EARLY DETECTION OF SIMULATED HERBIVORE ATTACKS IN SORGHUM FIELDS THROUGH THE DEPLOYMENT OF VERY-LOW-POWER GAS SENSOR NETWORK

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ABSTRACT

This *paper reports a novel method of detecting simulated herbivore attacks (mechanical damages) on a plant by sensing emitted gas, which was enabled by developing and deploying a very-low-power gas sensor network in an actual sorghum farm. When a group of nearby sorghum leaves were cut (simulating herbivore attacks), the damaged plants started emitting a unique volatile organic compound (VOC) marker, hexanal, ultimately increasing its concentration up to 60 ppm in 62 minutes within an area of less than 1.0 m diameter from the cut point. The emitted hexanal was detected by a near-zero-power (<100 pW) gas sensor that utilized a nanogap structure to provide normally-dormant (thus minimal power consumption) but continuously sensing capability for hexanal. When the near-zero-power gas sensor detected the target gas in concentrations above a pre-set threshold (29 ppm), it connected an internal switch to flow power and wake up the rest of the circuitry including a micro-controller, a display module and a wireless module, ultimately sending an alert through the wireless network to a central station. This result demonstrated the first, within our knowledge, gas sensor network and actual field demonstration of early (stimulated) herbivore attacks.*

KEYWORDS

low power, gas-sensor, prototype, field-deployment, herbivore- attack-simulation

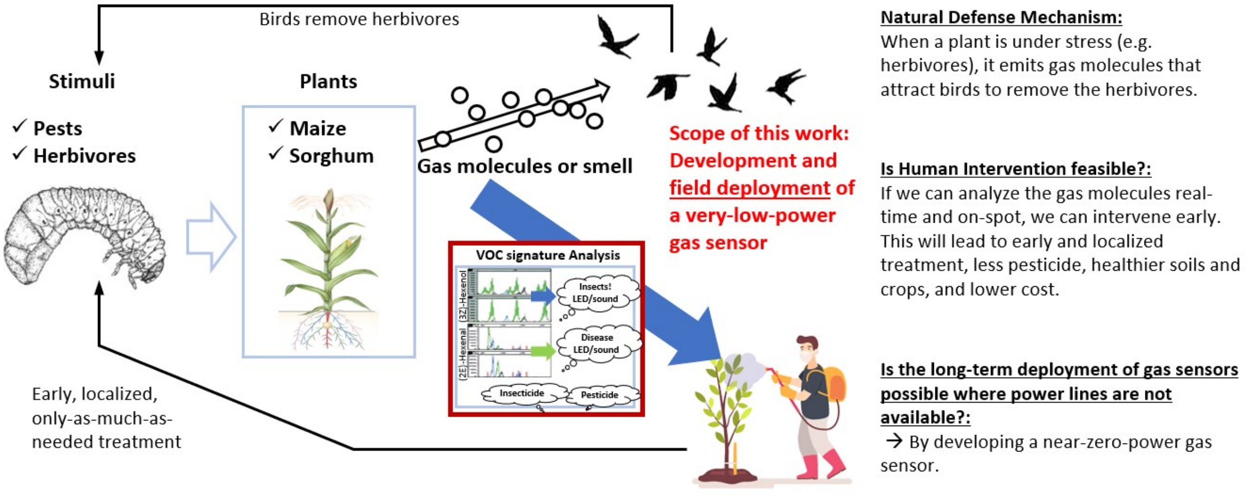
INTRODUCTION

Herbivores cause significant degrees of physical damages to the stems and leaves of crops, resulting in a yield loss of about 20% to 40% every year globally [1]. And such damages can be even higher for some particular crops [2,3]. Thus, early detection is a key to reduce such a loss as well as associated issues including the overuse of harmful agrochemicals and resultant contamination of crops, soils and water [4,5].

The gold standard pest detection method is currently a manual scouting [6,7], often involving trapping pests or visually checking, that is time-consuming, expensive, and difficult to cover a large area. Emerging technologies are satellite- or drone-based imaging [8-10] that, however, held a resolution issue due to line-of-sight limitation; acoustic sound detection [11,12] that, however, cannot detect larvae or insects that do not produce significant levels of sound; and on-spot gas sample collection through a micro gas chromatography system [13,14] that, however, is not practically long-term field-deployable yet.

