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Review Paper

Advances and prospects of electronic nose in various applications

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ABSTRACT

The olfactory sense is a vital aspect of human perception, historically essential for detecting scents and engaging with our surroundings. Over time, electronic olfactory systems, commonly referred to as e-noses, have evolved dramatically, shifting from large, expensive, and power-hungry devices to smaller, affordable, and energy-efficient versions. These systems combine hardware and software elements, utilizing electronic sensors to identify and evaluate chemical substances in the air. Central to this technology are scent detectors that replicate the complex functions of the human nose. This groundbreaking tool is utilized across various sectors, such as food inspection, healthcare, environmental tracking, security, and more. Within the food sector, e-noses have become highly adaptable and essential instruments, supporting quality control, supply chain transparency, process improvement, and waste minimization. This study explores the latest developments and progress in e-nose technology, offering a detailed yet easy-to-understand overview of the field. E-nose technology has shown exceptional adaptability, becoming a key resource in the food industry. A major use is the precise evaluation of food freshness, which plays a significant role in minimizing waste and ensuring consumer health. By supplementing or replacing conventional methods—often slow and resource-intensive—e-noses provide a distinct ability to assess, categorize, and measure scents, offering a powerful solution for analyzing olfactory data.

1. Introduction

The ability to detect scents is a crucial aspect of human perception, long used to recognize smells and interact with our surroundings. Modern advancements have led to the development of electronic olfactory devices, known as e-noses, which mimic the human sense of smell. These devices are capable of identifying and examining diverse scents, providing precise and comprehensive data about various gases and intricate scent combinations. This innovation is sometimes likened to a unique signature for odor analysis (Wang et al., 2024). A schematic illustration of an e-nose is presented in Figure 1 (Abasiyanik et al., 2023).

E-noses, or electronic olfactory systems, are typically composed of two main parts: a mechanism for detecting gases and a system for processing data. The data-processing unit incorporates a high-accuracy processor, auxiliary equipment, and sophisticated algorithms for recognizing patterns (Van Der Sar et al., 2023). Since the emergence of the idea of electronic olfactory systems in the 1980s, the field has witnessed remarkable advancements. Compact, budget-friendly, and efficient devices have now taken the place of older, bulkier, and more costly models (Abideen et al., 2024).

This tool is utilized in food analysis (Khodkam, 2021), medical diagnostics, environmental monitoring (Wojnowski et al., 2018), security, and various other fields. This paper examines the most recent developments and progress in electronic olfactory systems, commonly known as e-noses, providing a thorough exploration of the subject. Existing research primarily highlights three main areas: detection mechanisms, varied uses, and algorithms for analyzing data. These elements are methodically outlined in Table 1.

2. Materials and Methods

This review article investigates the advancements and applications of e-noses across diverse fields by compiling and analyzing studies published in recent years. Data were collected from reputable scientific databases, including PubMed, ScienceDirect, and Google Scholar. The focus was on articles about chemical sensors, data processing algorithms, and the utilization of e-noses in the food, environmental, and medical sectors. The analytical approach encompassed systematic reviews and the categorization of findings based on their application areas. To ensure a comprehensive understanding, studies highlighting technological advancements and challenges in the development of e-noses were also examined.

The study begins by examining the performance and types of olfactory sensors, including semiconductor sensors, metal-oxide sensors, and conductive polymers. Subsequently, it reviews data processing algorithms, such as principal component analysis (PCA) and artificial neural networks (ANN), which play a pivotal role in interpreting sensor data. Finally, the applications of e-noses across various sectors are explored, including their use in the food industry (e.g., detecting food contamination), environmental monitoring (e.g., assessing air quality), and medical diagnostics (e.g., identifying diseases through the analysis of volatile organic compounds). This review underscores the e-nose as a powerful and versatile tool with immense potential to drive innovation and transformation across multiple disciplines.

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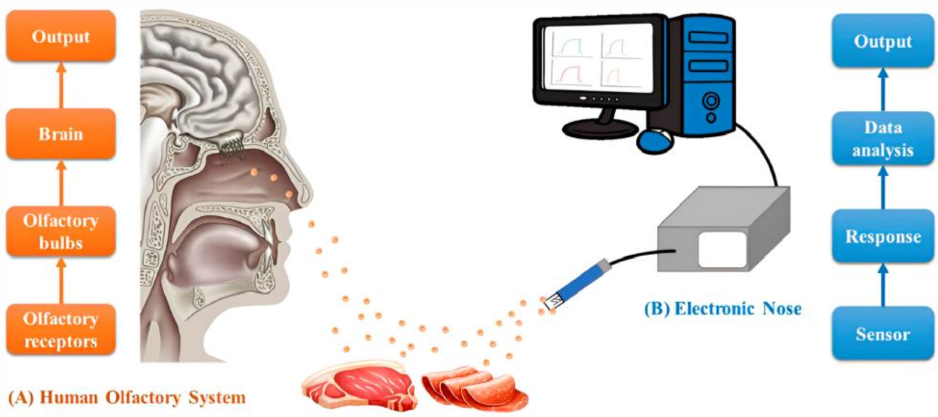

Figure 1. Schematic image of biological olfactory system (A) and e-nose technology (B)

