Original from: Majchrzak T., Wojnowski W., Dymerski T., Gębicki J., Namieśnik J.: Electronic Noses for Indoor Air Quality Assessment. Electronic Nose Technologies and Advances in Machine Olfaction, ed. Y. Albastaki, F. Albalooshi Bahrajn: IGI Global, 2018, p. 202-223. DOI: 10.4018/978-1-5225-3862-2

Chapter 10
Electronic Noses for Indoor Air Quality Assessment

Tomasz Majchrzak
Gdańsk University of Technology, Poland

Wojciech Karol Wojnowski
Gdańsk University of Technology, Poland

Tomasz Dymerski
Gdańsk University of Technology, Poland

Jacek Gębicki
Gdańsk University of Technology, Poland

Jacek Namieśnik
Gdańsk University of Technology, Poland

ABSTRACT

This chapter presents a proposal of the use of electronic noses in the monitoring of indoor air quality. The main focus is put on the detailed characteristics of today's indoor air quality control methods, the types of pollution in the air, and the development of electronic noses for air testing. Currently, scientists seek methodological and structural solutions that would enable real-time online indoor air control. It has been shown that using electronic noses in this situation is advantageous. In addition, potential uses of these devices are discussed, with particular focus on closed food processing spaces. The authors of the chapter argue that in the near future, the proposed solution could improve the quality of indoor air and thus the health of the users of the indoor environments, as well as the quality of the products prepared there.

DOI: 10.4018/978-1-5225-3862-2.ch010

INTRODUCTION

The composition of inhaled air has a direct impact on human health and well-being which is why it is crucial to examine the air quality in the environment. This applies to both outdoor and indoor air. Indoor air is a gas mixture in rooms, buildings and vehicles, which may be contaminated with compounds emitted by structural elements or room furnishings. Contamination can also come from outside the building, or from other rooms in the building. The composition of indoor air can change over time. It can be influenced by many factors such as the frequency of air exchange in the room, the temperature and the relative humidity of the air, or the manner of air exchange. The degree of air pollution in a room may also depend on the activities performed in it. According to various estimates, a person spends 70% – 90% of their life in closed spaces. These values refer to the time a person spends in houses, flats, public buildings, schools, offices, shops, factories, and means of transport. According to research conducted in the United States, on average people spend 88% of time in buildings, 7% in means of transport, and only 5% outside. In the gas mixture of a given room, there can be organic and inorganic compounds. These compounds can directly affect human health or be involved in chemical reactions that result in secondary pollution, which could be significantly more harmful than primary pollution. The topic of indoor air quality control is one of many fields of studies that have not been sufficiently researched/elaborated on. One of the priority needs for indoor air monitoring is to develop a tool to control the quality of air in real time. Sensory systems utilizing electronic nose technology are the perfect solution.

The authors of this chapter would like to review current and prospect solutions that use electronic noses to control indoor air quality. They believe that, in the first place, such a solution could be used in food processing plants, particularly in places where frying processes occur. The use of electronic noses in such places can not only improve the indoor quality, and thus the health of the people indoors, but also assure the quality of the products prepared there. This work also covers a whole range of aspects related to methods of indoor air quality control, pollution therein, as well as future directions for the development of electronic noses for indoor air testing.

BACKGROUND

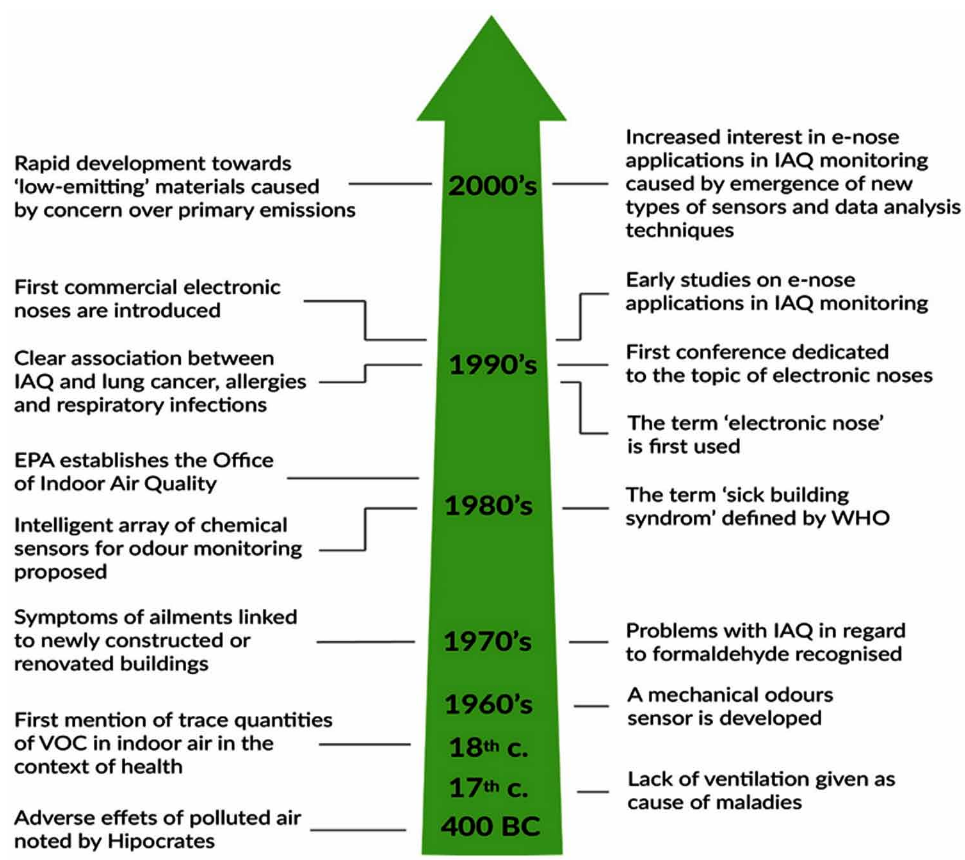
History of IAQ Control

In 1962, a book entitled "Silent Spring" by Rachel Carson was published. Paradoxically, increasing pro-environmental awareness caused indoor air quality not to be of concern to environmental researchers. Interest in indoor air increased drastically after the 1960s. Threats connected with radioactivity or the presence of formaldehyde in the air, as well as the emergence of the term sick building syndrome (SBS) in the late 1970s have brought renewed interest in indoor air quality issues to agencies in the field of environmental quality assessment. On the other hand, it became clear that the condition of indoor air depends on many factors, including the state of the external environment. In the 1970s there was an energy crisis connected with the rise in fuel prices, which forced manufacturers to develop new insulation materials such as PVC, mineral wool or styrofoam. Consequently, this has led to excessive sealing of buildings and accumulation of harmful chemicals in enclosed spaces. In 1982, the World

Health Organization presented the definition of SBS. According to this definition, a sick building is a place where at least 20% of its inhabitants state that staying in it contributes to their ill health. These symptoms disappear when the users leave the building. SBS can also concern specific rooms. The most common symptoms include chronic headaches, skin sensitization, irritation of the mucous membranes of the nose, eyes and throat, trouble with concentration, chronic fatigue and respiratory, digestive, and nervous system problems. It has been noted that staying in a sick building results in decreased employee productivity. The most common SBS cases concern older buildings and rooms. This syndrome also affects modern, so-called 'airtight' buildings equipped with air conditioning and mechanical heating systems. A timeline of the development of IAQ control methods and electronic olfaction is depicted in Figure1.

Currently, reliable methods for assessing indoor air quality are being sought. The basic criterion for these methods is low price of a single measurement, short analysis time, adequate sensitivity and versatility of the proposed solution. At the present time, there is no one universal method that would meet the aforementioned requirements. Depending on needs, it is possible to use sensory analysis, gas analysers or instrumental analysis techniques. The most commonly used instrumental analysis technique is gas chromatography.

Figure 1. Development of IAQ analysis and electronic noses



Sources of IA Contaminants

According to the information provided by US EPA, there are over 1000 different internal sources of pollution emission into the indoor air. Nearly 60 types of sources are responsible for the emission of carcinogens. The most frequently mentioned and most important sources of harmful substances include: furniture components, floor and wall coverings, thermal insulation, decorative or maintenance materials, but also emissions from heating, combustion of oil, coal, gas and tobacco, and emission from ventilation systems. It is worth noting that the composition of the air inside the building is also influenced by emission sources outside it.

