable and *easily adaptable* enclosures that would allow them to leave the lab and deliver on their vision.

This paper focuses on designing robust, durable enclosures for individual ENTS nodes deployed in outdoor environments. Our approach ensures scalability to accommodate other environmental data collection PCBs while addressing engineering challenges such as cost-effectiveness, ease of deployment, and reliable long-term operation in the field.

3 Enclosure Requirements for Sensitive Sensors

To turn the electronics of a measurement platform in a field-ready, scalable, deployable *sensor*, we must develop an enclosure that is cost-effective, modular, and reproducible. Modularity is essential to accommodate various wired and wireless connections. Most importantly, it allows for *deployment-time* (in contrast to *design-time*) selection of external sensors, power supplies, and communication modules. The cost should be comparable to or better than commercial off-the-shelf (COTS) solutions, approximately $50 USD [9]. Additionally, the design should be straightforward enough for domain scientists to reproduce or adapt with minimal effort.

3.1 Commercial-off-the-shelf Baseline

Collecting environmental data is often resource-intensive and time-consuming, making it crucial for the data collection platform to withstand environmental pressures and operate reliably. For this reason, we target designs that could meet environmental protection standard IP68, which equates to 1) no ingress of dust 2) waterproofing up to a depth of approximately 3 meters.

The ML-70F NEMA enclosure from Polycase comes with IP68 rating [9]. The case costs approximately $50 a unit. However, it comes with no internal mechanism to secure logging equipment, and it must be modified (typically using a drill press) to accommodate cabling. Indeed, for sensing applications nearly all (cost-effective) COTS options require some amount of destructive modification, which may compromises their environmental rating.

3.2 Considerations for a Custom Design

Balancing reproducibility, cost, robustness, and suitability for PCBs and supporting electronics presents difficult design trade-offs. Cheaper and more easily machined materials are usually less inherently weather resistant. As a consequence, maximizing ease of reproducibility might easily compromise overall durability. Our finalized designs balance these trade-offs for the use case of ENTS with SMFCs, while Section 7 discusses how others can follow the methods which follow to realize suitable enclosures for their differing needs.

4 Can 3D printed designs be waterproof?

We choose 3D printing and customized PVC to build our enclosures due to their widespread *availability*, durability, and affordability. These materials offer unique advantages. Although PVC is a well-established material for waterproofing, it is typically limited to cylindrical form factors and requires specialized equipment for modifications. In contrast, 3D printing offers a higher degree of flexibility in enclosure profiles. However, common 3D printing materials like PLA are less effective at waterproofing than extruded materials like PVC, which invites our first design exploration into waterproofing for PLA-based, 3D printed enclosures, requiring careful tuning of print settings and possibly the use of sealants to ensure water resistance. Models are also constrained by commonly available gasket sizes. Having to modify or custom-order gaskets can increase assembly time and expense.

4.1 3D Models Considered

We explore two 3D printed enclosure designs: a clamping box and hex screw-sealed tube (similar to PVC enclosures). The clamping box demonstrated high usability once assembled, as it could be opened or closed without additional tooling. However, it was difficult to manufacture and performed poorly in waterproofing tests. This design required more printed parts (eight in total) than its alternative and relied on additional metal fasteners. The poor waterproofing performance was likely due to uneven pressure distribution around the O-ring gasket, which compromised the seal.

The hex screw-sealed tube was significantly easier to reproduce, requiring only two printed components and an O-ring gasket. Its circular screw mechanism, combined with the additional barrier of threads, created a more effective seal. The main drawback of this design is that cable glands could only be placed at either end of the tube, as they require a flat surface for mounting.

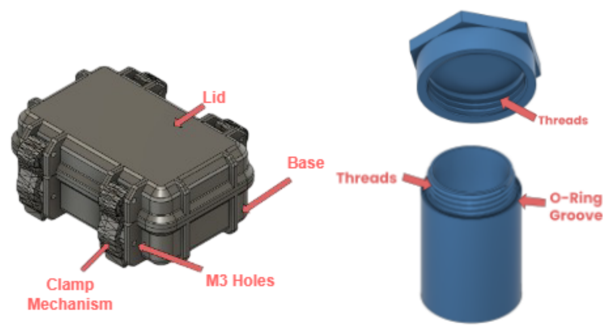


Figure 3: Two 3D printed enclosure designs: clamping box, hex screw-sealed tube

Table 1: Waterproofing test results for different 3D printed enclosure designs.