Table 1. A comprehensive review of e-nose examinations

Review titles	Focus	Content	Reference
A brief history of e-noses	Sensors, applications	A review of advances in e-nose technology and its application areas in the past 25 years	Gardner and Bartlett (1994)
E-noses and their application in food	Food analysis	It offers e-nose sensor technology and statistical analysis techniques in the field of food analysis.	Schaller et al. (1998)
E-noses	Sensor technologies	Examined sensor and data processing technologies.	Strike et al. (1999)
E-noses used in dairy products	Dairy analysis using e-noses	It highlights the potential benefits of e-noses in areas such as cheese evaluation, milk classification, and bacteria identification.	Mehdipour and Ghaffari (2021)
E-nose and disease diagnosis	Detecting microbial infections using e-noses	E-noses are used in the detection of volatile compounds related to microbial infections and their potential applications in early disease diagnosis.	Turner and Magan (2004)
The use of e-noses for disease diagnosis and food spoilage detection	E-noses in medical diagnosis and food quality control	E-noses are used to classify and quantify bacteria and fungi to achieve medical diagnoses and ensure food quality. This article includes examples of bacterial and fungal species that produce volatile compounds associated with infectious diseases or food spoilage.	Casalinuovo et al. (2006)
Applications and advancements of e-nose technology	E-nose technology	The evolution of e-nose technologies and their diverse applications in various industries were reviewed. Significant advances in sensors, materials, software, and microcircuitry have led to the emergence of new sensor types and applications.	Wilson and Baietto (2009)
E-nose for microbiological quality control of food products	E-noses, diet plans	Covers the detection of microbial contamination in fruit juices, processed tomatoes, corn kernels, and green coffee beans.	Falasconi et al. (2012)
E-noses for environmental monitoring applications	Sensors, environmental applications	Studies generally show that e-noses are well suited for analyzing environmental quality parameters, process control, and evaluating the efficiency of odor control systems.	Sironi et al. (2007)
Application of e-noses for clinical diagnosis in urine samples	E-noses for clinical diagnosis	It presents applications of e-noses in the medical field, focusing on the analysis of gaseous compounds present in human urine.	Baldini et al. (2020)
E-noses in medical diagnosis	E-noses, medical applications	Provides an overview of e-nose applications in medical diagnostics, focusing on how these devices and sensor technologies align with current trends in medicine.	Wojnowski et al. (2018)
E-nose as a new method for cancer detection	E-noses, medical applications	This study examines e-nose technology for early cancer detection. Among the published papers, promising results (with an accuracy of over 80%) were evident in lung cancer detection. However, there are many challenges to diagnosis.	Baldini et al. (2020)
Development of compact e-noses	Sensor technologies	It reviews the evolution of compact e-nose design and computation in recent decades and outlines potential future directions.	Zang et al. (2023)
E-noses based on metal oxide nanowires	E-noses, metal oxide nanowires	Metal oxide nanowires are used as gas sensors in e-noses. It covers various areas including basic research, agriculture, health, and security. It reviews the types of metal oxides used, surface modifications, sensor array characteristics, applications, algorithms, and information obtained from these e-noses.	Mirzaei et al. (2023)
E-noses and their applications for sensory and analytical measurements in waste management facilities	E-noses for waste management facilities	It highlights real-world applications of e-nose devices in waste treatment processes and odor assessment near waste management facilities.	Jońca et al. (2022)
Environmental engineering applications of e-nose systems based on MOX gas sensors	E-nose, environmental engineering applications	The use of metal oxide semiconductor sensors for the detection of volatile compounds in air, especially at low concentrations, is investigated. This study discusses the advantages and disadvantages of MOX sensors and reviews various research studies related to environmental pollution monitoring using e-noses.	Khorramifar et al. (2023)
Metal oxide-based e-noses for healthcare	Exploring e-nose technology for healthcare	It examines recent advances in e-nose technology and its applications in healthcare (e.g., medical diagnosis) through breath analysis and monitoring of hazardous gases. The study addresses challenges such as miniaturization and low power consumption and examines various sensor materials used to overcome them.	Abideen et al. (2024)

3. Principles of Odor Sensors

At the core of e-nose systems are scent detectors that replicate the complex functions of the human sense of smell. These devices use electronic sensors to identify and evaluate chemical substances present in the surrounding air. Scents are converted into measurable signals, which the system then analyzes and interprets (Du et al., 2024).

The e-nose system integrates both physical and digital elements, where the software acts as the brain of the device, and the hardware—comprising a group of sensors—replicates the role of scent detectors. In contrast to the human nose, which uses around 100 million receptors to identify smells, the e-nose accomplishes this task through its interconnected sensor network (Mirzaei et al., 2023).

Various types of detection materials are utilized, such as semiconductors based on metal oxides, metal oxide (MOX) detectors, field-effect transistors made from metal oxide semiconductors (MOS), sensors sensitive to mass changes, organic polymers with conductive properties (CPs), and sensors using solid electrolytes (Wawrzyniak, 2023), and fiber-optic sensors, contribute to the efficiency of e-noses (Iyovo et al., 2010). MOX sensors, widely employed in commercial settings, operate by sensing shifts in the oxide's conductivity upon contact with gases that either oxidize or reduce. This triggers surface-level redox reactions (Calvini and Pigani, 2022). At temperatures between 100 and 500 °C, MOX exhibits significant interaction with the atmosphere, a phenomenon known as biosorption, which involves the adsorption of various ions, including O_2- and O- (Barsan and Weimar, 2001). At moderately low operational temperatures, generally under 200 °C, the primary mechanism involves the attachment of electrons to oxygen molecules (O_2^-) on the surface of metal oxide (MOX), leading to the creation of O_2^- ions (Bhati et al., 2021). At higher operational temperatures, typically above 250 °C, a more intricate dissociation mechanism takes place. Increased thermal energy promotes the splitting of oxygen molecules, leading to the generation of oxygen ions and the liberation of electrons from the conduction band of the MOX structure (Bhati et al., 2021).

