An E-Nose Using Metal Oxide Semiconductor Sensors Array to Recognize the Odors of Fall Armyworm Pest for Its Early Detection in the Farm

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Abstract. Considerably decrease hunger and food insecurity in the world is one of sustainable development goals of the horizon 2030. Agriculture, which is one of most countries main sector and the only factor in the diet of the world's population, is challenged by pest attack. Technology tools offer real opportunities to better protect farms from many damages caused to crops. In this work, an e-nose system using Metal Oxide Semiconductor sensors for early detection of fall armyworm (FAW) pest is proposed. This is based on a special architecture designed to have an affordable and efficient e-nose. Detailed investigations were carried out to identify sensors with potential sensitivity to FAW odors. Then, the sensors were used in a sensor matrix as electronic nose. An electronic acquisition card was achieved to interface the electrical output of the array of seven metal oxide semiconductor gas sensors exposed to an odor diffusion system with the computer. A LabVIEW program was developed for data analysis. The system was successfully exploited to study the response of the sensor array to volatile organic compounds (VOC) released by FAW and for optimizing the data acquisition, as well as signal pre-processing, storage, and wave forms presentation. Experiments were carried out using real FAW. The results and analysis presented in this paper show evidence of discrimination of Fall armyworm's VOC signature, thus the first detection of FAW presence by e-nose system.

Keywords: E-nose · Odors recognition · Pest monitoring · Fall armyworm detection

1 Introduction

Sub-Saharan Africa has favorable climate and soils for agriculture. Thanks to this agricultural potential, most of the countries of this region are massively engaged in both

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export (cocoa, coffee, cotton) and local agricultural activity (many seeds such as cowpeas, maize, rice, pineapples, palm nuts, yam). Therefore, agriculture is the main vector of development of these countries. Nevertheless, this vital development sector faces various challenges such as global warming, invasion of insect pests. In the specific case of invasion of insect pests, one of the most devastating is fall armyworm (FAW) that can cause more than 70% of yield losses. So, concrete solutions are required to deal with the problem of invasion of insect pests and secure the yield of agricultural activity. The intuitive solution is the use of chemicals to kill the insects. But this approach, if it does not have drawbacks in environmental terms, still requires to be well managed for efficiency and economic viability. Moreover, in many sub-Saharan African countries, the detection of FAW by smallholder farmers is synonymous with the onset of an invasion of their maize fields. At this stage, the spread of invasion is difficult to counter, even with the support of government organizations in terms of phytosanitary treatment. Therefore, early detection of the presence of FAW before its spread may be a crucial information to take appropriate actions at the right time.

Intelligent data collection and processing systems are widespread and have several applications fields such as industry, building, road control, safety, health, etc. These smart systems, often based on smart sensors, could bring a significant advancement in specific agriculture [1]. This work focused on data collection system especially an e-nose coupled with data analysis tools for FAW early detection in crop fields. Biological studies of life cycle and behavior of FAW named scientifically Spodoptera frugiperda provides this important information that FAW has odorous sex-pheromones containing (Z) -9-tetradecenyl acetate (Z-9–14: OAca) [2]. These odorous sex-pheromones can be detected thanks to a suitable e-nose [3]. Making an e-nose specially designed for the detection of this particular type of odor is not easy. Therefore, a concisely review of the artificial olfaction technology as well as experimental tests to identify potentially sensitive materials and sensors for FAW odor were carried out. The main contribution of this work is to provide an alternative (approach) to the lack of specific sensors dedicated to FAW detection.

The paper presents the design and achievement of an affordable system for FAW data collection and preliminary results, based on judiciously identified commercial sensors. It is a first step of smart monitoring system for early detection of FAW in farm fields. Such a detection method can contribute to the establishment of an effective control protocol against fall armyworm as soon as it is detected around a monitored environment. This should reduce the use of plant protection products, pesticides, and Genetically Modified Organisms (GMOs) [4]. In sum, the system provides additional resources that can be involved in ecological management of the fall armyworm problem.