The atmospheric air in the vicinity of a building may have an adverse effect on the quality of the indoor air. Airborne impurities enter a building through its ventilation system. The composition of the air entering the building depends on the area where the building is located. It could be an agricultural, industrial or urbanized area. The building can also be located near landfill sites, highways, sewage plants or airports. Indoor air quality can also be influenced by factors such as atmospheric conditions: wind strength and direction, temperature and insulation.

Selecting suitable materials for construction does not only affect the strength of a structure, its capacity or thermal insulation, but also the indoor air quality. Contamination sources include paints, varnishes and structural coatings and preservatives. For example, building materials such as concrete or bricks may be the source of radioactive radon emission. Wood materials (particle boards, plywood) can emit formaldehyde which is present in synthetic resins, into the indoor air. Indoor air pollutants which are associated with certain types of rooms are listed in Table 1.

As mentioned above, the quality of indoor air may be influenced by the emission of pollutants from materials and objects in the room or the migration of pollutants from the outdoor air. However, situations in which indoor air quality may be related to activities performed inside the building must be taken into account. Depending on their purpose, rooms can be divided into residential, office, or public utility (hospitals, museums, schools, or churches). Rooms can be used for sleeping, hygiene, health care,

Table 1. Indoor air pollutants occurring in different types of rooms

Type/Function of a Room	Indoor Air Pollutants
Offices	VOCs, BTEX, chlorinated hydrocarbons and halogenated organic compounds (Chao & Chan, 2001)
Museums	BTEX, naphthalene, benzoic acid, limonene,SO_2, NO_2, O_3, formic acid, acetic acid (Krupińska, Van Grieken, & De Wael, 2013), formaldehyde, styrene, benzaldehyde (Schieweck, Lohrengel, Siwinski, Genning, & Salthammer, 2005)
Libraries	VOCs, formaldehyde (Chao & Chan, 2001), SO_2, NO_2 (Andretta, Coppola, & Seccia, 2016)
Temples and churches	NO_2 (Worobiec et al., 2006), formaldehyde, BTEX (Zhang, Chen, Li, Yu, & Zhao, 2015)
Schools	VOCs, SVOCs, polychlorinated biphenyls (Herrick, Stewart, & Allen, 2016), D- limonene, formaldehyde, acetic aldehyde, benzene
Hospitals	VOCs, radon (Śmiełowska, Marć, & Zabiegała, 2017), N_2O, formaldehyde, glutaraldehyde, ethylene oxide (Zeiger, Gollapudi, & Spencer, 2005), BTEX (Dascalaki, Lagoudi, Balaras, & Gaglia, 2008), acetaldehyde, phthalates (Wang et al., 2015)
Elderly care centres	Nitrogen oxides, formaldehyde, VOCs (Mendes et al., 2015)
Underground parking	BTEX (Marć, Śmiełowska, & Zabiegała, 2016)

entertainment, as well as for preparing and consuming food. In this chapter, the authors focus on indoor air quality in food preparation and processing facilities.

Indoor Air in Food Processing and Distribution Areas

There are many types of food processing and distribution areas. Three of them should be highlighted in terms of potential indoor air contaminant sources:

IAQ in Greenhouses

In closed food production halls, especially greenhouses, the quality of indoor air may depend on the agricultural practices that are carried out there. Pollution emissions may depend on parameters such as temperature, humidity, the stage of plant development, treatments (weeding, fertilization) and the applied plant protection products. It has been shown that some pesticides may be present in indoor air and dust (Roinestad, Louis, & Rosen, 1993). Pesticides and their metabolites can cause various diseases in humans and be dangerous to nervous, digestive or reproductive systems.

IAQ in Warehouses

Food should be stored and transported under specified conditions. However, it is often the case that parameters such as high temperature or excessive humidity are permanently or periodically present in food storages. Under the influence of these parameters, and as a result of the presence of bacteria, food can become spoiled. The direct effect of food degradation is its lower quality, but also reduced quality of air inside the storage area. Spoilage organisms typically present in food are fungi and bacteria. For example, under aerobic conditions at low temperatures organisms such as *Pseudomonas* and *Bacillus* can develop. When access to oxygen is limited, yeast, *Enterobacteriaceae*, *Photobacterium*, clostridia, various fungi and lactic acid bacteria (LAB) can proliferate. The amount and type of microorganisms responsible for food spoilage depend primarily on temperature, oxygen level, pH and substrate (growth medium). Volatile compounds, including inorganic gases and microbial volatile organic compounds (MVOCs) are a byproduct of microbial nutrition. The inorganic compounds resulting from microbial activity are hydrogen sulphide, ammonia and carbon dioxide. The MVOC group includes organic sulfur compounds such as dimethyl disulphide, trimethylamine, certain esters, organic acids, diacetyl or biogenic amines. These compounds not only cause the unpleasant odor associated with food spoilage, but may also exhibit toxic and carcinogenic properties. It is also dangerous to inhale air where hyphae and bacteria are present. In addition, in some warehouses, silos or grain elevators, there is a risk of inhaling particles emitted from dusty materials – for example from flour. In such cases, workers' respiratory tracts are the most vulnerable, and symptoms such as dyspnea or cough can appear. It is possible for diseases such as pneumoconiosis to emerge. In order to improve safety, workers in this type of food warehouses should use personal protective equipment.

IAQ in Restaurants and Food Processing Plants

In restaurants, the quality of indoor air can be influenced primarily by the way food is prepared. Depending on the profile of the restaurant and the frequency of food preparation, there can be emission of chemical compounds which are harmful and generate unpleasant odor. The following parameters can determine the type of emitted compounds: type, quality and freshness of the food used, the type of food preparation process (cooking, frying, smoking) and the type and quality of the frying oil. Depending on the type of restaurant, the composition of the gases produced during cooking may vary. Comparing food processing procedures such as grilling, immersion cooking, steam cooking and classic cooking shows that the worst air quality can be observed in restaurants where food is prepared by grilling and frying. It has been noted that in this type of restaurants the highest concentration of formaldehyde, benzene, toluene and chloroform is present. In addition, PM_{10} and $PM_{2,5}$ particles, which are hazardous to human health, are emitted. It is worth noting that some of the determined chemical compounds, for example formaldehyde, are described as being emitted from building materials and furniture in a given space more often than from food preparation processes. However, it is clear that food preparation processes have a direct effect on the quality of indoor air and therefore on the comfort of the users – both employees and customers. Some compounds the presence of which in the air is associated with particular food processing and production areas are listed in Table 2.

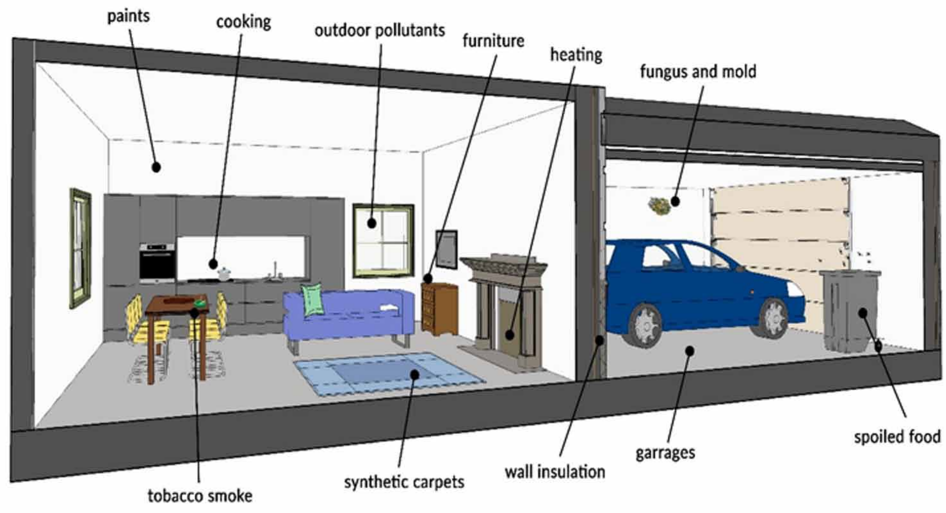
INDOOR AIR CONTAMINANTS

World Health Organisation in its guidelines regarding chemicals that are commonly present in indoor air lists those which and can be potentially harmful to human health, e.g. benzene, carbon monoxide, formaldehyde, naphtalene, nitrogen dioxide, polycyclic aromatic hydrocarbons (PAHs), trichloroethylene and tetrachloroethylene. Apart from outdoor pollutants which make their way into indoor environment the main sources of these volatiles are building materials and furniture, and also the burning of fuel either for cooking or heating. Mentioned above are chemical compounds that are considered to pose risk to public health due to their properties or abundance. Some sources of indoor air contaminants are depicted in Figure 2.