Design	Results
3D - Hex Screw-sealed	Still at ambient air moisture levels after 6 hours, small amount of water on threads after 12 hours.
3D - Clamp (V1)	Small amount of water after 10 min, after 12 hours around 100mL of water gathered in the bottom. Reached a humidity of 79% after 25 min.
3D - Clamp (V2)	Dry after 10 min but significant amount of water after 3 hr and reached humidity of 91%.
3D - Clamp (V3)	Reached a humidity of 70% after 10 min and 78% after 30 min.

We tested the waterproofing of each design through indoor immersion tests. As shown in Table 1, multiple iterations of the clamping box design consistently underperformed compared to the hex screw design in laboratory tests, taking on significantly more water. Consequently, we decided to proceed with the hex screw design.

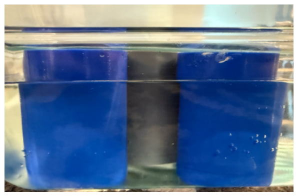
4.2 Iterative material waterproof testing

We explore four 3D printing parameters: perimeter count, infill density, filament selection, and the presence of an aquatic sealant. The perimeter count refers to the number of layers composing the walls of the print, while infill determines the internal structure's density. Both ASA and PLA, were tested, though PLA was preferred for it's wide-spread availability and compatibility with a large range of 3D printers.

To evaluate these factors, we conducted a leak test comparing perimeter count, sealant type, and filament selection. All test samples were printed with 60% infill. PLA samples were printed with 4, 5, and 6 perimeters, with an additional PLA sample printed with 5 perimeters and coated with aquarium sealant [1]. A final sample was printed in ASA with 5 perimeters. Each sample was filled to 75% capacity with water and placed on paper towels (see Figure 4a). Over three weeks, we visually inspected the samples and monitored their weight, finding no water permeation in any case.

A second leak test used the same samples, with an additional PLA sample featuring 5 perimeters and a ceramic coating. These samples were submerged in a water-filled basin up to 75% of their height and secured with weights (see Figure 13). Again, after three

(a) 3D printed testing cups filled with water



(b) 3D printed testing cups submerged in water

Figure 4: Material immersion testing

weeks of observation and periodic weighing, no water permeated any sample.

5 Final Design Overviews

We offer two design solutions: 3D printing and PVC assembly to cater to researchers with different resource constraints. We compare the strengths and weaknesses of each design to the ML-70F NEMA Enclosure in Table 2 [9].

Both enclosure designs can be easily scaled to accommodate different rectangular PCBs by adjusting the overall dimensions and repositioning the screw mounts on the node insert component to align with the chosen PCB. Both prototypes are designed to support 90° cable connections, which are essential for efficient cable management and compatibility with other PCB-based sensing platforms. By utilizing right-angle connectors and directing all cables toward the built-in cable glands, the enclosures ensure a streamlined and adaptable design that can be readily modified for various sensor configurations.

5.1 Deployment Time Convenience

A key limitation of existing COTS is the lack of securing mechanisms once the monitoring PCB is inserted into enclosure [9]. Additionally, inserting rectangular PCBs into cylindrical enclosures while routing cables can be unexpectedly challenging, leading to wasted deployment time.

To address this, both designs incorporate a custom node insert, which facilitates easier access to the monitoring equipment in the field. This insert utilizes a twist-lock mechanism (see Figure 5), consisting of a slot-and-notch setup. This allows the upper section to securely lock into the lower section using a friction fit. The node is attached to the insert with four standard screws and nuts. Additionally, a battery slot can be affixed to the backside of the node using the same screws. The notch is glued into the PVC design, and pre-integrated in the 3D printed design. To optimize space, researchers should use right-angle adapters to direct large cables toward the cable glands rather than against the cylindrical enclosure walls.

Since both the PLA and PVC designs can be sealed by hand, the addition of the node insert ensures that researchers only need two tools to insert and *secure* their PCB: a screwdriver to attach the PCB to the node insert and a wrench to tighten the cable glands.

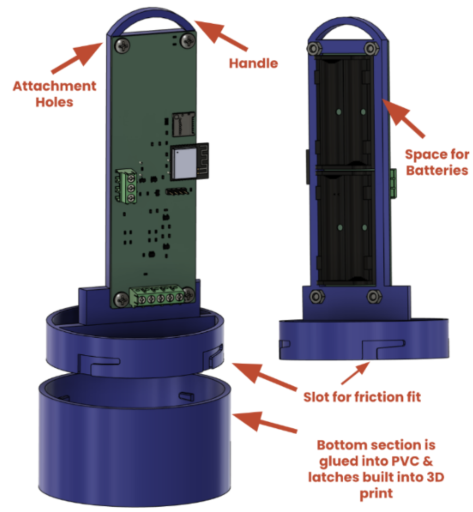


Figure 5: Node insert

5.2 3D Printed Enclosure

The 3D printed enclosure design is made using standard PLA material and measures 22.5 cm long with a diameter of 12.4 cm when sized for the ENTS node. The 3D print includes an O-ring groove at the top for a waterproof seal. This enclosure typically takes about 20 hours to print combined with manual cable gland and O-ring installation.

