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Advances in electronic nose sensors for plant disease and pest detection †

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Abstract: The spread of invasive pests is accelerated by globalization and changes in climate conditions, posing a significant threat to agricultural and forest ecosystems. Advances in electronic nose sensors (e-noses) have opened new avenues for monitoring and detecting plant diseases and pests through the analysis of emitted volatile organic compounds (VOCs). The current work reviews the most recent developments in e-nose sensors and their application in plant disease and pest detection over the past five years. It also explores the challenges associated with VOC detection in agricultural settings where field sampling has a focal role in monitoring and management.

Keywords: invasive pests; non-destructive detection; plant pest detection; sensor technology; VOCs analysis; volatile organic compounds

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1. Introduction

Invasive pests and pathogens pose a significant threat to plant health for the agronomy and forestry sectors. These organisms invade new geographic areas where they proliferate and damage the environment by altering ecosystems, often leading to the extinction of native species, or damaging agricultural production [1]. Since they disrupt the delicate environmental balance by outcompeting native species, plant pests contribute to the spread of diseases, reduce crop yield, and lead to economic losses and/or food shortage for communities. Moreover, they can have long-lasting impacts on the environment, altering habitats and reducing biodiversity [2]. In the last few decades, the spread of plant pests has been accelerated through an increased movement of materials, goods, as well as by large-scale trade and travel. Furthermore, warmer temperatures and changes in precipitation patterns enable pests to expand their geographic range into regions where they previously could not survive or reproduce successfully. Such fluctuations in climate conditions, and the increased frequency of extreme events, can impact the health and resilience of native plants, making them more susceptible to invasive pests. The loss of biodiversity can intensify the spread of invasive pests, through a disruption of e.g., natural predators, creating conditions that favour the proliferation of specific pests [3].

Phytophagous insects are in the forefront of pest invasions; however, it is important to keep in mind that extremely damaging plant pests also include disease-causing nematodes and parasitic protozoa as well as microorganisms such as bacteria, viruses and fungi. The European Commission recognized and designated 20 priority pests in the list of quarantine pests [4], whose economic, environmental, and social impact on EU territory is the most severe. Of these, four are non-insect pests, namely *Bursaphelenchus xylophilus* (nematode), *Candidatus Liberibacter* spp. (bacteria), *Phyllosticta citricarpa* (fungus) and *Xylella fastidiosa* (bacteria). The list is based on impact assessments carried out by The European Food Safety Authority (EFSA) and the European Commission's Joint Research Centre (JRC). The assessments considered a number of indicators such as impact on crop yields, damage to trade and the cost of control measures, social consequences such as unemployment, reduced food safety and security, as well as impact on landscapes and damage to the environment, e.g., reduced biodiversity and ecosystem services.

This underlines the relevance of controlling and managing invasive pests, practices that are essential for safeguarding plant health, preserving agricultural productivity, and maintaining the overall ecological balance. Therefore, the development of novel concepts for the timely and non-destructive pest detection and management of serious plant pests, both during import and in the field, is of the utmost importance. The application of electronic nose (e-nose) sensors contributes to the prevention and control of plant diseases by swiftly detecting changes in volatile organic compounds (VOCs) emitted by plants when they are infected or stressed, allowing for early intervention and targeted management strategies to curb disease spread.

2. Technology and rapid detection of plant diseases and pests

2.1. Electronic nose (e-nose) sensors

E-noses are devices that detect and analyse volatile organic compounds (VOCs) from targeted samples and have found wide applications in quality control, environmental monitoring, and agriculture [5], as well as proven to be a useful tool in plant protection [6-13]. The main constituents of an e-nose system are a sensor array, the signal conditioning unit, and a pattern recognition algorithm. E-nose systems utilize sensor arrays to generate a distinct response to specific VOCs and pattern recognition software for resolution and identification. When a sample is exposed to the sensor array, it triggers a reversible physical or chemical change in the sensing material, leading to alterations in its electrical properties. These changes are transformed into electrical signals, which are preprocessed and conditioned for identification by a pattern recognition system [14]. Therefore, the e-nose system ensures a unique overall response pattern from the array for a specific VOC within a group of VOCs considered by the system.

To improve sensitivity, selectivity and the ability to detect a wide range of VOCs, different sensor types can be employed. The most utilized classes of sensors are conductivity sensors, gravimetric sensors, and optical sensors [15]. Conductivity sensors employ conducting polymers (CP) and metal oxide semiconductors (MOS), while gravimetric sensors include surface acoustic wave (SAW) sensors and quartz crystal microbalance (QCM) sensors. Another approach to VOC identification in e-nose systems involves optical sensor arrays [11]. The choice of sensors depends on factors such as the targeted applications, desired detection capabilities, and environmental conditions, and must take into consideration the specific biological parameters of the targeted pest or disease.