Table 2. Chemical compounds occurring in indoor air associated with various food processing and production areas

Food Industry and Food Production Area	Compounds
Frying process	1-pentanol, hexenal, furfuryl alcohol, (E) -2- heptenal, 5-methylfuran, (E) -2- octenal, nonanal, (E) -2-nonenal, hexadecanoic acid and pyrazine (Takeoka, Perrino, & Buttery, 1996).
Meat and meat products production	Acetone, Carbon disulphide, Dimethyl disulphide, Dimethyl trisulphide, Ethanol, Ethyl acetate, Heptane, Hexanal, Hydrogen sulphide, Methyl benzoate, Methyl thioacetate, Toluene, 2,3-Butadienol, 2,5-Dimethylpyrazine, 2-Heptanone, Methanol, Methoxybenzene, 5-Methylpyrimidine, 2-Octanone, 2-Octenal, Phenol, Phenyl ethyl alcohol, Isoamyl acetate, methanethiol (Alexandrakis, Brunton, Downey, & Scannell, 2012; Senter, Arnold, & Chew, 2000)
Beverage production (distilleries)	Ethanol, octyl acetate, nonanal, limonene, linalool, 1-hexanol, benzaldehyde, ethyl cinnamate, γ-Decalactone, 2,4-decadienal, 2,6-nonadienal (Śliwińska, Wiśniewska, Dymerski, Wardencki, & Namieśnik, 2015)
Food storage (including spoilage)	Esters, trimethyl amine (TMA), NH_3, H_2S, dimethyl disulphide, 2-methoxy-phenol, trichloroanisol (Gram et al., 2002)
Mould and fungus in food industry	3-methylfuran, Dimethyl disulfide, Limonene, Pinene, 1-hexanol, 1-pentanol, 2-methyl-1-propanol, 2-methyl-1-butanol, 1-octen-3-ol, geosmin, 2-methyl-isoborneol, 3-octanone, 2-heptanone, 2-pentanone (Kuske, Romain, & Nicolas, 2005)

Figure 2. Some sources of indoor air contaminants



The determination of the above-mentioned compounds does not provide exhaustive information regarding indoor air quality. In reality, the constituents of air present at low concentration levels are numerous and their impact on human wellbeing is difficult to quantify, especially when one considers the effect not of a single gaseous substance, but of their complex mixture. Although construction and synthetic materials are the main sources of volatile compounds in indoor environments, emissions from processed and unprocessed food, potted plants, etc., should not be disregarded. For that reason, summary parameters, e.g. total volatile organic compounds (TVOC), were introduced, which, however, are not sufficient to determine air quality. An alternative approach is to measure the ambient air holistically, using an array of various sensors – electronic noses. This is especially important because of the growing popularity of the concept of so-called green buildings. Green buildings are buildings that are designed to promote efficient use of energy, water and materials, as well as sustainability. According to US EPA, green buildings are "the practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building's life-cycle from siting to design, construction, operation, maintenance, renovation and deconstruction." (EN Standard 15251, 2007). It appears that staying in this type of buildings can have a negative effect on human health and well-being. Despite the fact that most studies have shown higher air quality in green buildings compared to that in traditional construction, the risk to human health cannot be ruled out for the former. It is believed that some "green" practices such as use of waste-based materials or economical ventilation of rooms may adversely affect indoor air quality. Using new construction materials or new ventilation solutions may lead to the emergence of new, hitherto unknown, air pollutants. Therefore, the authors of the chapter believe that the most appropriate way to monitor indoor air quality would be to use sensor systems. In order to develop a universally applicable solution, suitable both for "green" solutions and traditional construction, full air quality information should be used. One of the most important challenges would then be the extraction and statistical analysis of data, as well as development of a monitoring network in the building, which would provide reliable and reproducible results.

CLASSICAL IAQ ASSESMENT METHODS

Sensory Analysis

Sensory analysis is a measurement method that uses one or more senses such as sight, taste, smell or touch. Due to the direct nature of the measurement, sensory analysis is a commonly used tool for evaluating people's reactions to stimuli in the environment (Lewkowska, Dymerski, Gębicki, & Namieśnik, 2016). In order to understand in detail how the quality of internal air can be determined using this method, it is necessary to understand how the human sense of smell works. Olfactory receptors are located in an area of about 3 cm^3 in the nasal mucosa. The olfactory epithelium contains bipolar neurosensory cells, basal cells and sertoli cells. Bipolar neurosensory cells together with mitral cells form the olfactory bulb. Mitral cells are responsible for the supply and discharge of nerve impulses. They are connected with other neurons which are located in the hematoma. There, information concerning smell is recorded and processed.

Due to the fact that sensory analysis is based on the subjective assessment of the panelist, it is necessary to adhere to the appropriate measurement principles. Following the rules and using statistical methods can lead to reliable and reproducible results. Sensory analysis can be carried out in many ways. In terms of procedure, sensory analysis methods can be divided into four basic groups: differential, scaling, descriptive analysis and threshold determination. In differential methods, a group of trained panelists determines the similarities and differences between test samples and a reference sample. The intensity of the differences is not assessed, only a similarity or dissimilarity is indicated. Scaling methods are used to determine the scale of odour intensity differences. Numerical or graphical scales are often used to present results. Descriptive analysis is based on allocating the appropriate descriptors, that is the characteristics of the odour, to a specific odour. One of the most commonly used descriptive methods is Quantitative Descriptive Analysis (QDA), where panelists themselves create a list of descriptors they use to describe the tested sample. This measurement is therefore individual and simultaneous. Threshold determination techniques are used to detect or identify substances based on their odour detection thresholds.

Sensory analysis methods are used in indoor air assessment and can be used to identify the source of odorous compounds emissions in various rooms, such as offices, department stores or classrooms. In addition, sensory analysis may be complementary to gas chromatography tests. Olfactometry has also been used to assess indoor air quality in livestock buildings.

Total Volatile Organic Compounds (TVOCs) Measurement

In the past, the commonly used parameter for assessing indoor air quality was the concentration of carbon dioxide. Nowadays, this type of solution would not work, because there are numerous other chemical compounds in the air, mainly volatile organic compounds. The measurement of the concentration of these compounds is currently an indicator of indoor air quality. One of the most common parameters used to determine the concentrations of VOCs is the parameter termed Total Volatile Organic Compounds (TVOC). Because of the simplicity of measurement and relatively short analysis time, the TVOC determination is used in IAQ.