The paper is organized as follows. Section 2 presents a short review on Electronic Nose, Metal Oxide Semi-Conductor Sensors, and their applications. In Sect. 3, the proposed electronic nose for early detection of FAW is described. Section 4 is devoted to experiments, results, and discussion.

2 Review on Electronic Nose and Metal Oxide Semi-conductor Sensors

2.1 Survey on Electronic Nose

E-noses are sensor systems that are designed to mimic the mammalian nose. This critical artificial function offers the possibility to recognize different olfactory signatures in correlation with a range of fields, including environment monitoring, disease diagnosis, public security affairs, agricultural production, food industry, etc. [5]. The first work on the development of a device truly capable of measuring odors dates back to the 1960s [6, 7]. However, the term electronic nose did not appear in the literature until twenty years later following research at the University of Warwick in Great Britain by the group of Dodd and Persaud [8]. E-noses are composed of an array of non-specific sensors that respond to either individual or classes of chemical volatiles [9]. As presented in Fig. 1, the odorant molecules to be studied are carried with a controlled concentration towards the E-nose using sampling or pre-concentrating technique. When the odorant land on the sensor array and interact with the sensing materials, a reversible change in a chemical or physical property is induced. These changes are transduced into an electrical signal. Due to the non-specificity of the electric signal about the chemical identity, the output of the sensor array is further processed by machine learning algorithms to correctly identify, classify, and quantify the analytes (VOC). Pattern recognition in electronic noses is a dynamic and fast developing field, due to the constant need to adapt the theory or methodology to the specific complexity or conditions of data acquisition [10–16].

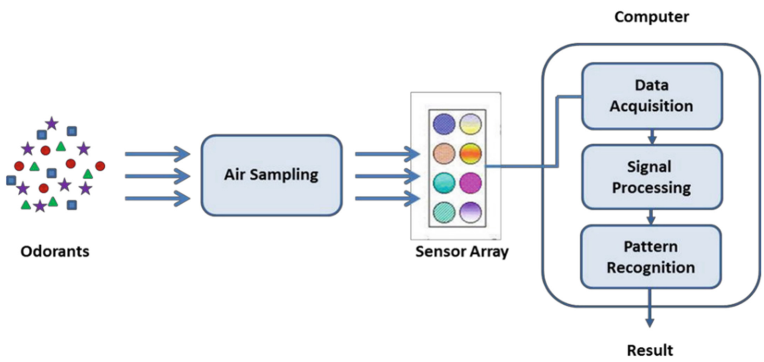

Fig. 1. Concept of E-Nose System Operation Principle [17]

Different sensing techniques have been use in the constructing of e-noses, which include surface acoustic wave (SAW) [18], quartz crystal microbalance (QCM) [19], metal oxides [20–22] conducting polymers [23, 24], carbon nanotubes (CNTs) [25], or a combination of multiple techniques [26].

In summary, many technologies of gas sensor exist, and several have already received attention for electronic nose applications. It is worthwhile noting that each of the technologies has favorable and critical points in terms of selectivity, sensitivity, response time, stability regarding environmental conditions (such as humidity and temperature). Metal oxide semiconductor (MOS) sensors are particularly useful for monitoring VOCs which are organic chemical compounds that evaporate easily at room temperature. Even though most of these sensors suffer the lack of selectivity towards VOCs from similar chemical classes, they are a promising technology within the framework of our experimental objectives which consist of detecting FAW odorous sex-pheromones ($C_{16}H_{30}O_2$) whose chemical nature is VOCs-type [27].

2.2 Survey on Electronic Nose

Metal oxide semiconductor (MOS) gas sensors are used in a variety of application fields. They are relatively inexpensive compared to other sensing technologies, robust, lightweight, long lasting and benefit from high material sensitivity and quick response times [28].