To address the limitations of existing methods, we tried to establish a closed-loop communication between plants and humans by developing a very-low-power, thus field-deployable (long-term sustaining), on-spot and real-time gas sensors and their wireless network, as described in Fig. 1. Recent literature reported that when herbivores attacked plants, the plants produced particular gas molecules to attract birds that can remove the herbivores as a natural defense mechanism. We hypothesized that if one could also sense the emitted gas molecules on-spot and early, one could utilize the detection to trigger earlier human interventions resulting in the enhancement of crop yields and energy efficiency in farming.

This paper reports the first time, within our knowledge, the



Natural Defense Mechanism:
When a plant is under stress (e.g. herbivores), it emits gas molecules that attract birds to remove the herbivores.

Is Human Intervention feasible?:
If we can analyze the gas molecules real-time and on-spot, we can intervene early. This will lead to early and localized treatment, less pesticide, healthier soils and crops, and lower cost.

Is the long-term deployment of gas sensors possible where power lines are not available?:
→ By developing a near-zero-power gas sensor.

Figure 1. *The concept of this work: the detection capability of gas markers, which are released from plants when the plants are damaged, can be enabled by developing and deploying a very-low-power gas sensor network. Based on the measurement results, this work showed a promise of utilizing the developed gas sensor system for early pest treatment through human intervention.*

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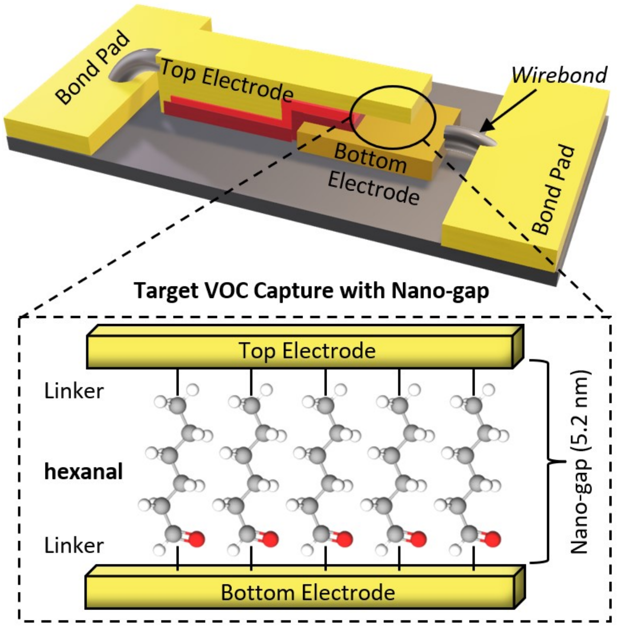


Figure 2. *(Top) Fabricated sensor chip, wire-bonded on both sides for integration to a circuit (Bottom) Capture of the target VOC within the nano-gap leading to current flow or sensor wake-up output.*

successful development and deployment of a very-low-power gas sensor network in an actual sorghum farm. This paper reports the operation principle, testing methodology and preliminary measurement results both in laboratory and in an actual sorghum field.

STRUCTURES AND OPERATION PRINCIPLE

The manufactured prototype (G1) was comprised of a nano-gap gas sensor, interface electronics (a transimpedance amplifier and a comparator), a microcontroller unit (MCU), a LED screen and a LoRa wireless module, as shown in Fig.3. The nano-gap sensor generated an electrical current upon capture of a target VOC. The generated current was then converted into a voltage signal by the transimpedance amplifier, and then the voltage signal was compared to a reference voltage by the comparator. If the voltage signal exceeded the reference value, the comparator turned on the MCU that subsequently activated both the LED screen display and the wireless alerting modules, allowing them to display or transmit data respectively.