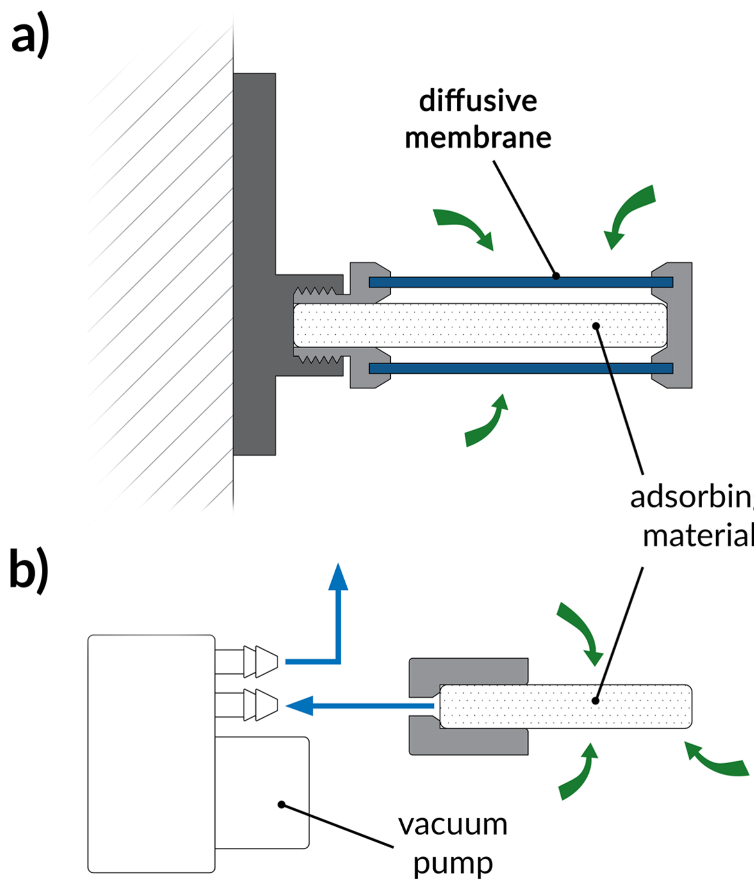
By determining TVOC values, comprehensive information on volatile organic compounds is obtained. This brings with it legitimate advantages, such as a holistic approach to the problem. The TVOC parameter describes the nature of a gas mixture quantitatively. It provides quantitative information even when the qualitative composition of the mixture changes. At the same time, it is one of the biggest limitations of this solution. Without knowing the composition of indoor air, we cannot determine the impact of chemicals on human health. Similarly, identifying the source of pollution can be difficult. It should be emphasized that only in an ideal scenario would TVOC represent the total concentration of volatile organic compounds present in an indoor air sample. In reality, the detectors such as FID, PID, or PAS are used to determine the TVOC parameter. In the first case, by using a flame ionization detector, a response signal is obtained through combustion of the substance in a hydrogen flame. Although the FID detector's response is very stable, not every volatile organic compound can give an analytical signal. In addition, two different VOCs with the same amount of carbons in the molecule, at the same concentration levels in the sample, can generate different signals. However, these detectors are most often used to determine the TVOC parameter. Using photoionization detectors (PIDs), it is possible to generate organic compound ions under the influence of UV radiation. For many VOCs, they are more sensitive than FIDs, but may be less stable, and compounds such as chlorinated VOCs are not ionized. A photo-acoustic (PAS) sensor can also be used to determine TVOCs. The signal is obtained as a result of both the change in vapor concentration of organic compounds caused by infrared radiation, and the temperature increase measurement. In this sensor, a change in acoustic wave frequency causes changes in the intensity of infrared radiation. These however are not as popular as older types detectors, since water vapor or methane concentration can lead to interference. It is worth emphasizing that usually these detectors are calibrated for one pure substance, such as n-hexane or toluene, thus the measurement may not produce sufficiently reliable results when measuring TVOC for a more complex matrix.

Passive and Active Sampling Coupled With Gas Chromatography

One of the major challenges in analyzing indoor air pollutants using gas chromatography is the method of sampling. When choosing a sampling technique, one should aim to obtain the most representative sample, enrich the analytes and reduce the matrix effect. Depending on the needs, the sampling method should allow the measurement of pollutants either for a long period of time (days, weeks, months), or for the moment in which the sample is being taken. The first solution involves continuous exposure to a given contaminant, while the second solution can be used for abnormal situations. Therefore, two main methods for sampling gas in closed spaces have evolved: the passive method and the active method. The principle of operation of both sampling methods is depicted in Figure 3.

Passive dosimetry is based on the extraction of analytes in the air without the use of forced airflow. This type of sampling is characterized by high susceptibility to air movements therefore its use in the assessment of outdoor air is very limited. However, because dosimeters are small devices that do not need to be plugged in and do not produce unpleasant sounds, they can be used indoors without disturbing the users of the room. Passive dosimetry is just as accurate as the active methods. The main drawback of this type of sampling is the relatively low sampling frequency. The result is most often presented as a time-weighted average (TWA) concentration. This type of approach is better suited for determining the long-term impact of harmful substances on the health of room users than the short-term concentrations measurement. For passive measurements, dosimeters are used, whose principle is based on diffusion or permeation phenomena. However, it should be remembered that the method of sampling depends mainly on the aim that is to be achieved. If we strive to determine the average concentration, passive dosimetry is more appropriate, but if we want to determine concentration levels over time, the active methods are better.

Figure 3. Development of IAQ analysis and electronic noses passive (a) and active (b) methods of sampling of volatile compounds present in the indoor environment



Active methods use forced air movement. Air is collected in sealed bags or containers, or passed through sorption tubes. Containers which will hold the air must be made of a possibly neutral material, such as Tedlar. However, a sample taken in this way is very diluted – most of the air in the container is inert. Therefore, a better solution is to pass the air through special sorption beds located in chemically inert tubes. The thus obtained analytes are either eluted with a solvent, or removed from the sorbent by thermal desorption. The most commonly used sorbents are 2,6-Diphenyl-p-phenyleneoxide (Tenax TA), molecular sieves (Carbosieve) or cross-linked polystyrene (Chromosorb). An important advantage of sorption tubes is their small size and storage possibility. By using thermal desorption, which is carried out directly in the chromatography system, the number of steps at the sample preparation stage is limited, which influences the duration of analysis as well as limits the possibility of errors. Such solutions can be used to determine pesticides and insecticides in indoor air, VOCs or polychlorinated biphenyls and fragrance allergens.

There are also other methods of sampling for GC analysis, including emission test chambers (ETCs) and field and laboratory emission cells (FLECs). In some cases it is worth using a natural sorbent present in most closed spaces, i.e. dust. For this purpose, a matrix solid-phase dispersion (MSPD) or solvent

Table 3. Advantages and disadvantages of various techniques used in IAQ analysis

Method	Main Advantages	Main Disadvantages
Sensory analysis	• Ease of use • Direct evaluation of quality • Relatively low cost • *In-situ* method	• Low sensitivity (detection threshold) • Lack of qualitative and quantitative information • The need to train a team of panellists • Sensory fatigue
TVOC	• Holistic analysis of indoor air • Ease of use • Measurement independent form qualitative change of air composition	• No quantitative identification of pollutants • Detectors calibrated to pure standards • High energy consumption • No information regarding toxicity
GC (passive sampling)	• Relatively small size • Low power consumption • No detrimental effect on the occupants of a room	• Susceptible to impact of air flow (drafts) • No possibility to register changes of concentration in time • Low sampling frequency • Poor enrichment of analytes
GC (active sampling)	• Good enrichment of analytes • High sampling frequency • Possibility to register changes of concentration in time (registering incidental emissions)	• Relatively expensive • Large sampling devices • Constant power consumption • Labour-intensive
Electronic nose	• Relatively small size • Capable of qualitative and quantitative analysis (depending on design) • Holistic evaluation of air quality • *In-situ* method • No sensory fatigue • Short time of a single analysis • Possibility to develop a maintenance-free solution	• Sensor drift • Moderate sensitivity • Need for statistical analysis of the response signal • Not suitable for screening of indoor air

extraction with solid-phase extraction (SPE) can be used to prepare a sample for analysis. Advantages and disadvantages of various analytical methods used in IAQ control are listed in Table 3.

ELETRONIC NOSES IN IAQ EVALUATION

Identification of Particular Compounds

One of the concepts of using electronic noses in indoor air monitoring is determining the concentration of particular harmful gaseous compounds. Unlike in the case of devices equipped with a single chemical sensor, such as a carbon monoxide sensor or a methane sensor, using a set of sensors allows multiple compounds to be analysed simultaneously. Additionally, using statistical data processing, the concentration of a chemical compound can be determined with greater accuracy and reliability. One of many examples of sensor systems used to determine the concentration of individual substances is a prototype built at Karlsruhe Forschungszentrum (Bender, Barié, Romoudis, Voigt, & Rapp, 2003). This device is equipped with 8 surface acoustic wave (SAW) detectors and is able to detect naphthalene, n-decane, styrene, xylene, ethylbenzene, n-octane, toluene, tetrachloroethene, benzene, n-heptane, tetrachloromethane, n-hexane, acetone, dichloromethane, ethanol and methanol at low- and sub-ppm concentrations. Before the analytes were introduced into the sensor chambers, they were enriched in a preconcentration unit - a sorption trap. The trap was made from a glass tube or PTFE (depending on the process conditions), where the sorption material was Tenax TA. The measuring system (without the preconcentration unit) is small in size – 6 cm x 3 cm. In addition to determining the concentration of the selected chemical compounds, a chemometric analysis was performed, in which PCA and LDA were used. The great advantage of this device is its sensitivity, which makes it possible to detect indoor air pollution below their perceptibility thresholds. In addition, the SAW sensors have a long life span, so they can be used for long-term, continuous indoor air monitoring.