2.2. Progression of scientific output

Over the past two decades, there has been a growing research interest in the application of e-noses for detecting plant pests (Figure 1). However, a comprehensive review of the bibliographic data using Web of Science search engine, encompassing all available databases and published works that report the application of e-noses to detect volatiles of pests or pest-related diseases, reveals that the intensity of research has fairly increased in the last five years. By researching the topics of "nose", "volatiles" and "pest" from 2019 to 2023, a total of 12 publications were identified reporting the use of electronic sensors for detecting plant pests and diseases.

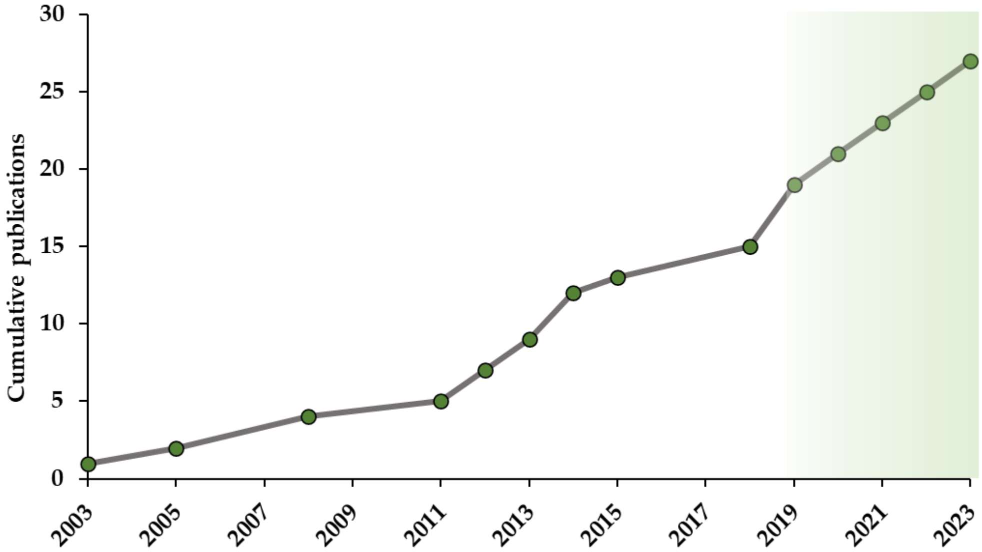

Figure 1. Cumulative number of published works reporting on the application of e-noses to detect volatiles of pests or pest-related diseases, obtained from Web of Science (https://www.webofknowledge.com, accessed 14 July 2023).

The journals where these works were published cover mainly the scientific fields of chemistry (25%), plant sciences (24%), engineering (19%), agriculture (16%) and environmental sciences (16%) (Figure 2). The listed publications were cited in 79 works, with an average of 7 citations per work. These citations were included in journals specialized in chemistry, plant sciences, environmental sciences, agriculture, instruments and instrumentation, engineering, and molecular biology. The plants that receive the most attention include Poaceae, e.g., wheat, Solanaceae, e.g., tomato, Oleaceae, e.g., olive and green ash, Theaceae, e.g., tea, Rutaceae and Cupressaceae [6-8,13,16-21]. Furthermore, since 2019, the cumulative number of citations of all publications (2003 to 2023) on this topic has greatly increased, indicating a surge in application and research.

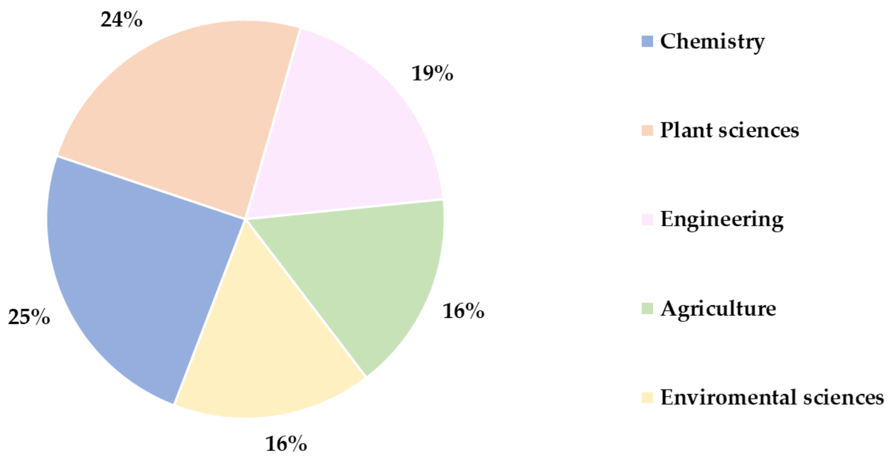

Figure 2. Scientific fields covered by the journals of the publications on electronic noses identified from 2019-2023, according to the Web of Science (https://www.webofknowledge.com, accessed 14 July 2023).

