chemosensors

MDPI

Review

Methods for Early Detection of Microbiological Infestation of Buildings Based on Gas Sensor Technologies

Monika Garbacz [1], Agnieszka Malec [2], Sylwia Duda-Saternus [1], Zbigniew Suchorab [2], Łukasz Guz [2] and Grzegorz Łagód [2,*]

[1] Department of Woman Health, Institute of Rural Health in Lublin, 20-090 Lublin, Poland; monika.garbacz@interia.pl (M.G.); sylwia.m.duda@gmail.com (S.D.-S.)

[2] Faculty of Environmental Engineering, Lublin University of Technology, 20-618 Lublin, Poland; aga_malec@interia.pl (A.M.); z.suchorab@pollub.pl (Z.S.); l.guz@pollub.pl (Ł.G.)

* Correspondence: g.lagod@pollub.pl; Tel.: +48-81-538-4322

Received: 30 November 2019; Accepted: 2 January 2020; Published: 6 January 2020



Abstract: In this review, the problem of microbiological infestation of buildings was discussed. The techniques of detection were described as well, with special attention drawn to the rapid-early detection methods based on gas sensor arrays. The physical and chemical conditions of the building environment conducive to the development of microorganisms and the technical conditions influencing the problem of microbiological infestation were investigated. Additionally, the harmful effects on human health caused by the microbiological contamination were discussed, with a short review of particular groups of microorganisms causing sick building syndrome. Among the detection techniques, the traditional microbiological techniques as well as the molecular and chemical methods were presented. Different designs of the gas sensor arrays together with the various techniques of analyzing the received multidimensional signal were described, analyzed, and compared in detail.

Keywords: microbiological infestation; mold; fungi; gas sensor array; electronic nose; voc detection; chromatography; PCR; NGS; SBS

1. Introduction

Microorganisms are found in almost every ecological niche. They are necessary to recycle the organic compounds consumed by plants and animals. Fungi represent a large share of the total biodiversity on Earth, and they are regarded as key players in performing numerous ecosystem functions, especially in soil [1]. Molds are ubiquitous in the environment; hence, people are exposed to their presence. In most cases, they do not harm human health and exposure to them, such as inhalation of airborne mold spores, is tolerated by their physical expulsion or elimination by the immune system. However, for immunologically sensitive people, the inhalation of mold spores can cause asthma, rhinitis, or bronchitis [2–4].

According to the World Health Organization (WHO), indoor air quality has a greater impact on human health than outdoor air. This is due to the fact that the people in developed countries spend up to 90% of their time indoors [5]. The first topics related to the problem of indoor air quality impact were connected with radon presence, tobacco smoke, and lung cancer, followed by the volatile organic compounds, formaldehyde, sick building syndrome (SBS), house dust-mites, asthma and allergies, Legionnaires disease, and other airborne infections [6–8]. Topics such as dampness and mold, together with associated problems such as allergies and today's concern with "modern exposures-modern diseases", emerged afterwards. The indoor air, as a scientific area, is vast, covering public health,

medicine, environment, engineering, chemistry, physics, microbiology, sociology, psychology, economy, architecture, and more. Per its definition, indoor air science (IAS) is multidisciplinary, originating from interest in the health effects resulting from the exposure to the indoor air and thus part of public health and preventive medicine [9–12].

Moreover, numerous studies conducted worldwide confirm that the concentrations of contaminants in indoor environments are much higher than in outdoor environments [13,14]; thus, the indoor environment is the most probable source of human exposure to the inhalation of mold spores. Building pathology is an interdisciplinary branch of knowledge and practice combining the problems of biology with the building and technical problems [15]. Microbiological corrosion is one of the difficult and often underestimated problems of the building sector. The growing number of people suffering from allergies caused by mold fungi leads to a greater interest in this problem and its impact on human health [16].