A similar solution which used SAW sensors was presented at the 9th IEEE Conference on Nanotechnology in 2009 (Yao, 2009). A device composed of 7 piezoelectric sensors was used to determine the concentration of 5 volatile chemicals: ammonia, trimethylamine, methanol, ethanol and acetone. Two-way hierarchical cluster analysis was used to determine which sensors exhibited the highest sensitivity to the selected analytes. Under real conditions, it would be necessary to have several "electronic nose" devices placed throughout the building in order to comprehensively monitor indoor air quality. The devices, although identically constructed and equipped with the same set of sensors, can produce different output signals even if they are exposed to the same gas mixture. It is therefore necessary to properly calibrate the devices. For this purpose, global affine transformation (GAT) and Kennard-Stone sequential algorithm (KSS) can be used. The calibration was done for six devices: one served as "master" and the other was "slave". "Slave" devices were calibrated based on the information received from the "master" device. As a result of the on-line sensor calibration, each set of sensors worked with similar accuracy.

One of the hitherto proposed solutions has been the use of a matrix of 7 sensors with quartz crystal microbalance (QCM) to detect 23 different compounds belonging to alkanes, aromatic hydrocarbons, chlorocarbons, ketones and alcohols (Seyama, Sugimoto, & Miyagi, 2002). The sensors were covered with an organic film using plasma-deposition technology. The tests were conducted for two rooms: one with fresh air and the other – a smoking area. QCM sensors grant a significantly higher sensitivity than commercially available VOC analyzers, where MOS or PID sensors are most commonly used. Due to the sensitivity of detection, electronic noses with such sensors could be used in areas where very clean air is required, such as in cleanrooms, in some laboratories or in hospital rooms.

Holistic Approach

Due to the very complex composition of the gas mixture that is indoor air, it is difficult to determine the concentration of all pollutants, especially if there are chemical reactions leading to the formation of secondary compounds. In addition, there may be emerging contaminants in the indoor air, maximum permissible levels of which have not yet been determined. From a legal point of view, monitoring of the concentration of the chemical compounds specified in the regulations is justified. However, taking the health of the room users into account, holistic analysis of indoor air is also necessary. Then, such parameters as air quality indexes can be referred to. The obtained value does not provide information on the amount or type of the chemical compounds, but gives a simple signal which shows whether the air is of bad or good quality.

An important element in indoor air quality assessment is the monitoring of pollution in a building. However, it is important to remember that the quality of air in a room depends mostly on the materials used to build and furnish it. By controlling the quality of materials such as structural elements, thermal insulation, floor coverings or paints and varnishes used to finish surfaces, the state of the environment inside the room can be influenced. Currently, the use of paints and varnishes which contain volatile solvents or toxic protective substances is restricted in order to limit the emission of harmful or odorous chemical compounds. Therefore, acrylic paints or natural protection agents, such as linseed, are used. There are several solutions for using sensor systems to evaluate the quality of materials used in building a room. One example may be the use of an electronic nose with 32 sensors made from conductive polymers (Aromascan 32S) to identify indoor paints based on acrylic, alkyd, polyurethane and vinyl resins (Ramalho, 2000). The obtained results were compared with those obtained using gas chromatography and olfactometry. The measurements were carried out 3 days after the application of paints on the surface, which is a relatively short period. With longer exposure of the paint to room conditions such as forced airflow, lighting, or the presence of reactive inorganic compounds, it is possible that the impact of such a paint on the environment would be greater. Tests were carried out for eight pure compounds most often emitted from building materials: toluene, ethylbenzene, propylbenzene, styrene, phenylacetylene, ortho-xylene, meta-xylene, para-xylene, with the use of an electronic nose (Xu, He, Duan, Wu & Wang, 2016). These were some of the first uses of electronic noses in evaluating indoor air quality. Due to the fact that the experiment was not very advanced, pure chemical substances dissolved in synthetic air were analyzed and it cannot be determined whether this solution could in future be used for routine air quality monitoring.

One of the most commonly studied indoor air pollutants is formaldehyde. This is mainly due to the fact that it is a very volatile chemical that is suspected to be carcinogenic, and can lead to other health conditions, such as nervous system or immune system diseases. Classically used methods to identify formaldehyde in the indoor air are gas chromatography, FTIR and MS. By using these methods, low detection limits are possible, but the cost of analysis, the necessity of sampling, or relatively long analysis time, exclude such methods from routine, real-time measurements of formaldehyde concentration in the indoor air. The problem with chemical sensors used to detect volatile organic compounds is that they are not selective. The presence of compounds such as terpenes, which may come from natural sources (e.g. α-pinene) may impair the correct determination of formaldehyde concentration. The solution may be to use a sensor array and an electronic nose, and extract the results in such a way that information is obtained about the concentration of only one substance (Lv, Tang, Wei, Yu, & Huang, 2007). For this purpose, a miniature electronic nose system was used and the data was processed using artificial neural networks. Based on the results, formaldehyde can be detected at concentrations below ppm, even if there are impurities such as ethanol, toluene, acetone or α-pinene in the indoor air. However, it is important to remember that indoor air is a more complex matrix, thus it is important to continue this type of research in this area.

Another approach to assessing odour nuisance is the use of sensor systems in a composting hall (Nicolas, Romain, & Ledent, 2006). Nicolas et.al., similarly to previous studies, used olfactometry to compare results. The device they used was a prototype electronic nose equipped with 6 MOS sensors. It was proved that unsupervised methods (PCA) cannot be used to identify all sources of odour and it is necessary to use methods that utilize the learning stage. Due to the fact that during the storage of compost there is a variety of additional activities, it was attempted to take into account different sources of compound emissions that can affect the signal generated by the sensors. Four potential sources were identified: compost heap, vehicles and other machines in the composting facility, neutralizer added to the compost, and background. For this purpose, a discriminant function analysis (DFA) was used. Summarizing the study, it can be concluded that electronic noses can be used to detect sources and to determine the degree of odour nuisance in closed spaces.

Another specialized application is detecting fires using electronic noses. It is customary to use detectors equipped with single sensors for fire detection. They may, however, react to the presence of various chemical compounds, which did not originate from fires. This can lead to false alarms, which in the case of industrial plants, offices or public buildings, involves taking appropriate actions such as evacuation or shutdown. Persaud's research team dealt with separating and distinguishing the sensor response signal associated solely with the occurrence of a fire. They developed an electronic nose for this purpose in 2006 (Scorsone, Pisanelli, & Persaud, 2006), This device consisted of 8 sensors made of conducting polymers (CP) and the entire sensor array was the size of a coin. A specially prepared test kit was used in the study, consisting of a reaction chamber and a sampling system. Conditions present during a fire were simulated in the reaction chamber. Smoke was directed to a sampling system in which the gas stream was separated. Smoke samples were directed to a commercial carbon monoxide detector – a MOS sensor, electronic nose, optical sensor and the Fourier transform infrared spectrometer (FTIR). Furthermore, by placing an SPME fibre in the sampling system, it was possible to analyse the smoke composition using GC-MS. Based on the SPME-GC-MS analysis, it was possible to select markers for the test fires: smouldering cotton, wood, paper, cigarette smoke and flaming polyurethane. The electronic nose was initially used to determine the sensitivity to individual fire markers, and then the ability to classify the selected fires was tested using PCA. Using the electronic nose, it was possible to identify a fire event and a non-fire event. It is especially important to distinguish cigarette smoke from fire smoke, as the most common cause of false alarms is the presence of cigarette smoke in indoor air.

In addition, as mentioned above, indoor air quality also applies to means of transport such as cars, trains, aircraft, ships, etc. Quality control of particular vehicle equipment, such as vehicle seats, can significantly improve the quality of use of these vehicles. An example of the use of electronic noses for the characterization of volatile organic compounds emitted from car seat foams is research conducted by Morvan *et al.* (Morvan, Talou, & Beziau, 2003). Polyurethane foams, which are commonly used as filling in car seats, were used as samples. They differed in origin (3 different manufacturers), colour, moulding (warm or cold) and place of application (different parts of the seat). The NST3320 commercial electronic nose (Applied Sensor AG, Germany) with 11 MOS sensors and 11 MOSFET sensors was used for the characterization of volatile fraction. The obtained results were juxtaposed and compared with ATD-GC-MS and sensory analysis. It was shown that similar information can be obtained using an electronic nose and using a sensory panel. Researchers believe that information obtained using a sensor system provides less quantitative information than sensory analysis. In addition, an unsatisfactory correlation between the identified compounds and the sensor response signals was obtained. These studies may be proof that electronic nose systems cannot completely replace advanced instrumental analysis or the work of panellists in sensory analysis. They may, however, be supplementary to research, or be used for preliminary screening of a sample. It is estimated that concentrations of pollutants such as carbon monoxide, hydrocarbons, VOCs and nitrogen oxides in vehicles are significantly higher than the standards set by Occupational Safety and Health Administration (OSHA) and World Health Organization (WHO). This is primarily due to the materials used for the interior of vehicles, the internal temperature and the air exchange system. Air quality in vehicles can be influenced by parameters such as temperature, humidity and chemical composition of the air. By using a sensor system equipped with temperature sensors, humidity sensors, a CO2 sensor and a VOC (Indoor Air Quality Sensor - IAQ sensor) classes of air quality in vehicles can be distinguished (Szczurek & Maciejewska, 2015). It has been shown that the quality of air that the driver and passengers breathe changes with time spent in the car.