MOS sensor is the most widely used technology for e-noses, and the most common sensing materials of MOS are semi-conducting or metal-oxides including, iron oxides, titanium di-oxide, tin dioxides, zinc oxides, nickel oxide, cobalt oxide etc. The sensing materials are put on a ceramic substrate, like alumina. Generally, the device also has a heating element [29]. Working of this sensor depends on the types of the sensing materials (reduction or oxidization). When analytes collect upon the surface of these materials certain reactions occur resulting in electron transfer from the analytes to the conducting materials, which trigger changes in the electrical signals. Sambemana's works [28] have led to the adaptation of an electronic nose to the essential oils intensities detection. Detection of volatilized substances was achieved using a network of commercial metal oxide sensors. Response signals analysis from the sensors to different concentrations of the oils, after adequate digital filtering, revealed good cross-sensitivity of the sensors both in terms of the time response and in terms of its derived curve. Analysis using classification methods (unsupervised then supervised) revealed the best combination of parameters for rapid and reliable identification of VOCs concentrations.

In the agriculture field, Kanade's work [30] deals with the development of an artificial olfactory system as based on an array of metal oxide semiconductor gas sensors to be used for the classification of different fruits (Guava, Orange and Banana) and exploration of its application in measurement of fruit ripening stages. Study of E-nose show that Metal oxide semiconductor Gas sensors are usually used in e-nose technology for many applications.

The main disadvantage of the MOS sensor array is that the devices require to operate at temperatures between 250 and 450 °C [31]. Therefore, they consume a significant amount of energy and need a relatively long time for heating before they are ready to take measurements.

A typical structure of a MOS sensor is given in Fig. 2. The semiconducting layer oxidizes the sample compound. Gas concentration is detected by measuring the resistance change of the Metal Oxide sensing layer. The resistance change is related to the effect of oxidizing or reducing reaction at the surface and in grain boundaries area, which results in the modulation of the potential barrier, thus electrons flow in the circuit. The sensitivity of the sensor can be tuned by adjusting the operation temperature or by using noble metals as catalytic dopants.

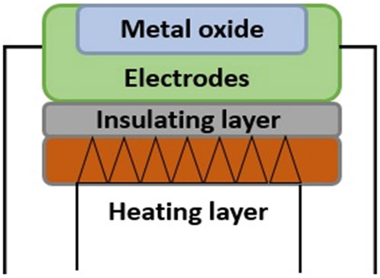

Fig. 2. Scheme of a metal oxide sensor

Two families of metal oxides exist, p-type and the n-type. N-type sensors which respond mainly to reducing compounds (e.g. CO, H_2, CH_4, C_2H_5 or H_2S), and p-type sensor which respond mainly to oxidizing compounds (O_2, NO_2, and Cl_2). The reactions occurring between these sensing materials and gases are described in Eqs. (1), (2):

$$\frac{1}{2}O_2 + e^- \rightarrow O^-(g) \quad (1)$$

$$R(s) + O^-(g) \rightarrow RO(s) + e^- \quad (2)$$

where e is an electron from the oxide, $R(s)$ is the reducing gas, s is the sensing materials, and g is gas. In the first step, oxygen from the environment is incorporated in the surface semiconductors lattice of the sensor, setting its electrical resistance to a stable state. During the measurement, target volatile molecules near the surface of the sensing material react (oxidation/reduction) with the incorporated oxygen species causing a change of the electrical properties, such as capacitance and resistance of the device [13].

SnO_2 is one of the most widely used metal oxide (N-type) gas-sensing material because of its high sensitivity and simple fabrication. This family of metal oxide gas sensor is available in commercial version as MQ sensors and still used in recent applications for odor detection [32, 33].

3 Proposed Sensor Based on Electronic Nose for Early Detection of FAW

3.1 Monitoring and Detection of FAW

A bibliographic review of the different methods of fighting against FAW [3] shows that it is a very current research subject which is still under investigation. Indeed, no solution at present offers a full protection of crop guarantee to farmers against FAW attacks. In this work, an original and new tool based on E-nose is proposed for a FAW monitoring strategy in order to early detect its presence in the corn fields.