MOS are crucial components in gas sensing technologies and are categorized into two main types depending on their dominant charge carriers. N-type MOS materials, like zinc oxide (ZnO), primarily utilize electrons as their key charge carriers (Jing and Zhan, 2008), In_2O_3 (Yao et al., 2023), Fe_3O_2 (Xie et al., 2023), TiO_2 (Gupta et al., 2023), WO_3 (Megersa et al., 2023) and SnO_2 (Yang et al., 2022), exhibit electrons as their main carriers, while p-type semiconductors, such as NiO (Qin et al., 2023), Co_3O_4 (Guo et al., 2023), Cr_2O_3 (Yao et al., 2023), Mn_3O_4 (Tarighi et al., 2024) and CuO (Tsymbalenko et al., 2023), have holes as their main carriers.

4. E-nose Intelligence: Algorithms and Visualization

Electronic sensing serves as a fundamental element in e-nose systems, often considered the brain of the technology. Among the recognition methods employed in e-noses, PCA stands out as a common tool for analyzing data and identifying patterns (Borràs et al., 2015), as well as linear discriminant analysis (LDA) (Zakaria et al., 2012), partial least squares regression (PLSR) (Abdi, 2010), support vector machines (SVM) (Guermoui et al., 2022), and ANN (Darvishi et al., 2024).

5. Application Areas

Over time, e-nose systems have seen considerable progress and thorough testing in numerous applications. By examining a range of uses and presenting key instances, the review emphasizes the adaptability and innovative impact of e-nose technology.

5.1 Applications in food sectors

E-noses have become essential and highly adaptable tools in the food sector, offering diverse applications that greatly improve quality control, traceability, process efficiency, and waste management. Their ability to evaluate the quality and source of products in industries like olive oil and green tea has proven to be a valuable resource (Ordoñez-Araque et al., 2020). These olfactory systems facilitate the accurate classification of products based on their unique quality characteristics.

Precisely evaluating food freshness is a key goal in minimizing food waste and safeguarding consumer health. In this regard, e-noses are becoming essential tools, providing a versatile method for tracing the intricate patterns of odor shifts linked to food degradation. Systems incorporating semiconductor thin-film sensors and dynamic principal component analysis (DPCA) have effectively been used to accurately track freshness decline in milk (Phukkaphan et al., 2021). In addition to milk, e-noses are also effective across various meat types, such as beef, poultry, and fish. These sophisticated systems allow for accurate spoilage evaluation by identifying volatile organic compounds (VOCs) released as meat breaks down (Timsorn et al., 2016).

By identifying the unique odors released by different meats as they spoil, e-noses act as essential tools for spotting early spoilage indicators, reducing health hazards, and supporting efforts to minimize food waste. Incorporating e-nose sensors into packaging materials marks a revolutionary step in tackling food waste. This cutting-edge method allows for ongoing tracking of packaged food quality, addressing a major issue: the lack of clarity about product freshness and safety before consumption. Offering real-time updates on a product's status to producers, distributors, and consumers throughout its lifecycle, this technology enables prompt actions and well-informed choices.

5.2 Environmental monitoring

E-noses are employed in various environmental applications, covering several key areas: tracking and examining air quality indicators, evaluating water conditions, boosting efficiency in process management, ensuring worker safety, especially in enclosed industrial environments like factories and mines, and analyzing the effectiveness of odor management systems (Eusebio et al., 2016). In various fields, e-noses function as effective substitutes or supplementary tools to traditional analytical methods. For example, in air quality assessment, an e-nose equipped with MOX sensors can be paired with gas chromatography to detect and measure a broad spectrum of pollutants (Özmen and Doğan, 2009). Likewise, e-noses provide an economical and creative approach to overseeing processes that are difficult to control with conventional, labor-intensive analytical techniques. For example, avoiding unwanted anaerobic conditions in composting operations requires monitoring critical factors like temperature, oxygen concentration, pH, and microbial activity (Romain et al., 2005).

E-noses function as both supplements and substitutes for conventional analytical techniques, while also providing the distinct ability to evaluate and categorize odors, a key factor in measuring olfactory perception. Consequently, specialized assessment methods are employed to ensure precise and quantitative odor analysis. Ensuring the safety of coal miners has been a primary driver behind the advancement of gas sensor technology. In the past, the coal mining sector encountered major obstacles due to the presence of dangerous gases like hydrogen sulfide (H_2S) and methane (CH_4) within mine environments (Heriyadi et al., 2021). In the modern era, e-noses mark a pivotal advancement in this ongoing evolution. Equipped with cutting-edge gas sensors, these tools enable accurate, real-time identification of diverse volatile substances and gases. For example, they support uninterrupted air quality surveillance in cities, notifying officials about contaminants like nitrogen dioxide, sulfur dioxide, and ozone (Castelli et al., 2020).

A recent study introduced a novel e-nose system designed for safety monitoring in refinery settings. The work emphasized the early and widespread detection of dangerous gas combinations through a sensor array. The system incorporates sophisticated algorithms for identifying gas types, estimating concentrations, and issuing alerts based on predefined thresholds, all while considering essential variables like oxygen content, temperature, and humidity. This research underscores the promise of affordable e-nose solutions for extensive surveillance of hazardous environments in industrial applications (Pace et al., 2012).

A critical and comparative review of odor assessment methods in landfills was conducted (Capelli et al., 2008). This study provides valuable insights into the complex nature of odor emission assessment through the use of chemical analysis, dynamic olfactory sensing, and e-noses (Gostelow et al., 2001). Every approach has unique features that allow it to reveal the makeup of odors via chemical examination. For example, e-nose systems are used to track surrounding air continuously, offering data on the levels of temporary odor exposure near landfill boundaries and locations (Capelli et al., 2008). Figure 2 shows an example of an e-nose (Eusebio et al., 2016). E-nose systems are also employed for the in-depth assessment of multiple factors linked to environmental odor sources and air contamination. These tools address a wide range of origins, such as landfills, wastewater treatment facilities, incinerators, composting sites, and livestock operations. A detailed examination of these varied uses is comprehensively outlined in Table 2.