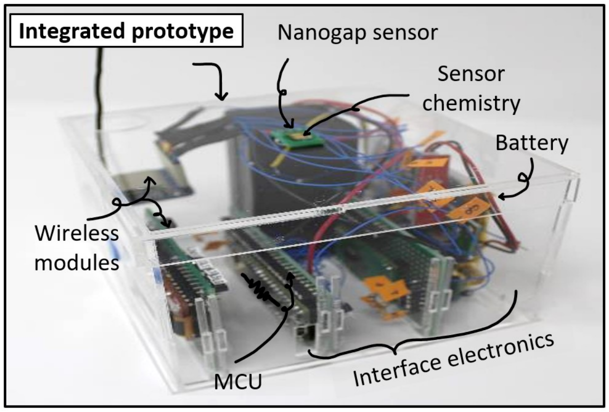
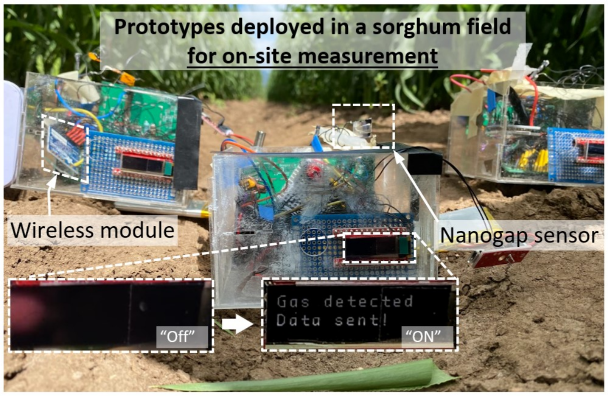


Figure 3. *Integrated prototype (G1) (10 × 10 × 7 cm^3) that was deployed in sorghum field.*



Prototypes	Temp. (ºC)	RH (%)	Wind speed (mph)	Distance from plant (m)	Height (cm)
× 4	*25*	*25*	*11*	*<1*	*10*

Figure 4. *Deployed prototypes in a sorghum farm for field testing. Each prototype included a nanogap sensor, a wireless module, a display and electronics. Four different prototypes were deployed with 3 being control and 1 equipped with a working sensor.*

The manufactured prototype normally remained in a power-conserving mode until being awoken up by the target gas detection when it actively consumed power for wireless alerting. Such a wake up was initiated by a nanogap-based wake-up gas sensor, of which the operation principle was reported previously [15]. Briefly, the nanogap-based sensor operated by utilizing a ~5.2 nm gap coated with a molecular probe or linker molecule to capture a target (hexanal in this case) resulting in a switch-like action in electrical current, as described in Fig. 2. Note that for the target gas for plant damage detection, sampling and analysis of gases from the ambient air near the sorghum plants before and after the damages were performed. The standard GC-MS measurement results, in comparison to the NIST database [16], clearly confirmed that hexanal was actively emitted from the damaged sorghum plants.

EXPERIMENTAL PROCEDURE

In-Lab Testing

In-lab tests were performed on the fabricated nano-gap sensor to determine (1) the lowest concentration of hexanal it can detect (estimated limit of detection), (2) the repeatability of the sensor response and (3) the possibility of interference from other gases during detection (selectivity), all prior to field deployment. For the limit of detection test the target concentration was reduced down to 50.00 ppm starting from 1418.44 ppm while the sensor response ratio being recorded. For the repeatability testing, the sensor was exposed to target gas in ~15,000 ppm for 45 minutes and alternatively to ambient air for 10 to 60 minutes in consecutive cycles, allowing it to be turned "on" the "off" until no further response was observed (the sensor remained off). For the selectivity tests the sensor was exposed to various types of gases including IPA, pentane, acetone and indole, all of which were known gases existing in sorghum fields.

For the In-lab tests, a flow setup was utilized which mainly consisted of multiple mass flow controllers that determined flow rates of either the target gas or a carrier gas (N_2) and thus manipulated the final concentrations. During the exposure, the output resistance of the sensor was monitored at a biasing voltage of 0.7 V over time for a period of 45 minutes. The utilized target gas, hexanal, for in-lab testing was commercially available.