The idea is to contribute to the development of a new and ecological approach in the fight against FAW. In this work, the objective is not the measurement of fall armyworm VOCs concentration but their detection and at the end, two architectures of the E-nose are explored (Fig. 3).

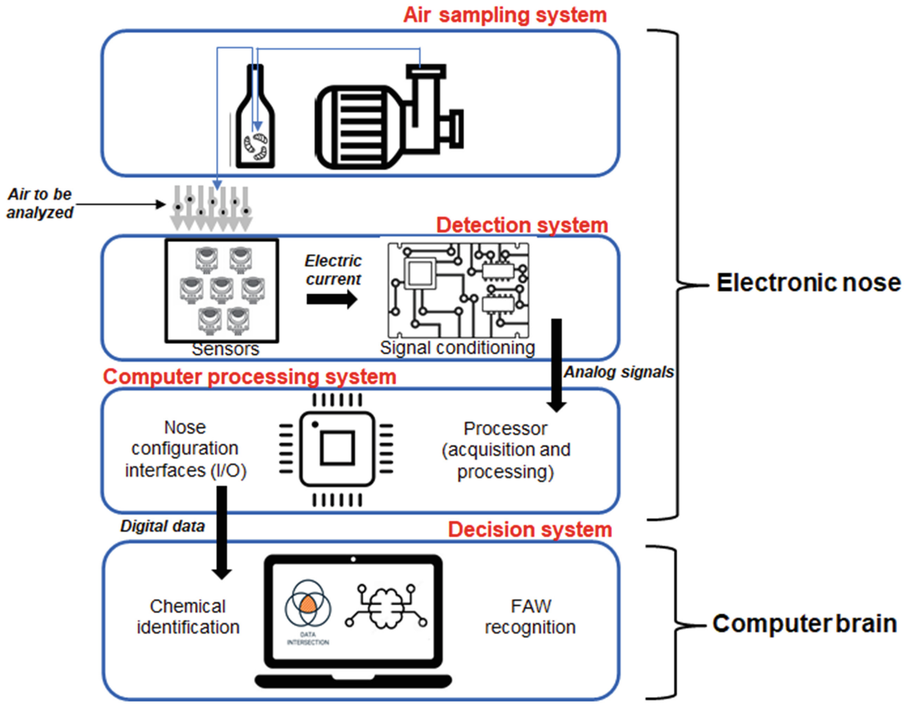

Fig. 3. E-nose's Structure for FAW detection

This architecture uses a classical air sampling method at the air collecting stage. It is divided into four main parts. The proposed architecture for FAW detection is detailed as follows:

- **The air collecting system (The air sampling system)** is the first part of the E-nose, through which the air to be analyzed is carried to the sensors. This stage is the mechanical part of the system**.** It consists of a glass enclosure connected to a solenoid valve and a pump to convey the air to be analyzed in the measuring enclosure.
- **The detection system** is based on a matrix of sensors and signal conditioning circuits that are the reactive parts of the e-nose. It is mainly based on semiconductor type metal oxide transducers that are installed in the measurement enclosure. Their electrical parameters (conductivity, resistivity) are modified as soon as they enter into contact with volatile substances such as FAW's odor.
- **The computer processing system** has microcontroller (Arduino MEGA 2560 microcontroller board) as the main component of this part. When the sensors detect a volatile substance, a specific response (Voltage) corresponding to the digital measurement of each of the sensors is filtered, recorded and accessible in a memory.
- **The decision system** (Informatique brain) part has two main roles. Firstly, it treats the data from the e-nose and displays them in a usable form for analysis and secondly, it compares the data from the e-nose with specific signatures of FAW's volatile

substances. Different methods such as Support Vector Machine (SVM) or Linear Discriminant Analysis (LDA) can be used to realize pattern recognition. In our case signal profile recognition was used.