5.3 Disease diagnosis

The distinct odor profiles identified by e-noses originate from specific metabolic pathways associated with various diseases. For example, in diabetes, VOCs such as acetone, ethanol, and isoprene are generated as metabolic byproducts of abnormal glucose metabolism (Belizário et al., 2021), reflecting processes like ketogenesis and glycolysis. Similarly, lung infections release VOCs such as nitric oxide and volatile fatty acids due to inflammatory responses triggered by bacterial or viral pathogens. In certain cancers, metabolic dysregulation results in the production of unique VOC signatures (Pan and Yang, 2007). Grasping these unique metabolic pathways and their corresponding VOC patterns will enable the creation of more accurate diagnostic methods utilizing e-noses. This progress will result in quicker diagnoses and enhanced intervention techniques, ultimately leading to better patient outcomes (Xiang et al., 2021).

5.4 Human clinical pathology

The domain of clinical pathology and diagnostic medicine has seen remarkable progress in creating advanced electronic techniques and strategies designed to enhance the precision and efficiency of early disease detection in humans (Tiele et al., 2019). Given the increasing incidence of gastrointestinal (GI) disorders, improving the detection of inflammatory bowel disease (IBD), such as Crohn's disease (CD) and ulcerative colitis (UC), has emerged as a key research priority. IBD is a persistent and recurring disorder characterized by inflammation of the intestines, leading to symptoms like abdominal pain, diarrhea, nausea, exhaustion, and weight reduction. Importantly, UC mainly affects the colon, whereas CD can involve any part of the digestive system, highlighting the need for timely and precise diagnosis to prevent further complications (Zang et al., 2023).

Nevertheless, diagnosing IBD presents several hurdles. Existing methods often involve invasive and costly techniques, such as endoscopic evaluations, imaging of the lower gastrointestinal tract, tissue analysis, and the measurement of inflammatory markers in stool samples (Zang et al., 2023).

Amid the challenges, recent research has unveiled promising avenues for diagnosing IBD, particularly through the analysis of VOCs in exhaled breath. A breath analysis study was conducted using an experimental e-nose (Wolf eNose) and a commercial gas chromatography-ion mobility spectrometer (G.A.S. BreathSpec GC-IMS). The findings underscored the significance of specific VOCs, such as butanoic acid and acetic acid, in differentiating IBD patients from healthy individuals (Tiele et al., 2019).

In the study of urinary tract infections, e-noses have been employed to examine urine samples, both directly and after brief incubation in test tube systems that simulate complex environments (Kodogiannis and Wadge, 2005). One study reported the successful differentiation of infected and non-infected urine samples containing Escherichia coli, Proteus mirabilis, and Staphylococcus species using an e-nose (Esfahani et al., 2016). This highlights the potential of e-noses in revolutionizing medical diagnostics and deepening our understanding of microbial complexity.

Figure 2. (a) E-noses used in the laboratory and (b) EOS 507 in the field

Table 1. Applications of an e-nose for environmental odor monitoring

A place where bad smell is emitted	Sensor type	Description and results	Reference
Landfill areas	6-8 Tin oxide sensor	It creates an e-nose-based system for continuous odor monitoring at specific receptors.	Sironi et al. (2007)
Waste incinerator	Chemosensor system with microbalance quartz sensors	A novel odor vector system utilizing microbalance quartz sensors coated with gas chromatography stationary phases effectively monitored odors in a waste incineration plant. A strong correlation was observed between the specific sensor responses and odor concentrations in the range of 0 to 500 ou/m^3.	Haas et al. (2007)
Compost plant	6 Tin oxide sensor	This study involves real-time monitoring of compost odor emissions using a self-made e-nose consisting of a sensor with six tin oxide gas sensors. The system effectively detects compost odor, estimates the emission rate, and uses supervised data processing methods for identification.	Nicolas et al. (2006)
Poultry farm	12 sensors (MOS, hybrid, tin dioxide, tungsten oxide) with humidity and temperature sensors	A portable e-nose for measuring odors in livestock and poultry farms, which includes 14 gas sensors, a humidity sensor, and a temperature sensor to detect odor compounds in the farm. Artificial intelligence is used for better odor control decisions, predicting odors with high accuracy (R = 0.93).	Pan and Yang (2007)

Detecting VOCs in breath using e-nose technology to diagnose respiratory diseases such as chronic obstructive pulmonary disease (COPD) presents several challenges. The exhaled breath is composed of various VOCs from metabolic processes, environmental exposure, and physiological factors, which complicates the isolation of COPD-specific VOCs. A significant challenge is the background noise present in breath samples, consisting of numerous VOCs not related to the respiratory condition under study (Fens et al., 2011). Additionally, variations in VOC concentrations in breath samples from COPD patients may stem from factors such as disease severity, comorbidities, and individual physiological differences. This variability, coupled with confounding factors like environmental pollutants, dietary influences, and medications, complicates breath analysis. As a result, meticulous consideration and advanced data preprocessing techniques are essential to minimize their impact on the analysis outcomes.

6. Challenges

The growing prominence of e-nose technology for detection and classification has revealed a complex web of challenges across critical fields such as healthcare, environmental monitoring, food safety, and industrial applications. These challenges are multifaceted, involving key issues like sensor sensitivity, selectivity, data accuracy, and system integration, all of which require careful attention to ensure the smooth implementation of e-nose systems. One major hurdle is developing sensors that can accurately detect and distinguish a wide range of VOCs, especially in complex mixtures. Additionally, integrating e-nose systems with existing technologies—such as electronic health records or industrial automation platforms—requires overcoming interoperability and data communication barriers.