The most characteristic example of improper indoor air quality is the Sick Building Syndrome (SBS) and Building-Related Illness (BRI). This topic is related to the health problems of the people staying in buildings and is still not well known yet. SBS is considered to be a new pathogenic entity, causing serious health risks. The term sick building syndrome was described in scientific journals in the 1980s [17] and 1990 [18,19], and by the World Health Organization (WHO), this syndrome was defined as a disease condition [20,21]. More specifically, it is a combination of various health conditions associated with the presence of people in specific enclosed spaces. Initially, this problem mainly concerned the office space, but over time, it has been noted that it may also affect the living quarters [4,22,23]. The moisture in buildings and, thus, the presence of mold and its metabolites are indicated as the most likely cause of SBS [20,24–26]. A detailed understanding of its causes and consequences is essential for people's health and the performance of buildings. Traditional assessment methods have so far been the basis for fungal contamination detection and identification in buildings. Such techniques require time and microorganism culturing; however, irrespective of their advantages, the scope of information they provide is limited to identifying living organisms which can grow under standard laboratory conditions. Most natural sample microorganisms cannot be cultured in accordance with standard procedures, while culture-specific methods give a constrained amount of information on the biodiversity of the on-site microorganisms. On the other hand, molecular methods as the Polymerase Chain Reaction (PCR) or Next-Generation Sequencing (NGS) can be successfully used to analyse the structure of microbiological communities and to aid in the assessment of the buildings' microbiological threat. Still, microbiological and molecular methods remain quite an expensive option. In their case, the contaminated materials must be sampled and tested ex situ in the laboratory, and the whole process requires expertise. Therefore, faster, early detection techniques must be implemented for resource efficiency to be improved [15,27]. The last few years saw great progress in the development of sensor-based devices, thus providing an opportunity to use these tools for the betterment of fungi detection in contaminated materials.

2. Microbiological Contamination in the Building Sector

2.1. Causes of the Microbiological Threat

Biological corrosion in the building sector is a process involving destruction of materials by living organisms, mainly house fungi, molds, and algae. The microbiological infestation is closely linked to factors favoring the development of biological pests. Improper building construction creates optimal humidity conditions for microorganisms, and thus, the incidence of fungi and algae in the building envelope is increasing. Importantly, it is estimated that between 20% and 40% of the existing buildings in North America and Europe are subject to microbiological corrosion [5].

The losses caused by corrosion can have a very wide range: from the destruction of wall structures, increased costs of repairs, reduction of the lifespan of buildings, and premature demolition of buildings damaged by fungi to very harmful effects on human and animal health [28].

The task to state with absolute certainty which pollutants only cause discomfort to residents and which may be the cause of diseases is difficult. For years now, the Sick Building Syndrome (SBS) has been an important topic and it remains the most characteristic consequence of inadequate indoor air quality [29]. Factors such as thermal comfort (subjective sensation, connected with humidity and temperature), odors, and other odorless substances, all contribute to the quality of indoor air. Different fungi types are capable of producing significant amounts of these substances [30,31]. Moist building materials are a source of nutrients for the microorganisms and the most common place of fungal colonies' development [32]. The invention of energy-efficient building technologies allowed the architects to focus on developing and improving heat-loss-reducing methods in building construction, e.g., by introducing airtight windows and doors. Increasingly thicker insulation layers are being built in the walls which shield against indoor temperature drops, wind influence, and exfiltration of water vapor, which is considered a negative phenomenon. Another fact contributing to an increased concentration of air pollutants is houses being far more airtight when compared to the past conditions. Every day, household members are exposed to mold spores, pollen, dust, and chemical pollutants released by building materials, home furnishings, and equipment. Furthermore, people exhale carbon dioxide and water vapor when performing domestic activities—bathing, washing, cooking, etc., which constitute a significant moisture source [33].

2.2. *Physical and Chemical Conditions Conducive to the Development of Micro-Organisms*

Certain numbers of microorganisms, including fungal spores, are an inseparable part of atmospheric air. What should be remembered is that the number and types of indoor and outdoor microorganisms are similar under normal conditions. On the other hand, it is a known fact that these aspects differ entirely in humid buildings [29]. Microorganisms cannot multiply in atmospheric air; it is only used as a carrier of the spores. The source of fungal spores in the air involves the fungi that develop on the surfaces of damp building partitions or interior furnishings, which can meet the nutritional requirements of the developing microorganisms (they can use, e.g., cellulose from wallpaper or starch contained in the wallpaper paste). Wooden furniture and textiles are also susceptible to mold colonization and development due to the presence of dirt, dust, and food debris [4,34]. The pace of their development is influenced by many factors. The main parameters are temperature and humidity, which determine the development of fungi to the greatest extent [35].