The biggest benefit of the PLA construction is the ease of assembly. While printing the two components takes a significant amount of time, it is entirely a hands-off process, reducing actual research hours committed to enclosure manufacturing.

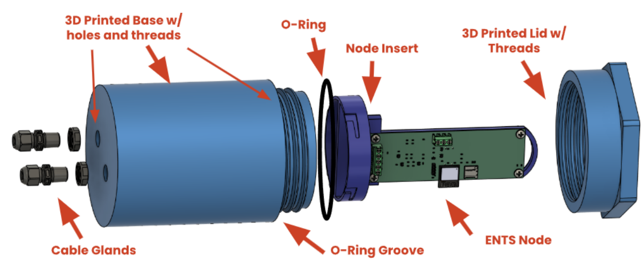


Figure 6: Exploded view of 3D printed enclosure

5.3 PVC Enclosure

The PVC enclosure design uses four off-the-shelf standard PVC Schedule 40 components. This includes a female socket end cap, 20.32 cm section of cut PVC tube, male threaded adapter and a

Table 2: Properties of design solutions compared to an industry standard IP68 enclosure

	Industry IP68 enclosure	3D Printing	PVC
Cost	$49	$32	$37
Working Time	15 minutes	15 minutes	30 minutes
Idle Time	0 hours	20 hours	2.5 hours
Tool Requirements	Power Drill, Phillips Screwdriver	3D Printer, PLA, Sealant	PVC Cement, Power Drill, Saw
Concerns	Cost, Size	Waterproofing, Reproducibility	Size, Scalability

threaded end cap. PVC cement is used to seal and secure the flat end cap and adapter, while the threaded end cap is secured using Teflon tape. Primer is also necessary to use PVC cement to ensure a strong bond. Cable glands are installed into the flat end cap to allow for easy access and cable slack to be stored internally. A 3D printed insert is glued into the bottom of the enclosure to allow for the data collection platform to be easily inserted, removed and secured during deployment. This enclosure generally takes 30 minutes to manufacture, which includes using a bandsaw/saw to cut the PVC tube into appropriate length, drilling holes for cable glands, applying PVC primer/cement and waiting for it to dry, printing and installing the insert, and finally applying Teflon tape to the threads.

An intrinsic advantage of PVC is its proven waterproofing and durability in the face of challenging environmental conditions, at the cost of more active assembly time per enclosure that requires heavier tooling.

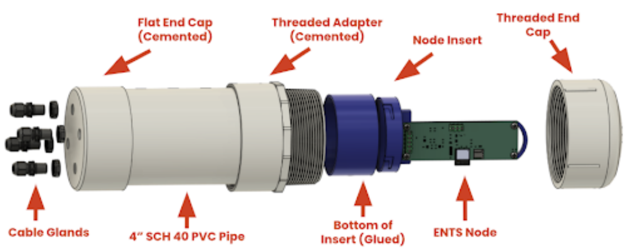


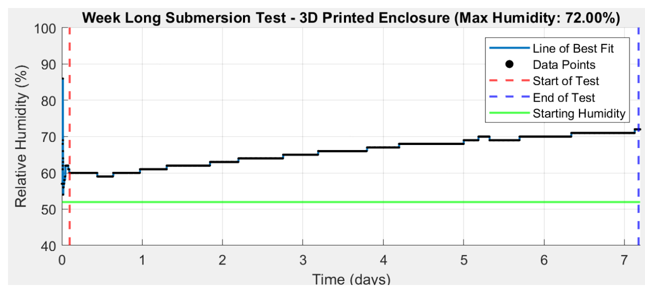
Figure 7: Exploded view of PVC enclosure

6 Evaluations and Field Tests

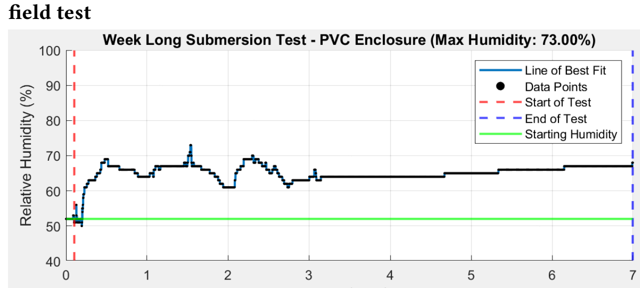
Figure 8: Prototypes deployed in marsh

Both the PVC enclosure and a base 3D printed enclosure (no additional sealant) were tested for 24 hours, and than 7 days at the Kendall-Frost Reserve Marsh. Ambient humidity was tracked using a SwitchBot humidity sensor [10], and the enclosures were visually inspected for leakage.