Identification of Microbal Volatile Organic Compounds (MVOCs)

The dampness in a room, as well as appropriately high temperature and growth medium may result in the emergence of germs indoors. Due to bacteria and fungi residing on walls, furniture, carpeting, etc., harmful compounds, such as mycotoxins and microbial volatile organic compounds (MVOCs) may be emitted. What is very dangerous is the appearance of fungi indoors. Some of them may be visible, for instance sporocarps of certain fungi, but the vast majority of fungi are not easily recognizable. In most cases, scientists focus on air pollution caused by emissions from surfaces of furniture or building materials. Volatile pollutants, which develop due to the activity of living organisms, are often forgotten. Microbial volatile organic compounds (MVOCs) include mostly alcohols, terpenes, ketones, furans and sulfur compounds. Part of them is not harmful to human health, however they can act as markers of fungi occurrence indoors. Such chemical compounds may be identified with a variety of instrumental techniques. Sensor systems enable us to carry out real-time monitoring. Existing research proves the usefulness of electronic noses in identifying certain fungi strains. The majority concerns the analysis of foods such as cereal and cereal products. There are, however, reports in the literature, in which mold detection indoors was the subject of research. Using an electronic nose equipped with 15 MOS sensors and employing chemometrics such as LDA, KNN or LS enabled to detect and classify five fungi which can commonly be found in indoor environments. Persuad's team used a system with 32 sensors to detect dry rot wood decay fungi. These types of fungi occur mostly in old, antique indoor environments with wooden construction elements. Using microextraction in a stationary phase as a method of retrieving and enriching MVOCs proved to be an interesting solution. Another application of an electronic nose was using commercial electronic noses MOSES II and KAMINA to assess the quality of indoor air in which MVOCs occur. In artificial conditions, on agar media, three types of mold were cultured: *Aspergillus niger*, *A. versicolor* and *Cladosporium sphaerospermum*. Analysis of the main components enabled to detect the mold, however the precise assessment of the strain of fungi was difficult. What is important, detecting MVOCs in indoor air may in practice facilitate an early detection of mold indoors, thereby allowing to take remedial measures.

Application in Frying Processes

Some volatiles in the indoor environment can be of fungal or bacterial origin, being emitted either by mold or microorganisms responsible for decomposition of food products. Volatiles from fungi and mold developing on food products such as cereals can be detected using electronic olfaction. Apart from extreme instances of spoilage, electronic noses can be successfully used to detect expired food products, either in retail stores or at home. For example, a system for automatic detection of spoiled fruit in a domestic environment based on an array of SAW sensors was tested successfully. A similar study was also carried out in regard to dairy products, namely milk and yogurt. A holistic approach was also taken when detecting volatile indicators of fish and meat spoilage in a supermarket, where there are numerous interferences from various sold food products. Still, it was possible to detect spoilage of particular products against the background noise of numerous different volatile compounds.

There are numerous methods of processing food. One of the crucial food processes, due to the frequency of occurrence in households, restaurants, as well as big food processing facilities, is frying. As a result of thermal processing, harmful volatile compounds may be generated. They can enter the human body through the respiratory system. Reactions which occur during frying are oxidation, hydrolysis, cyclization, polimerization, and Maillard reactions. As a result of frying, harmful substances may be created: aldehydes, ketones, chain hydrocarbons and aromatic hydrocarbons, lactones, carboxylic acids, and esters. With the increase in concentration of aldehydes, the food safety decreases. Aldehydes such as acrolein or olefin-aldehydes are hazardous to human health. In addition, oxidated aldehydes from α,β-unsaturated aldehydes (OαβUAs), which prove to be carcinogenic, can also cause diabetes or arteriosclerosis and may trigger Alzheimer's disease and Parkinson's disease. Another compound important due to its harmful properties is acrylamide, which is generated during a series of reactions called Maillard reactions. Acrylamide has serious neurotoxic effects, it can cause genetic and cancerous changes. Other products of the Maillard reaction are polycyclic aromatic amines (PAAs), which prove to have mutagenic and carcinogenic properties. Similar compounds may be produced during baking bread or pastry. In the air in such indoor environments, substances can be emitted from sources such as furniture, equipment or a ventilation system, as well as products of thermal degradation of food. It is important to emphasize that workers in such rooms rarely employ means of personal protection such as protective masks.

The quality of indoor air in places of food preparation depends mostly on the quality of food products, for instance the quality of frying oil. It is hence crucial to indicate the quality of the used frying oil. This is when electronic noses may be employed. The process of oil spoilage, which is caused by oil oxidation, is called rancidification. Using electronic noses enables to tell whether or not the oil is fit for consumption, as well as to assess its thermostability. Rancidification can also occur during storing oil, even if it is kept in a tightly closed container. On opening the container, the products of oil oxidization are emitted into the indoor air. Research using electronic noses was also carried out in this field, for example in canola oil (Mildner-Szkudlarz, Jeleń, & Zawirska-Wojtasiak, 2008; Shen et al. 2001), corn oil and soybean oil (Shen et al., 2001).