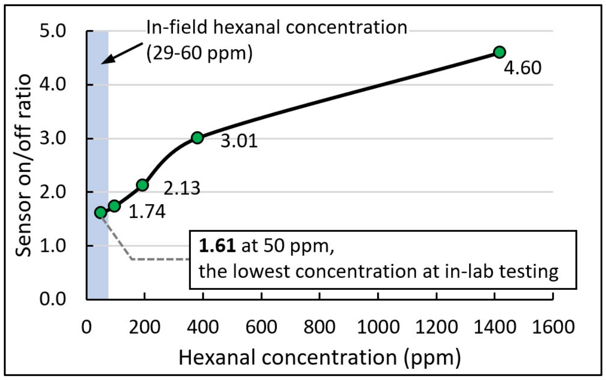


Figure 5. *Sensor on/off ratio with increasing concentration of hexanal. The lowest tested and detected concentration was 50 ppm that was within the on-field hexanal concentrations.*

Field Testing

The field testing was performed to demonstrate the detection capability of the integrated prototype in response to hexanal released by damaged plants in an actual farm, as shown in Fig. 4. Tests were performed in a sorghum field in Lincoln, Nebraska with four different 4 prototypes deployed over 5 hours. Sorghum plant leaves were instantly cut up within 30 cm away from the prototypes. Field temperature was recorded to be 25 ºC and relative humidity was 25%. From the prototype, a wireless gateway station was placed at a 5-m away position, although it could be wireless tethered up to 70 m. When triggered, the gateway station sent an alert message to a database that could be accessed from any computers connected to internet.

RESULTS

In-lab Testing: Limit of Detection

The lowest concentration of commercial hexanal detected with a microfabricated nano-gap sensor, in the lab, was measured as 50.00 ppm with the output current response ratio of 1.61, as shown in Fig.5. Indeed 50 ppm was the lowest limit that our testing set-up could provide. The sensor woke up to a range of hexanal concentrations above 50.00 ppm up to 1,418.44 ppm, as shown in Fig. 5. When the sensor was awoken, the response ratios were 1.61 times for 50.00 ppm, 1.74 for 97.04 ppm, 2.13 for 192.8 ppm, 3.01 for 380.95 ppm and finally 4.6 times for 1418.44 ppm of commercial hexanal. The sensor overall demonstrated an increasing trend of the response ratios with increasing concentrations (in ppm) of hexanal.

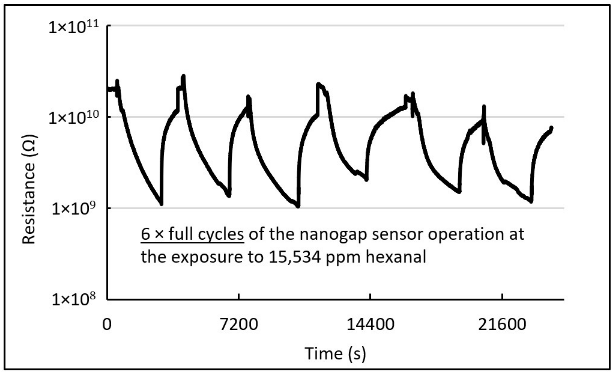


Figure 6. *Repeatable response to hexanal exposure was observed from the nano-gap sensor with 6 full cycles of sensor on and off obtained.*

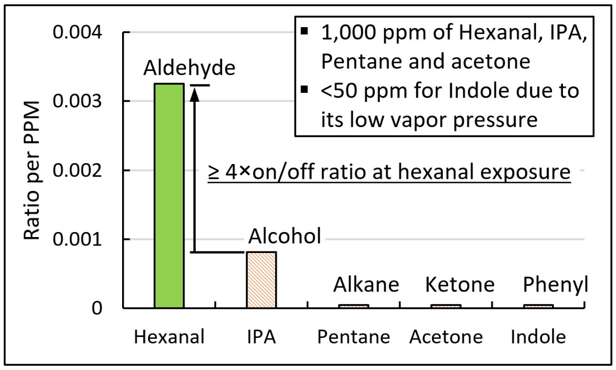


Figure 7. *Selectivity of the hexanal response was demonstrated against 4 other gas types belonging to alcohol, alkane, ketone and phenyl groups.*