3.2 Metal Oxide Device

SnO2 semiconductor based MQs were used in our experiments. This type of MQ has low conductivity in clean air. In the presence of a detectable gas, the sensor's conductivity increases (for reducing reaction) depending on the gas concentration in the air. A simple electrical circuit can convert the change in conductivity to an output signal which corresponds to the gas concentration. The change of Vo the output voltage of the e-nose obeys the following equations:

Equation (3). Change of V_0 through to use V_C and metal oxide sensor conductivity (GMOS) with the resistor R_L.

Equation (4). Based on GMOS estimation through the use V_C and V_0 with the resistor R_L by.

$$V_0 = \frac{R_L}{R_L + \frac{1}{G_{MOS}}} \bullet V_c \tag{3}$$

$$G_{MOS} = \frac{1}{R_L} \bullet \frac{V_0}{V_C - V_0} \tag{4}$$

$$R_{MOS} = R_L \bullet (\frac{V_C}{V_0} - 1) \tag{5}$$

With GMOS the conductivity of the Metal oxide sensor.

For instance, in contact with a reducing gas, an SnO2-MOS sensor fixes more electrons, which increases its conductivity, thus decreasing its resistance. Inserted in a voltage divider bridge structure as shown in Fig. 4, the reduction reaction causes an increase in the voltage Vo (Eq. (3)). A Metal oxide sensor conductivity (Eq. (4)) or resistor (Eq. (5)) can also be estimate to appreciate chemical reaction.

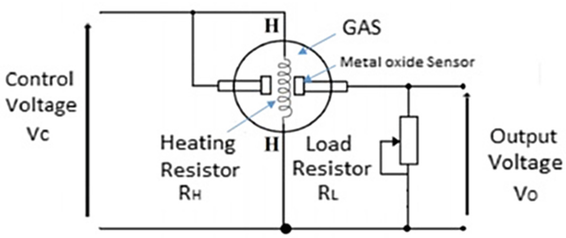

Fig. 4. Electronic diagram of the conditioning circuit of a metal oxide gas sensor

3.3 Sensor Array Module

This In our experiment, the sensor array was mainly composed of SnO2 based commercial MQs. This choice was guided by the olfactory nature of FAW. Studies and research on FAW show that female species naturally release sex pheromones which are closely-related analogue of (Z)-9-tetradecenyl trifluoromethyl ketone (Z9–14:TFMK) [34] with the chemical formula $C_{16}H_{30}O_2$. This chemical formula is an organooxygen compound like a number of substances which are detected by the sensors used in this work and presented in Table 1.

Table 1. MQ series metal oxide gas sensors choose for e-nose's array sensor

Sensor No	Sensor model	Target Gas sensitivity
1	MQ2	Alcohol, CH4
2	MQ3	Alcohol, Solvent vapors
3	MQ4	LPG, CH4
4	MQ5	LPG, Natural gas, Coal gas
5	MQ6	LPG, Propane
6	MQ7	Carbon Monoxide (CO)
7	MQ8	Alcohol, H2

The air temperature and relative humidity data were collected during the experiments, thanks to a temperature and humidity sensor (DHT22). The objective is to study how these factors might affect the response of the sensor array.

3.4 Experimental Tools

In accordance with proposed architecture, experimental setups were explored. In what follow, the results from the two setups are evaluated. Figure 5 presents the experimental tools.

Here, ambient air is pumped and filtered through a coal tube before being brought to the olfactive tube where FAWs are captured (Fig. 5). The air is charged by FAW's volatile organic compound and enters the sensor array enclosure with a dynamic flow. The electrical signals generated from the sensors are digitally filtered, processed with Arduino MEGA 2560 board and sent to the computer for analysis. LabVIEW instrumentation software was used to develop a program for electronics control and data acquisition from the e-nose. The programmed VI Shows real time voltages from the sensor array.