FUTURE RESEARCH DIRECTIONS

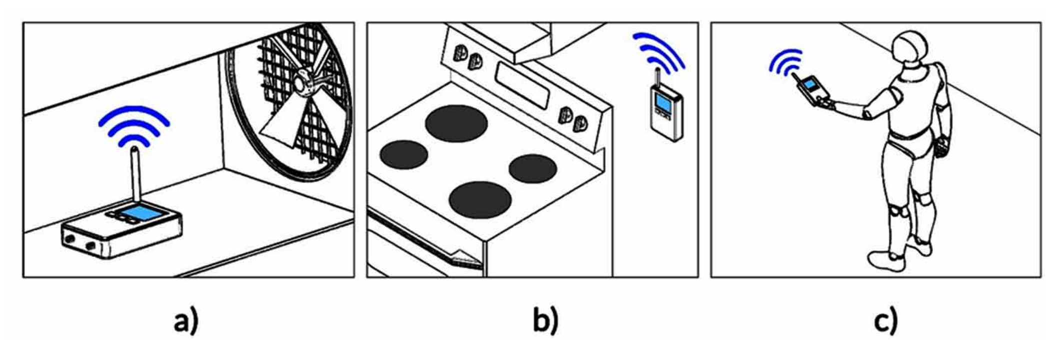
Wireless E-Nose Networks

Devices such as an electronic nose may be equipped with a Wi-Fi module. As a consequence, the device can be significantly smaller in size, because the data collecting and analyzing system may be omitted from its construction. Storing data and processing it is hence done in the central device, which collects data from numerous devices that make up a monitoring network. Moreover, powering the electronic nose from an interior source enables to place the device anywhere in the building and measure the air quality. A good example of a device employing the Wi-Fi module is an electronic nose equipped with eight MOS sensors (Wongchoosuk, Khunarak, Lutz, & Kerdcharoen, 2012). This device was placed in two different indoor environments, namely in an office and in a kitchen, and then measurements were taken for seven hours in each of these places. Some possible placements of electronic nose devices in indoor environment are depicted in Figure 4. The authors of this experiment focused mainly on defining the concentration of carbon monoxide in both of these environments. The advantage of this solution was the small size of the developed device (15x10 cm). What is more, employing the statistical data processing with a PCA method enabled to distinguish the air coming from the kitchen from the air coming from the office. Yet another example of an electronic nose equipped with a Wi-Fi module is a device composed of three MOS sensors. This device was developed at the University of Science and Technology Beijing (Xu et al., 2016). Because of the fact that MOS sensors are extremely susceptible to temperature and humidity, the device was equipped with an additional humidity and temperature sensor. To stream data, the team employed a commercially available Wi-Fi module Xbee. The research was carried out in controlled conditions, in a custom-made chamber. A model gas used in this experiment was formaldehyde, because it can be emitted from the surface of furniture or the equipment of indoor environments. To statistically process data, the team employed machine learning algorithms such as artificial neural networks with back propagation (BP ANN) and with radial basis function (RBF ANN) and support vector regression. The device's responses for different temperature and humidity conditions were assessed. The obtained results were subjected to validation. The use of this type of device, however, was limited to detecting formaldehyde in indoor air. The authors predict that these types of devices can in the nearest future be used for holistic assessment of indoor air quality. Another technical solution is Indoor Air Quality Monitoring System, presented in 2017 (Saad et al., 2017). It is a network used for monitoring air inside a building. It consists of units of measurement which form a sensor module cloud (SMC). Each sensor module consists of sensors used for measuring such pollutants as nitrogen dioxide, carbon dioxide, ozone, carbon monoxide, oxygen, volatile organic compounds and suspended matter PM10. In addition, this device was equipped with temperature and pressure sensors. These modules stream data using wireless network to a hub, where the signal is processed with probabilistic neural network and multilayer perception classifier. The obtained classification accuracy was satisfactory (99.98%) for five different samples of indoor air: ambient air, chemical presence, fragrance presence, foods and beverages, and human activity.

Electronic Noses as an Element of Heating, Ventilation, and Air Conditioning Systems

One of the biggest challenges that creators of electronic noses face is to reduce electrical energy use. The necessity for powering the system of chemical sensors, the support software and the pneumatic system, significantly limits the possibilities of using these types of devices for constant monitoring of indoor air quality. A solution to this problem may be to develop of an electronic nose without pneumatic system (valves, pumps, filters). This kind of device, proposed by Zampolli et al., was used to identify such gases as NO2 or CO (Zampolli et al., 2004). The device was equipped with four MOS sensors, driven by an ad hoc electronic circuit. Such a device is an example of a new class of low-cost e-noses, which can be used as integral elements of such devices as air conditioners or ventilation systems in buildings.

Figure 4. Possible placement of electronic noses in indoor environment: In ventilation ducts (a), on a wall next to potential sources of emission (b) or as a hand-held portable device (c)



This solution can be used not only for monitoring the condition of air indoors, but also to improve the effectiveness of HVAC systems, which can lead to lowering overall power consumption. Miniaturized electronic noses integrated with the ventilation systems may be utilized in the newest building concept, namely smart buildings.

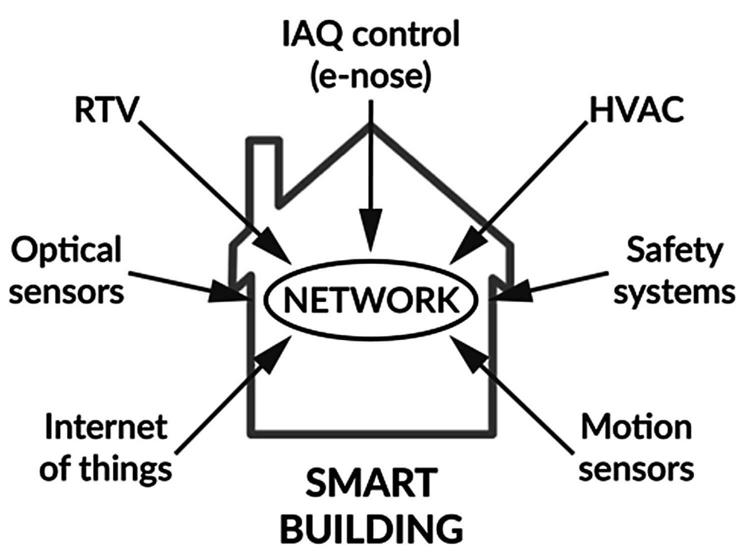
Electronic Noses in Smart Buildings

In pursuit of developing the indoor space in buildings in a user-friendly manner, scientists have devised a new concept called smart buildings. The concept is based on the idea that such elements as ventilation, lighting or anti-burglar devices could be automatically operated. The system is based on a network of sensors, including gas or movement sensors, which collect data from the surroundings (see Figure 5). With this information, the system can control such things as blinds in windows or air conditioning. It can also switch on and off some devices, for example television sets. Smart houses work like neural networks, which learn and remember preferences of the user of the building. Air quality is controlled by chemical sensors, which send response signals that may be used to regulate the workings of ventilation or air conditioning systems. Currently, there is no solution that takes electronic noses into account. The authors of this chapter are certain that employing e-noses would fit into the concept of smart houses perfectly. Using electronic noses as main elements of control systems in smart buildings would be the newest development direction for this type of device in indoor air quality assessment.

CONCLUSION

The development of electronic noses is closely linked with the development of sensor technology. Over the last 30 years, electronic noses have found many uses in various areas of industry.

Figure 5. Various possible components of a 'smart building' network



In most cases, however, highly skilled specialists are needed to understand the chemistry of the measurement process and statistical data analysis methods. Nevertheless, the authors of this chapter believe that in the near future it will be possible to utilize them in everyday life. These devices can be customized for a specific application. The measurement process can be automated and the final measurement result can be presented in a manner understandable to most potential users, for example “the air is clean/safe”. While using electronic noses to control indoor air quality, there are numerous ways to integrate these devices into the monitoring network. Their biggest advantage is that the results are obtained in real time and in digital form. This gives the possibility to create a wireless monitoring network with multiple electronic nose units, and integrate it into the overall room management system, which is the core element of smart homes. In addition, using the existing indoor systems, such as heating, ventilating or air conditioning systems, some elements of the pneumatic system in electronic noses can be omitted, thus reducing energy consumption.

The use of these devices for indoor air measurements seems to be more desirable also due to the fact that sensors used in electronic noses are not selective. It is thus possible to identify individual chemicals present in indoor air, or multicomponent gas mixtures, if the research is carried out in accordance with the holistic concept of measurement. This is the research approach that is more useful when different chemical processes occur in a closed space, often in a similar, but not identical way. A standard example may be the use of electronic noses to control air quality in food processing facilities (restaurant kitchens, large food processing facilities), and in particular in indoor environments where the frying process is carried out, as it may cause the production of carcinogenic chemicals. The use of electronic noses to control indoor air quality is a promising solution that can be used for indoor air monitoring, also because their chemical sensors are more suitable for emission rather than emission measurements.

ACKNOWLEDGMENT

This work was financially supported by the Grant No. PBSII/B9/24/2013 obtained from the National Centre for Research and Development of Poland and Grant no. 2015/19/B/ST4/02722 received from the National Science Center of Poland.

REFERENCES

Alexandrakis, D., Brunton, N. P., Downey, G., & Scannell, A. G. M. (2012). Identification of Spoilage Marker Metabolites in Irish Chicken Breast Muscle Using HPLC, GC–MS Coupled with SPME and Traditional Chemical Techniques. *Food and Bioprocess Technology*, *5*(5), 1917–1923. doi:10.1007/s11947-010-0500-8

Andretta, M., Coppola, F., & Seccia, L. (2016). Investigation on the interaction between the outdoor environment and the indoor microclimate of a historical library. *Journal of Cultural Heritage*, *17*, 75–86. doi:10.1016/j.culher.2015.07.002

Bender, F., Barié, N., Romoudis, G., Voigt, A., & Rapp, M. (2003). Development of a preconcentration unit for a SAW sensor micro array and its use for indoor air quality monitoring. *Sensors and Actuators. B, Chemical*, *93*(1-3), 135–141. doi:10.1016/S0925-4005(03)00239-9

Chao, C. Y., & Chan, G. Y. (2001). Quantification of indoor VOCs in twenty mechanically ventilated buildings in Hong Kong. *Atmospheric Environment*, *35*(34), 5895–5913. doi:10.1016/S1352-2310(01)00410-1

Dascalaki, E. G., Lagoudi, A., Balaras, C. A., & Gaglia, A. G. (2008). Air quality in hospital operating rooms. *Building and Environment*, *43*(11), 1945–1952. doi:10.1016/j.buildenv.2007.11.015