3. Advantages and challenges

3.1. VOCs profiles for plant pest detection

Developing technologies in plant pest detection minimizes the reliance on subjective human judgment and offers consistent, objective results, providing consistent and datadriven insights to optimize pest management practices and ensure sustainable plant health. E-nose based detection drastically reduces the time needed for analysis compared to conventional methods for VOCs identification and enables early intervention and immediate response to mitigate plant pest infestations. It is a non-invasive method of pest detection, minimizing harm to plants and reducing the need for extensive manual inspections. High sensitivity enables e-noses to detect pests at low infestation levels, helping the implementation of targeted pest management strategies and reduce the need for excessive pesticide use. Furthermore, e-noses can be integrated into real-time monitoring systems.

As stated before, the appropriate e-nose sensor relies upon the specific application, nature of the sample and the environment. Recognizing the value and advantages of customizing e-nose devices for specific tasks [22], rather than aiming for a general-purpose device that works for a wide range of gas-sensing uses, results in a more accurate, efficient, and reliable tool. Targeting specific pests offers a precise, user-friendly, and cost-effective approach for larger scale pest control. However, e-nose technology faces several challenges.

Plant environments often contain complex mixtures of VOCs, including compounds from sources other than the plants themselves. For differentiating pest-specific profiles within these mixtures, structured research and comprehensive databases of both plant specific volatiles and pest VOCs are necessary. Additionally, pests of the same species can exhibit variations in VOC emissions based on such factors as age, sex, and physiological state, or the plant may even be infected with different pests and diseases simultaneously, complicating an accurate identification. Therefore, validating e-nose results against traditional pest detection methods is essential to ensure the accuracy of the e-nose approach. The extensive data generated by e-noses requires advanced data analysis techniques, including pattern recognition and machine learning. To compare obtained results across different studies and/or devices standardized protocols should be outlined.

3.1. In-situ detection

Profiling plant VOCs is conventionally carried out in a sealed chamber with controlled temperature and humidity, which simulate the environment of a greenhouse and the field [15]. Yet, the most powerful approach in larger scale pest control is obtaining real-time, accurate, and contextually relevant data for decision-making and intervention in the field. Still, deploying e-nose in outdoor agricultural settings requires addressing challenges like sensor stability, power sources, and data communication. As changes in environmental conditions, such as temperature, humidity, and background, can affect sensor responses, tailored and targeted devices become even more important.

Addressing the complexity and variability of VOC profiles when using e-nose technology in the field requires a multifaceted approach. Appropriate sensor selection targeting specific VOC profiles, multivariate analysis, baseline correction, and regular equipment calibration help enhance data accuracy and reliability. Simultaneous environmental monitoring, which records temperature, humidity, wind direction, GPS location, and other relevant factors that could influence VOC emissions, alongside VOC measurements, can provide context and validation [23]. Machine learning and pattern recognition models aid in interpreting complex VOC profiles [24], while real-time monitoring facilitate quick responses and adjustments in the field.

The advancement of smaller, lightweight, and portable e-nose devices offers a more efficient means for early disease diagnosis in field scenarios. To enhance practicality for plant pest detection, especially in open-field situations, the development of small-scale sensor arrays utilizing integrated circuit technologies and micro-electromechanical systems [25] can lead to the production of highly portable and cost-effective detectors. The costs can be mitigated by 3D printing of some components. Also, coupling of e-nose with a drone, allows sampling on the larger surfaces or infected plant communities [12]. These advances will allow real-time monitoring and the creation of field-deployable devices tuned to specific plants, pests, seasonal variations, and sample locations, providing more effective means of achieving early disease diagnoses in the field. Research is ongoing to develop specialized equipment based on e-noses, for example, a project financed by European Commission [26] is developing an innovative sensor platform that can rapidly detect different pests during import and in the field, to stop their establishment and reduce pesticide inputs, in Europe. Five pests were selected for the first optimization that include insects, nematodes and Oomycota, but will be extended to other important pests in later stages. Headspace GC-MS is being employed to profile VOCs and then used to fine-tune sensor components for the development of optimized sensor systems. Ultimately, a sensor system prototype will be validated in the field and at import control sites, leading to the development of a powerful e-nose-based specialized tool that can boost European plant pest control.

4. Conclusions

Advances in e-nose sensors have enhanced the approach to plant disease and pest detection. Key developments in e-noses include improved sensing technology, advanced data analysis techniques, real-time monitoring, portable and field-deployable devices and disease differentiation leading to early detection and prevention as well as reduced environmental impact. In addition to technological improvement, effectively addressing current challenges of plant pest control requires international cooperation, rigorous biosecurity measures, early detection systems, and inclusive management strategies to minimize the impact of invasive pests on agricultural and ecosystems. The application of e-nose contributes to efficient, sustainable, and environmentally conscious agricultural practices, with the potential to transform how we manage plant health issues. This ensures both economic viability and ecological responsibility.

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