The Marsh Reserve was chosen for its history of scientific deployments and the particularly challenging environment that coastal wetlands provide. Coastal wetlands are open to the sea, and therefore are subject to tidal changes. They also typically have a higher salt content than freshwater systems. Both enclosures had a normal progressive build-up of humidity and no signs of leakage. In a real-world deployment, the enclosures would be deployed with silica moisture wicking packets to prevent this issue.



(a) Humidity tracking over the 3D printed enclosure after a 7 day field test



(b) Humidity tracking over the PVC enclosure over a 7 day field test

Figure 9: Immersion test results in a marsh - 7 days

The observed variance in humidity levels within the PVC enclosure may be attributed to several factors. First, the PVC enclosure may have retained more moisture during assembly, resulting in higher initial humidity. Additionally, its lower air permeability could have prolonged the time required for internal conditions to stabilize. Differences in the thermal properties of PVC compared to the 3D-printed enclosure could also have influenced condensation dynamics, contributing to the fluctuations before reaching equilibrium.

7 Designing Environmental Enclosures for other Environmental Monitoring Platforms

The critical design components for most environmental sensing platform enclosures are as follows:

Low-cost: Although commercial, industry-standard waterproof cases are effective, they are expensive when scaling up deployments. A ML-70F NEMA enclosure costs $48 USD at an order of 50 units [9]. That is, a deployment of 50 would cost $2,100 USD.

Accessible/Easily Reproducible by Research Groups: The enclosure must be easy to manufacture without specialized fabrication tools. This requirement eliminates complex machining processes and favors widely available methods such as 3D printing and PVC construction.

Waterproof (IP68 dustproof and waterproof rating): Since sensing nodes are deployed in environments such as wetlands, agricultural fields, and coastal areas, the enclosure must protect internal electronics from exposure to moisture, dust, and physical stress.

Allows Wireless Communication: Given the increased availability of wireless infrastructure, the enclosure must not interfere with wireless communication capabilities. Since many environmental sensing platforms enable wireless data collection, enclosure designs must allow for adequate signal transmission.

Cross-compatible with multiple sensors: Some sensing platforms support multiple external sensors connected via wired interfaces. To maintain sensor compatibility, the enclosure must include waterproof cable glands that accommodate various connector types while preserving the enclosure's environmental seal.

With these design principles in mind, if a research group wanted to base their own enclosure off our design we recommend:

(1) Assess manufacturing capabilities – Determine whether PLA or PVC is more suitable for fabrication based on factors such as durability, availability, and ease of processing.
(2) Modify the design for compatibility – The enclosure design is available as an open-source project [6], but must be adapted to meet specific environmental sensing requirements. Consider key parameters such as the number and diameter of required cable glands, as well as adjustments to the node holder and overall enclosure dimensions.
(3) Evaluate environmental resilience – Conduct standardized water and dust ingress testing in real-world settings for at least 1 week to ensure the modified enclosure meets durability requirements.
(4) Field deployment and validation – Deploy the modified enclosure in its intended environment and assess long-term performance under relevant field conditions.

8 Future Work

Outdoor deployments can be on time-scales of days, months, or years. Future evaluations of the enclosures need to reflect the longer time horizons of experimental environmental sensing. The authors identify designing and implementing environmental enclosure tests on the scale of weeks to months as the most critical next step in making environmental sensing platforms more robust. Along with more thorough comparisons of how water-proofing sealants impact the performance of 3D printed enclosures in real-world settings.

A key area for future work is cost reduction. While current iterations are competitively priced against commercial alternatives, large-scale deployments may still be cost-prohibitive for some research groups. Further, reducing production costs remains a critical next step in design and research.

9 Conclusions

This work presents two novel enclosure designs for protecting outdoor sensing platforms from environmental exposure. These designs are adaptable to other PCB-based data collection systems and offer weatherproofing and cost performance comparable to off-the-shelf solutions. Additionally, they are specifically tailored for sensing platforms, facilitating smoother outdoor deployments. This work addresses the environmental sensing community's lack of emphasis on ensuring platform functionality in challenging conditions.

Acknowledgments

The authors thank Jerry Tustaniwskij for his invaluable guidance. This work was supported by USDA National Institute of Food and Agriculture [grant number 2023-67021-40628].

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Received 07 March 2025; revised 03 March 2025; accepted 21 March 2025