In-Lab Testing: Repeatability

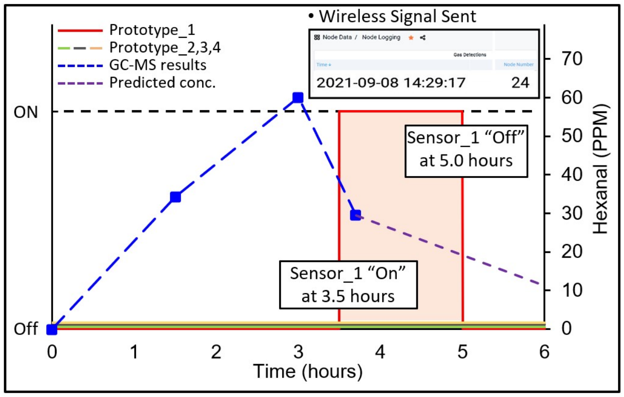
Measurement results from the in-lab testing showed that the sensor was repeatable to 6 times when exposed to a hexanal concentration of 15,534 pm (saturation concentration), as shown in Fig. 6. Note that the saturation concentration was utilized assuming the worst case. It was believed that the repeatability would increase further at the exposure to a lower concentration of a target gas. After the 6th cycle, the sensor did not respond to any further hexanal exposure. The sensor demonstrated the ability to recover naturally, once the test chamber was purged of hexanal indicative of the reversible nature of the target capture mechanism. The results indicated that the developed sensor prototype deployed in the field would be able to respond at least 6 times to damaged plants.

In-Lab Testing: Determining Sensor Selectivity

The sensor response was demonstrated to be selective by at least 4.06 times per unit ppm when compared to a list of pre-selected gases. The list of gases the sensor was exposed included alcohol, ketone, alkane, phenyls and hexanal, all of which have the possibility of being present in a farm (Fig. 7). Sensor response ratio per unit concentration (ratio per unit ppm) was calculated by dividing the on/off ratio with the concentration of gas exposure. The response to hexanal was 0.0035 ratio/ppm compared to the 2nd highest response to alcohol (IPA) at 0.0008 ratio/ppm. Sensor response ratios for other different groups were negligible with gases from the alkane (pentane), ketone (acetone) and phenyl (indole) functional groups generating no response. Concentrations of all the target gases were 1000 ppm except for indole which had a considerably low vapor pressure of 0.0122 mmHg. This response pattern indicated that the nano-gap sensor could be deployed in-field without any significant interference from false signals from other gases present.

Field Testing: Simulating Pest Damage to Plants

The sensor integrated prototype detected hexanal released from mechanically damaged or leaves cut with clippers 3.5 hours after deployment (Fig. 8). Until the sensor response was obtained, sorghum leaves were continuously cut with leaves belonging to around 80 plants damaged at the moment of detection. Upon detection the prototype displayed a gas detected message on the LED and triggered the LoRa module to send a wireless signal via the gateway, which was observed from 1415 km away. After 1.5 hours the prototype was removed from the field at which point the LED message disappeared indicating sensor recovery in the absence of hexanal. During the testing only the prototype that had



Detection Time (hours)	Recovery Time (hours)	Concentration (ppm)	Plants Damage	Wireless Signal Distance (km)
3.5	*1.5*	*29~60*	*× 80*	*1415*

Figure 8. *G1 Prototype field testing results: (Top) Time line of sensor response with prototype triggered at 3.5 (Bottom) Summary of the results obtained from field testing.*

a working sensor triggered while the three other controls that were deployed remained off. This test demonstrated that the sensor was indeed capable of detecting actual hexanal emitted from plants as was theorized from our in-lab commercial hexanal testing.

Field collection of air samples and post-analysis in the standard GC-MS proved the presence of hexanal which was found to be continuously increasing from 29 ppm and to 60 ppm. The accumulation of the hexanal around the prototype during the cutting caused the concentration of hexanal to build up allowing the nano-gap sensor to wake-up the rest of the circuit once a threshold concentration (29 ppm $\leq C_{\text{threshold}} <$ 60 ppm) was reached.

CONCLUSION

This paper reported a novel method of detecting simulated herbivore attacks on plant through sensing biomarker gases including demonstration of a low power gas sensor network in an actual sorghum farm. The gas sensor network was developed and deployed to implement the method. Damages done to the sorghum plants triggered the plants to release hexanal with the concentration reaching 60 ppm in 62 minutes. The gas sensor was able to detect this emitted hexanal within an area of less than 1 m diameter from the cut point once the concentration crossed the threshold of 29 ppm and consumed less than 100 pW of an operation power. Detecting the actual hexanal by the sensor, waking up the circuit and alerting through a wireless network to a central station were successfully performed in the field.

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