4 Experimental Results and Discussion

4.1 Measurement Protocol

Proper use of MQ sensor begins with the preheating phase. MQ sensors have their own heating element. Prior to experimental measurements, the sensor matrix is powered and

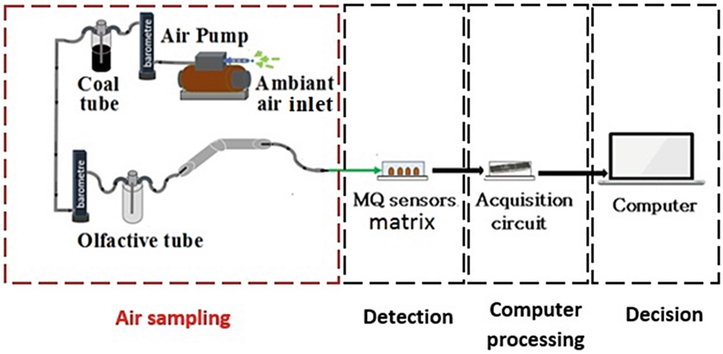

Fig. 5. Experimental setup for the detection of FAW based on e-nose.

brought to the operating temperature. During the preheating of the sensors, the temperature inside the chamber increases and stabilizes in the range 55 °C–58 °C (experimental measurement). The measured relative humidity in the chamber during the experiments was stable around 60%.

The procedure is to put adult female FAW (which produces sex pheromones) in a sealed chamber with two ports (input-output) for controlled air circulation. Input is filtered air which is pumped from ambient. The air that passes through the FAW's chamber becomes charged with VOCs and goes out to the measurement enclosure. The measurements are carried out over periods of 10 min [35], taking into account the recovery time of the sensors. The data are displayed and saved on LabVIEW VI for analysis. Figure 6 shows the experimental setup.

5 Results and Discussion

The characteristics of the sensor's matrix in the air sampling classic e-nose setup are depicted on Fig. 7. Figure 7(a) shows the output signal of the sensors during the preheating phase and when the sensors are exposed to ambient air. It may be seen that around t = 550 s, the output signal is disturbed by the adsorption of ambient chemical species. Then, after about 500 s exposure (beyond t = 1100 s) sensor's response are stable, which is a favorable situation for the detection of chemical elements other than those constituting the ambient air. Afterwards, similar experiments were carried out with the presence of FAW inside the sealed chamber. Figure 7(b) shows the resulting output signals, first with 10 FAWs and then with 20 FAWs. The first observation to underline is the low signal-to-noise ratio (SNR). Nevertheless, small variations of the output voltage are noticed with sensors MQ2 and MQ3 over a long period of measurement. This variation shows that the sensors resistance decreases through a reduction reaction on the Metal oxide transductors. Further increase of the number of FAWs did not increase the output signal, which may be explained by the logarithmic increase of odor intensity with a given quantity of VOCs. The other MQs show the same light variation of the signal, but the signal gradually decreases and reaches initial level after about 350 s. This