Data processing and analysis further complicate matters, as e-noses generate large volumes of data that demand advanced algorithms and machine learning models for accurate interpretation. Acquiring sufficient training datasets for these models, particularly for rare or emerging compounds, remains a significant challenge. Regulatory and standardization issues also hinder widespread adoption, as establishing industry-wide standards for performance and calibration is essential to build trust and ensure reliability. Finally, the high costs associated with research, development, and production limit accessibility, especially for smaller organizations or developing regions. Addressing these challenges requires collaborative efforts among researchers, industry stakeholders, and policymakers to unlock the full potential of e-nose technology and enable its transformative impact across various sectors.

Data challenges. In the era of big data, the information collected varies significantly due to differences in experimental and analytical setups. Obtaining labeled data for e-nose systems is both labor-intensive and time-consuming. Relying on a limited amount of labeled data for classification, especially in large-scale applications, often leads to oversimplified and unreliable models. Additionally, addressing data drift—where data changes over time or comes from diverse sources—poses considerable challenges (Tiele et al., 2019). Ensuring accurate and uniform data collection across various fields is a complex task, which in turn impacts the dependability of classification models.

Technical intricacies. E-nose sensor arrays utilize a variety of partially overlapping sensors to measure volatile compounds in sample headspaces. The primary challenge lies in optimizing these sensors to produce accurate odor fingerprints. Temperature modulation, which depends on sensor temperature and heating voltage, plays a crucial role in e-nose performance. It is essential to carefully differentiate between static and dynamic temperature modulation in temperature-controlled e-nose systems (Ren et al., 2024).

Sample size challenges. Gas detection operates based on changes in electrical resistance within metal oxide sensors. These changes are affected by several factors, such as sensor sensitivity, environmental conditions, sensor lifespan, and device precision. Consequently, new data can differ significantly from older data, making previously developed models ineffective. To tackle this issue, it is crucial to carefully manage both the volume and composition of the data (Tiele et al., 2019). Additionally, the number of samples, the characteristics of the data, and supplementary information can impact the methods used to test the models. If we use too few samples to build a model, the results may become unpredictable and unreliable.

Feature extraction challenges. Feature extraction is a crucial step in e-nose systems, as it involves transforming high-dimensional data into a lower-dimensional subspace. This process retains essential structures and enhances discriminative capabilities (Zhang and Zhang, 2018). Although deep learning methods have been applied to extract features from unlabeled gas samples (Sun et al., 2022), identifying the optimal combination of extracted features and preprocessing techniques remains a significant challenge. Extracting meaningful insights from sensor responses while maintaining data integrity and improving model efficiency is a complex task (Borràs et al., 2015).

7. Conclusions

E-nose technology offers a promising avenue for innovation with vast potential across various sectors, from ensuring food safety to enhancing environmental monitoring and healthcare diagnostics—including the non-invasive early detection of diseases in plants and animals. The adaptability and efficiency of e-noses make them a groundbreaking tool for analyzing complex gaseous mixtures of VOCs, providing comprehensive metabolite profiles that are highly valuable in healthcare settings. While e-nose devices are increasingly gaining attention from healthcare providers, several key challenges in disease diagnosis and identification must be addressed. Developing robust e-nose databases for disease diagnosis, identifying unique VOC signatures, expanding clinical applications, and advancing diagnostic electronics and software are critical steps for widespread adoption and integration into clinical practice.

In essence, continued research and innovation are essential to maximize the accuracy, reliability, and effectiveness of e-nose devices as critical tools in clinical diagnosis. With focused efforts and advancements in various aspects of e-nose technology, these devices have the potential to revolutionize disease diagnosis and monitoring in healthcare settings worldwide. The diagnosis of IBD, including CD and UC, is particularly significant, as early detection is crucial for patients. Current diagnostic methods—such as endoscopy, imaging, histological examination, and inflammatory biomarker analysis—are expensive, time-consuming, and often uncomfortable for patients. The e-nose offers a promising alternative for early and cost-effective diagnosis, potentially replacing these conventional methods.

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Competing interests

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Data availability statement

No original data were used in this review study.

References

Abasiyanik, F., Munekata, P. E. S., Finardi, S., de Souza, C. K., Meinert, C., Pateiro, M., Hoffmann, T. G., et al. (2023). Applications of electronic nose, electronic eye and electronic tongue in quality, safety and shelf life of meat and meat products: A review. *Sensors*, *23*, 672. https://doi.org/10.3390/s23020672

Abdi, H. (2010). Partial least squares regression and projection on latent structure regression (PLS regression). *Computational Statistics*, *2*(1), 97–106. https://doi.org/10.1002/wics.51

Abideen, Z. U., Arifeen, W. U., & Bandara, Y. M. N. D. Y. (2024). Emerging trends in metal oxide-based electronic noses for healthcare applications: A review. *Nanoscale*, *16*(19), 9259–9283. https://doi.org/10.1039/d4nr00073k

Baldini, C., Billeci, L., Sansone, F., Conte, R., Domenici, C., & Tonacci, A. (2020). Electronic nose as a novel method for diagnosing cancer: A systematic review. *Biosensors*, *10*(8). https://doi.org/10.3390/bios10080084

Barsan, N., & Weimar, U. (2001). Conduction model of metal oxide gas sensors. *Journal of Electroceramics*, *7*(3), 143–167. https://doi.org/10.1023/A:1014405811371