Gram, L., Ravn, L., Rasch, M., Bruhn, J. B., Christensen, A. B., & Givskov, M. (2002). Food spoilage—interactions between food spoilage bacteria. *International Journal of Food Microbiology*, *78*(1-2), 79–97. doi:10.1016/S0168-1605(02)00233-7 PMID:12222639

Herrick, R. F., Stewart, J. H., & Allen, J. G. (2016). Review of PCBs in US schools: A brief history, an estimate of the number of impacted schools, and an approach for evaluating indoor air samples. *Environmental Science and Pollution Research International*, *23*(3), 1975–1985. doi:10.1007/s11356-015-4574-8 PMID:25940477

Krupińska, B., Van Grieken, R., & De Wael, K. (2013). Air quality monitoring in a museum for preventive conservation: Results of a three-year study in the Plantin-Moretus Museum in Antwerp, Belgium. *Microchemical Journal*, *110*, 350–360. doi:10.1016/j.microc.2013.05.006

Kuske, M., Romain, A.-C., & Nicolas, J. (2005). Microbial volatile organic compounds as indicators of fungi. Can an electronic nose detect fungi in indoor environments? *Building and Environment*, *40*(6), 824–831. doi:10.1016/j.buildenv.2004.08.012

Lewkowska, P., Dymerski, T., Gębicki, J., & Namieśnik, J. (2016). The Use of Sensory Analysis Techniques to Assess the Quality of Indoor Air. *Critical Reviews in Analytical Chemistry*, *47*(1), 37–50. doi:10.1080/10408347.2016.1176888 PMID:27105173

Lv, P., Tang, Z., Wei, G., Yu, J., & Huang, Z. (2007). Recognizing indoor formaldehyde in binary gas mixtures with a micro gas sensor array and a neural network. *Measurement Science & Technology*, *18*(9), 2997–3004. doi:10.1088/0957-0233/18/9/034

Marć, M., Śmiełowska, M., & Zabiegała, B. (2016). Concentrations of monoaromatic hydrocarbons in the air of the underground car park and individual garages attached to residential buildings. *Science of the Total Environment Journal*, *573*, 767–777. doi:10.1016/j.scitotenv.2016.08.173 PMID:27591527

Mendes, A., Bonassi, S., Aguiar, L., Pereira, C., Neves, P., Silva, S., ... Teixeira, J. P. (2015). Indoor air quality and thermal comfort in elderly care centers. *Urban Climate*, *14*, 486–501. doi:10.1016/j.uclim.2014.07.005

Mildner-Szkudlarz, S., Jeleń, H. H., & Zawirska-Wojtasiak, R. (2008). The use of electronic and human nose for monitoring rapeseed oil autoxidation. *European Journal of Lipid Science and Technology*, *110*(1), 61–72. doi:10.1002/ejlt.200700009

Morvan, M., Talou, T., & Beziau, J.-F. (2003). MOS–MOSFET gas sensors array measurements versus sensory and chemical characterisation of VOC's emissions from car seat foams. *Sensors and Actuators. B, Chemical*, *95*(1-3), 212–223. doi:10.1016/S0925-4005(03)00425-8

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. doi:10.1016/j.snb.2005.11.085

Ramalho, O. (2000). Correspondences between olfactometry, analytical and electronic nose data for 10 indoor paints. *Analusis*, *28*(3), 207–215. doi:10.1051/analusis:2000280207

Roinestad, K. S., Louis, J. B., & Rosen, J. D. (1993). Determination of pesticides in indoor air and dust. *Journal of AOAC International*, *76*(5), 1121–1126. PMID:8241815

Saad, S. M., Shakaff, A. Y. M., Saad, A. R. M., Yusof, A. M., Andrew, A. M., Zakaria, A., & Adom, A. H. (2017). Analysis of feature selection with Probabilistic Neural Network (PNN) to classify sources influencing indoor air quality. *AIP Conference Proceedings*, 1808.

Schieweck, A., Lohrengel, B., Siwinski, N., Genning, C., & Salthammer, T. (2005). Organic and inorganic pollutants in storage rooms of the Lower Saxony State Museum Hanover, Germany. *Atmospheric Environment*, *39*(33), 6098–6108. doi:10.1016/j.atmosenv.2005.06.047

Scorsone, E., Pisanelli, A. M., & Persaud, K. C. (2006). Development of an electronic nose for fire detection. *Sensors and Actuators. B, Chemical*, *116*(1-2), 55–61. doi:10.1016/j.snb.2005.12.059

Senter, S. D., Arnold, J. W., & Chew, V. (2000). APC values and volatile compounds formed in commercially processed, raw chicken parts during storage at 4 and 13 C and under simulated temperature abuse conditions. *Journal of the Science of Food and Agriculture*, *80*(10), 1559–1564. doi:10.1002/1097-0010(200008)80:10<1559::AID-JSFA686>3.0.CO;2-8

Seyama, M., Sugimoto, I., & Miyagi, T. (2002). Application of an array sensor based on plasma-deposited organic film coated quartz crystal resonators to monitoring indoor volatile compounds. *IEEE Sensors Journal*, *2*(5), 422–427. doi:10.1109/JSEN.2002.804576

Shen, N., Moizuddin, S., Wilson, L., Duvick, S. A., White, P. J., & Pollak, L. M. (2001). Relationship of electronic nose analyses and sensory evaluation of vegetable oils during storage. *Journal of the American Oil Chemists' Society*, *78*(9), 937–940. doi:10.1007/s11746-001-0367-z

Śliwińska, M., Wiśniewska, P., Dymerski, T., Wardencki, W., & Namieśnik, J. (2015). The flavour of fruit spirits and fruit liqueurs: A review. *Flavour and Fragrance Journal*, *30*(3), 197–207. doi:10.1002/ffj.3237

Śmiełowska, M., Marć, M., & Zabiegała, B. (2017). Indoor air quality in public utility environments—a review. *Environmental Science and Pollution Research International*, 1–11. PMID:28236201

Szczurek, A., & Maciejewska, M. (2015). Classification of air quality inside car cabin using sensor system. Sensornets.

Takeoka, G., Perrino, C., & Buttery, R. (1996). Volatile Constituents of Used Frying Oils. *Journal of Agricultural and Food Chemistry*, *44*(3), 654–660. doi:10.1021/jf950430m

Wongchoosuk, C., Khunarak, C., Lutz, M., & Kerdcharoen, T. (2012). WiFi electronic nose for indoor air monitoring. *9th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology*, 1–4. doi:10.1109/ECTICon.2012.6254166

Worobiec, A., Samek, L., Spolnik, Z., Kontozova, V., Stefaniak, E., & Van Grieken, R. (2006). Study of the winter and summer changes of the air composition in the church of Szalowa, Poland, related to conservation. *Mikrochimica Acta*, *156*(3–4), 253–261. doi:10.1007/s00604-006-0619-5

Xu, L., He, J., Duan, S., Wu, X., & Wang, Q. (2016). Comparison of machine learning algorithms for concentration detection and prediction of formaldehyde based on electronic nose. *Sensor Review*, *36*(2), 207–216. doi:10.1108/SR-07-2015-0104

Xu, L., Yu, X., Liu, L., & Zhang, R. (2016). A novel method for qualitative analysis of edible oil oxidation using an electronic nose. *Food Chemistry*, *202*, 229–235. doi:10.1016/j.foodchem.2016.01.144 PMID:26920289

Yao, D. (2009). A gas sensing system for indoor air quality control and polluted environmental monitoring. In *9th IEEE Conference on Nanotechnology 2009* (Vol. 8, pp. 806–811). IEEE.

Zampolli, S., Elmi, I., Ahmed, F., Passini, M., Cardinali, G. C., Nicoletti, S., & Dori, L. (2004). An electronic nose based on solid state sensor arrays for low-cost indoor air quality monitoring applications. *Sensors and Actuators. B, Chemical*, *101*(1), 39–46. doi:10.1016/j.snb.2004.02.024

Zeiger, E., Gollapudi, B., & Spencer, P. (2005). Genetic toxicity and carcinogenicity studies of glutaraldehyde—a review. *Mutation Research/Reviews in Mutation Research*, *589*(2), 136–151. doi:10.1016/j.mrrev.2005.01.001 PMID:15795166

Zhang, J., Chen, W., Li, J., Yu, S., & Zhao, W. (2015). VOCs and Particulate Pollution due to Incense Burning in Temples, China. *Procedia Engineering*, *121*, 992–1000. doi:10.1016/j.proeng.2015.09.067