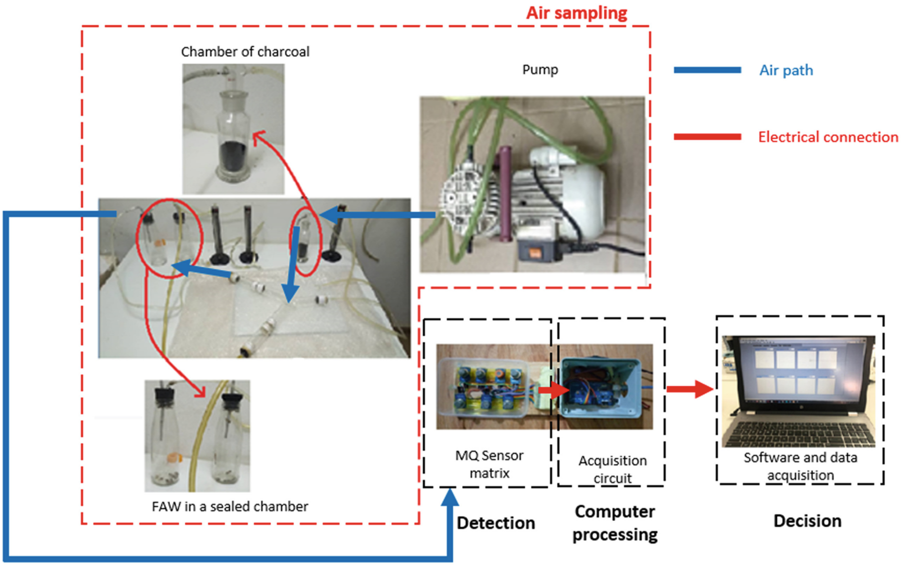

Fig. 6. Experimental setup with e-nose procedure.

phenomenon which resembles an adsorption/desorption mechanism, reflects a very low sensitivity of these sensors to FAW.

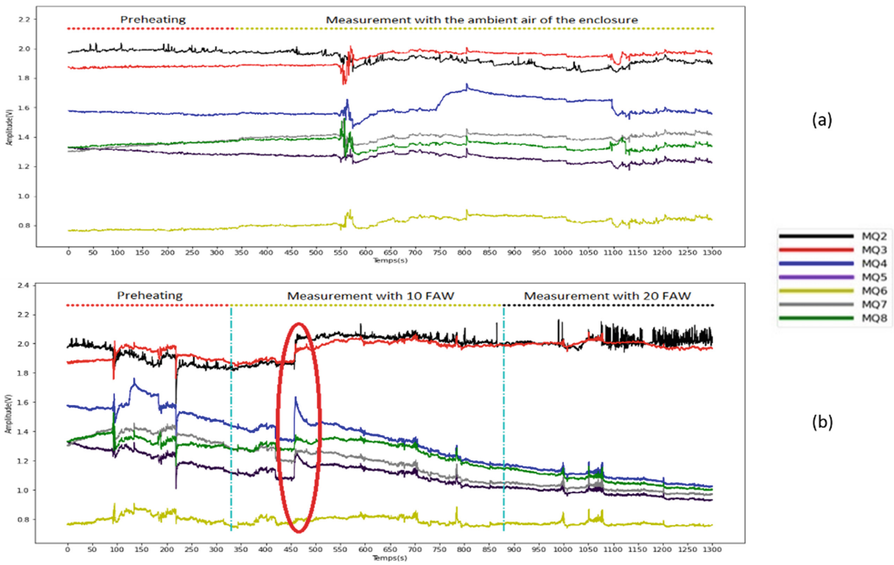

Fig. 7. Sensors array signals with FAW's data collected with e-nose

For all the sensors, the variation of the output signal (in red circle) begins 120 s after the presence of FAW in sealed chamber. This delay may be due to the fact that FAWs do not produce VOC immediately after they are introduced into the sealed chamber. This delay can also be explained by the high dilution of FAWs pheromones by ambient air.

Due to the low SNR ratio of the measurements results, the signals should be filtered to give more information. And data analysis tools should be developed to extract automatically the FAW's parameters for its detection.

6 Conclusion and Future Work

In this work, we have revised the current state of e-noses, focusing on MOS sensors and its ability to be used for versatile applications. To ecologically monitor Fall armyworm Pest, we proposed an electronic nose to detect and collect Fall armyworm VOC data. The air collecting systems were explored. This first FAW detection in laboratory experiment is very promising for further improvement and deployment for an automatic and real time detection in agricultural fields. Future work will be devoted to noise filtering of the sensors signal data analysis tools to perform accurate FAW detection and making a custom-built air concentration system to have more sensibility performance compared to the classic air sampling system.

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