Belizário, J. E., Faintuch, J., & Malpartida, M. G. (2021). Breath biopsy and discovery of exclusive volatile organic compounds for diagnosis of infectious diseases. *Frontiers in Cellular and Infection Microbiology, 10*, 564194. https://doi.org/10.3389/FCIMB.2020.564194

Bhati, V. S., Kumar, M., & Banerjee, R. (2021). Gas sensing performance of 2D nanomaterials/metal oxide nanocomposites: A review. *Journal of Materials Chemistry C, 9*(28), 8776–8808. https://doi.org/10.1039/d1tc01857d

Borràs, E., Ferré, J., Boqué, R., Mestres, M., Aceña, L., & Busto, O. (2015). Data fusion methodologies for food and beverage authentication and quality assessment – A review. *Analytica Chimica Acta, 891*, 1–14. https://doi.org/10.1016/j.aca.2015.04.042

Calvini, R., & Pigani, L. (2022). Toward the development of combined artificial sensing systems for food quality evaluation: A review on the application of data fusion of electronic noses, electronic tongues and electronic eyes. *Sensors, 22*(2), 577. https://doi.org/10.3390/s22020577

Capelli, L., Sironi, S., Del Rosso, R., Céntola, P., & Il Grande, M. (2008). A comparative and critical evaluation of odour assessment methods on a landfill site. *Atmospheric Environment, 42*(30), 7050–7058. https://doi.org/10.1016/j.atmosenv.2008.06.009

Casalinuovo, I. A., Di Pierro, D., Coletta, M., & Di Francesco, P. (2006). Application of electronic noses for disease diagnosis and food spoilage detection. *Sensors, 6*, 1428–1439.

Castelli, M., Clemente, F. M., Popovič, A., Silva, S., & Vanneschi, L. (2020). A machine learning approach to predict air quality in California. *Complexity*, *1*, 8049504. https://doi.org/10.1155/2020/8049504

Darvishi, P., Mirzaee-Ghaleh, E., Ramedani, Z., Karami, H., & Wilson, A. D. (2024). Detecting whey adulteration of powdered milk by analysis of volatile emissions using a MOS electronic nose. *International Dairy Journal, 157*, 106012. https://doi.org/10.1016/j.idairyj.2024.106012

Du, S., Xi, G., Chen, X., Wang, X., Ai, B., Wu, S., Li, S., & Zhao, W. (2024). Applications of electronic nose technology in the tobacco industry: A comprehensive review. *Measurement Science and Technology, 35*(3), 032002. https://doi.org/10.1088/1361-6501/ad13e5

Esfahani, S., Sagar, N. M., Kyrou, I., Mozdiak, E., O'Connell, N., Nwokolo, C., Bardhan, K. D., Arasaradnam, R. P., & Covington, J. A. (2016). Variation in gas and volatile compound emissions from human urine as it ages, measured by an electronic nose. *Biosensors, 6*(1), 4. https://doi.org/10.3390/bios6010004

Eusebio, L., Capelli, L., & Sironi, S. (2016). Electronic nose testing procedure for the definition of minimum performance requirements for environmental odor monitoring. *Sensors*, *16*(9), 1548. https://doi.org/10.3390/s16091548

Falasconi, M., Concina, I., Gobbi, E., Sberveglieri, V., Pulvirenti, A., & Sberveglieri, G. (2012). Electronic nose for microbiological quality control of food products. *International Journal of Electrochemistry*, *2012*(1), 715763. https://doi.org/10.1155/2012/715763

Fens, N., De Nijs, S. B., Peters, S., Dekker, T., Knobel, H. H., Vink, T. J., Willard, N. P., et al. (2011). Exhaled air molecular profiling in relation to inflammatory subtype and activity in COPD. *European Respiratory Journal, 38*(6), 1301–1309. https://doi.org/10.1183/09031936.00032911

Gardner, J. W., & Bartlett, P. N. (1994). A brief history of electronic noses. *Sensors and Actuators B: Chemical, 18*(1–3), 210–211. https://doi.org/10.1016/0925-4005(94)87085-3

Gostelow, P., Parsons, S. A., & Stuetz, R. M. (2001). Odour measurements for sewage treatment works. *Water Research, 35*(3), 579–597. https://doi.org/10.1016/S0043-1354(00)00313-4

Guermoui, M., Abdelaziz, R., Gairaa, K., Djemoui, L., & Benkaciali, S. (2022). New temperature-based predicting model for global solar radiation using support vector regression. *International Journal of Ambient Energy, 43*(1), 1397–1407. https://doi.org/10.1080/01430750.2019.1708792

Guo, W. Q., Niu, J. Y., Hong, B., Xu, J. C., Han, Y. B., Peng, X. L., Ge, H. L., et al. (2023). Mesoporous Co_3O_4/In_2O_3 nanocomposites for formaldehyde gas sensors: Synthesis from ZIF-67 and gas-sensing behavior. *Materials Research Bulletin, 164*. https://doi.org/10.1016/j.materresbull.2023.112264

Gupta, A., Dargar, S. K., & Dargar, A. (2023). TiO_2 thick film gas sensor for detection H_2S gas using ANN and machine learning technique. *ICCECE 2023 – International Conference on Computer, Electrical and Communication Engineering*. https://doi.org/10.1109/ICCECE51049.2023.10085220

Haas, T., Schulze Lammers, P., Diekmann, B., Horner, G., & Boeker, P. (2007). A method for online measurement of odour with a chemosensor system. *TRANSDUCERS and EUROSENSORS '07 – 4th International Conference on Solid-State Sensors, Actuators and Microsystems*, 2481–2484. https://doi.org/10.1109/SENSOR.2007.4300674

Heriyadi, B., & Zakri, R. S. (2021). Evaluation and analysis of needs for air ventilation systems in underground coal mine (Case study in underground coal mine, Sawahlunto City). *Journal of Physics: Conference Series, 1940*(1), 012077. https://doi.org/10.1088/1742-6596/1940/1/012077

Iyovo, G. D., Du, G., & Chen, J. (2010). Sustainable bioenergy bioprocessing: Biomethane production, digestate as biofertilizer and as supplemental feed in algae cultivation to promote algae biofuel commercialization. *Journal of Microbial and Biochemical Technology, 2*(4), 100–106. https://doi.org/10.4172/1948-5948.1000032

Jing, Z., & Zhan, J. (2008). Fabrication and gas-sensing properties of porous ZnO nanoplates. *Advanced Materials, 20*(23), 4547–4551. https://doi.org/10.1002/ADMA.200800243

Jońca, J., Pawnuk, M., Arsen, A., & Sówka, I. (2022). Electronic noses and their applications for sensory and analytical measurements in the waste management plants—A review. *Sensors, 22*(4). https://doi.org/10.3390/s22041510

Khodkam, H., & Najafi, B. (2021). The impact of wealth on the amount and type of waste produced and choosing the best place to build a biogas plant using hierarchical. *Journal of Renewable and New Energy*.

Khorramifar, A., Karami, H., Lvova, L., Kolouri, A., Łazuka, E., Piłat-Rożek, M., Łagód, G., et al. (2023). Environmental engineering applications of electronic nose systems based on MOX gas sensors. *Sensors, 23*(12). https://doi.org/10.3390/s23125716

Kodogiannis, V., & Wadge, E. (2005). The use of gas-sensor arrays to diagnose urinary tract infections. *International Journal of Neural Systems, 15*(5), 363–376. https://doi.org/10.1142/S0129065705000347

Megersa, D. D., Cho, H. H., Kim, Y., Gudena, G. T., Lee, J., Bae, J. S., Chae, S., & Yu, H. K. (2023). Position-selective growth of WO_3 nanosheets for NH_3 gas sensors. *Crystal Growth and Design, 23*(5), 3447–3454. https://doi.org/10.1021/ACS.CGD.3C00005

Mehdipour, R., & Ghaffari, A. (2021). Solar dryer performance simulation: Experimental and numerical study. *Journal of Food Process Engineering, 44*(11). https://doi.org/10.1111/JFPE.13875

Mirzaei, A., Lee, M. H., Pawar, K. K., Bharath, S. P., Kim, T. U., Kim, J. Y., Kim, S. S., & Kim, H. W. (2023). Metal oxide nanowires grown by a vapor–liquid–solid growth mechanism for resistive gas-sensing applications: An overview. *Materials, 16*(18). https://doi.org/10.3390/ma16186233

Nicolas, J., Romain, A. C., & Ledent, C. (2006). The electronic nose as a warning device of the odour emergence in a compost hall. *Sensors and Actuators B: Chemical, 116*(1–2), 95–99. https://doi.org/10.1016/j.snb.2005.11.085

Ordoñez-Araque, R., Rodríguez-Villacres, J., & Urresto-Villegas, J. (2020). Electronic nose, tongue and eye: Their usefulness for the food industry. *Vitae, 27*(3), 1–13.

https://doi.org/10.17533/udea.vitae.v27n3a01
Özmen, A., & Doğan, E. (2009). Design of a portable e-nose instrument for gas classifications. *IEEE Transactions on Instrumentation and Measurement, 58*(10), 3609–3618. https://doi.org/10.1109/TIM.2009.2018695
Pace, C., Khalaf, W., Latino, M., Donato, N., & Neri, G. (2012). E-nose development for safety monitoring applications in refinery environment. *Procedia Engineering, 47*, 1267–1270. https://doi.org/10.1016/j.proeng.2012.09.384
Pan, L., & Yang, S. X. (2007). A new intelligent electronic nose system for measuring and analysing livestock and poultry farm odours. *Environmental Monitoring and Assessment, 135*(1–3), 399–408. https://doi.org/10.1007/S10661-007-9659-5
Phukkaphan, N., Eamsa-Ard, T., Chairanit, C., & Kerdcharoen, T. (2021). The application of gas sensor array based electronic nose for milk spoilage detection. *2021 7th International Conference on Engineering, Applied Sciences and Technology (ICEAST 2021) – Proceedings*, 273–276. https://doi.org/10.1109/ICEAST52143.2021.9426263
Qin, L., Gao, H., & Meng, F. (2023). Perovskite-structured $NiTiO_3$ modified NiO gas sensor for xylene detection. *Chemosensors, 11*(5). https://doi.org/10.3390/chemosensors11050264
Ren, L., Cheng, G., Chen, W., Li, P., & Wang, Z. (2024). Advances in drift compensation algorithms for electronic nose technology. *Sensor Review*. https://doi.org/10.1108/SR-06-2024-0554
Romain, A. C., Godefroid, D., & Nicolas, J. (2005). Monitoring the exhaust air of a compost pile with an e-nose and comparison with GC-MS data. *Sensors and Actuators B: Chemical, 106*(1), 317–324. https://doi.org/10.1016/j.snb.2004.07.035
Van Der Sar, I. G., Wijsenbeek, M. S., Braunstahl, G.-J., Loekabino, J. O., Dingemans, A.-M. C., In 't Veen, J. C. C. M., & Moor, C. C. (2023). Differentiating interstitial lung diseases from other respiratory diseases using electronic nose technology. *Springer, 24*(1). https://doi.org/10.1186/s12931-023-02575-3
Schaller, E., Bosset, J. O., & Escher, F. (1998). 'Electronic noses' and their application to food. *LWT - Food Science and Technology*.
Sironi, S., Capelli, L., Céntola, P., & Del Rosso, R. (2007). Development of a system for the continuous monitoring of odours from a composting plant: Focus on training, data processing and results validation methods. *Sensors and Actuators B: Chemical, 124*(2), 336–346. https://doi.org/10.1016/j.snb.2006.12.037
Strike, D. J., Meijerink, M. G. H., & Koudelka-Hep, M. (1999). Electronic noses – A mini-review. *Fresenius' Journal of Analytical Chemistry, 364*(6), 499–505. https://doi.org/10.1007/s002160051375
Sun, J., Tian, L., Chang, J., Kolomenskii, A. A., Schuessler, H. A., Xia, J., Feng, C., & Zhang, S. (2022). Adaptively optimized gas analysis model with deep learning for near-infrared methane sensors. *Analytical Chemistry, 94*(4), 2321–2332. https://doi.org/10.1021/ACS.ANALCHEM.1C05059
Tarighi, J., Khodkam, H., & Ghorbani, A. (2024). A review of optimizing biogas production through pretreatment and pollution reduction. *Journal of Renewable and New Energy*.
Tiele, A., Wicaksono, A., Kansara, J., Arasaradnam, R. P., & Covington, J. A. (2019). Breath analysis using eNose and ion mobility technology to diagnose inflammatory bowel disease—A pilot study. *Biosensors, 9*(2), Article 55. https://doi.org/10.3390/bios9020055
Timsorn, K., Thoopboochagorn, T., Lertwattanasakul, N., & Wongchoosuk, C. (2016). Evaluation of bacterial population on chicken meats using a briefcase electronic nose. *Biosystems Engineering, 151*, 116–125. https://doi.org/10.1016/j.biosystemseng.2016.09.005
Tsymbalenko, O., Lee, S., Lee, Y. M., Nam, Y. S., Kim, B. C., Kim, J. Y., & Lee, K. B. (2023). High-sensitivity NH_3 gas sensor using pristine graphene doped with CuO nanoparticles. *Microchimica Acta, 190*(4). https://doi.org/10.1007/S00604-023-05717-Y
Turner, A. P. F., & Magan, N. (2004). Electronic noses and disease diagnostics. *Nature Reviews Microbiology, 2*(2), 160–166. https://doi.org/10.1038/nrmicro823
Wang, M., Chen, Y., Chen, D., Tian, X., Zhao, W., & Shi, Y. (2024). A food quality detection method based on electronic nose technology. *Measurement Science and Technology, 35*(5). https://doi.org/10.1088/1361-6501/ad29e4
Wawrzyniak, J. (2023). Advancements in improving selectivity of metal oxide semiconductor gas sensors opening new perspectives for their application in food industry. *Sensors, 23*(23), 9548. https://doi.org/10.3390/s23239548
Wilson, A. D., & Baietto, M. (2009). Applications and advances in electronic-nose technologies. *Sensors, 9*, 5099–5148. https://doi.org/10.3390/s90705099
Wojnowski, W., Dymerski, T., Gębicki, J., & Namieśnik, J. (2018). Electronic noses in medical diagnostics. *Current Medicinal Chemistry, 26*(1), 197–215. https://doi.org/10.2174/0929867324666171004164636
Xiang, L., Wu, S., Hua, Q., Bao, C., & Liu, H. (2021). Volatile organic compounds in human exhaled breath to diagnose gastrointestinal cancer: A meta-analysis. *Frontiers in Oncology, 11*. https://doi.org/10.3389/FONC.2021.606915
Xie, D., Zhang, F., Yu, K., Li, X., & Qu, F. (2023). A bimetallic MOF-derived α-Fe_2O_3/In_2O_3 heterojunction for a cyclohexane gas sensor. *New Journal of Chemistry, 47*(17), 7995–8001. https://doi.org/10.1039/d3nj00442b
Yang, N., Li, F., Liu, Y., Dai, T., Wang, Q., Zhang, J., Dai, Z., & Yu, B. (2022). Environmental and economic life-cycle assessments of household food waste management systems: A comparative review of methodology and research progress. *Sustainability, 14*(13), 7533. https://doi.org/10.3390/su14137533
Yao, Y., Wang, Z., Han, Y., Xie, L., Zhao, X., Shahrokhian, S., Barsan, N., & Zhu, Z. (2023). Conductometric $Cr_2O_3/TiO_2/Ti_3C_2Tx$ gas sensor for detecting triethylamine at room temperature. *Sensors and Actuators B: Chemical, 381*. https://doi.org/10.1016/j.snb.2023.133412
Zakaria, A., Md Shakaff, A. Y., Masnan, M. J., Saad, F. S. A., Adom, A. H., Ahmad, M. N., Jaafar, M. N., Abdullah, A. H., & Kamarudin, L. M. (2012). Improved maturity and ripeness classifications of *Mangifera indica* cv. Harumanis mangoes through sensor fusion of an electronic nose and acoustic sensor. *Sensors, 12*(5), 6023–6048. https://doi.org/10.3390/s120506023
Zang, C., Zhou, H., Ma, K., Yano, Y., Li, S., Yamahara, H., Seki, M., Iizuka, T., & Tabata, H. (2023). Electronic nose based on multiple electrospinning nanofibers sensor array and application in gas classification. *Frontiers in Sensors, 4*. https://doi.org/10.3389/FSENS.2023.1170280
Zhang, L., & Zhang, D. (2018). Efficient solutions for discreteness, drift, and disturbance (3D) in electronic olfaction. *IEEE Transactions on Systems, Man, and Cybernetics: Systems, 48*(2), 242–254. https://doi.org/10.1109/TSMC.2016.2597800