Microorganisms can only develop in a suitable environment and under favorable conditions: presence of food, adequate humidity and temperature (both substrate and air), access to air, limited light (e.g., northern facades, faults, and recesses), and optimal pH value. The most favorable pH is slightly acidic, but in general, it ranges from 0.5 to 11 depending on the species of fungus [35–38]. Of course, these conditions have to be taken into account together; only then do they create an environment that determines the development of biological life [39].

Temperate climate countries are home to the most dangerous fungus, *Serpula lacrymans*. It infects deciduous and coniferous woods as well as wood-like materials. This fungus prefers 30% wood humidity and temperature of 23 °C. The wood affected by *Serpula lacrymans* loses 7% of its weight per month and its strength parameters decrease by 20–50%. [40].

The fungi can be observed in a wide but limited range of temperatures. Fungi can survive even at temperatures below 0 °C, but this temperature prevents them from developing. However, the limit temperature is 50 °C, at which the growth of most fungi is stopped or inhibited [35].

The most favorable humidity and temperature ranges vary depending on the type or substrate of the fungus. It can be assumed that relative air humidity above 75% creates optimal conditions for the development of mold and, thus, contributes to the pollution of buildings [35]. Water vapor is formed during normal indoor activities such as meal preparation or personal hygiene. According to sources [41], a four-person household emits about 14–15 L of water vapor a day, which is more than 5 tons per year.

A further consequence of this problem is an increase in room humidity due to too slow removal of the water vapor present in the air [42].

Today, materials of biological origin, such as hemp, flax, sunflower, or wood, are becoming more common [36,37,41,42]. Their application further increases the popularity of the sustainable construction idea [43], which prescribes the use of ecological building materials capable of reducing the impact of the construction sector on the environment and of mitigating CO_2 emissions. Unfortunately, the building composites of plant origin contain many nutrients which are attractive for microorganisms; therefore, they are highly susceptible to fungal contamination.

2.3. Technical Conditions Conduicive to the Development of Mold

New trends in building design concerning the energy efficiency aspects in some cases may lead to levels of humidity that could be optimal for the growth of microorganisms. The influence of moisture can come both from outside and inside the building. However, this is closely related to the poor workmanship and the type of materials used as food for the microorganisms developing on the wall surfaces [44]. In addition, fungi may occur due to technical reasons related to improper design, construction, or operation of the building, where important issue for extended fungal development is the insufficient, improperly designed ventilation of the rooms—a factor favoring an increase in the concentration of bioaerosols in closed spaces. This mainly results from the following [44,45]:

- Inappropriate selection of building materials that lack properties protecting against the harmful influences of ground and atmospheric moisture;
- No water or moisture insulation;
- No thermal insulation and improper construction of thermal insulation of walls;
- Lack of ventilation or poor design of ventilation ducts in rooms such as kitchens, bathrooms, laundries, etc.;
- Airtight building envelope;
- Obstruction of ventilation and air-conditioning ducts;
- Incorrect drainage of rainwater from roofs, balconies, etc.;
- Use of building materials with increased humidity;
- The building is put into service before the required drying time;
- Lack of proper maintenance of buildings;
- Leakage of central heating or water supply system or even sewage installation.

Identifying the causes of microbial infestation requires the study and analysis of specific construction cases. In recent years, fungal infestation has mainly occurred in old, damp, or unheated buildings, but it is becoming more and more common in the newly built buildings. In order to minimize the risk of microbiological contaminations of the new buildings, preventive measures have been proposed to reduce the potential for the developing mold contamination [4,46]:

- Minimizing the exposure of construction products inside buildings to external factors;
- Monitoring and maintaining the integrity of the building envelope;
- Checking the supplied clean and dry material and discarding any wet or moldy material;
- Protecting the stored materials from moisture;
- Minimizing the accumulation of moisture during construction;
- Balancing the HVAC (Heating, Ventilation, and Air Conditioning) systems to control comfort and humidity.

For the problems arising in existing buildings, testing or evaluation strategies have been published [47,48]. These include but are not limited to the following:

- Transparent inspection of rooms, including HVAC systems;
- Documentation of the history of water damage;
- Measurement of temperature, relative humidity, and air;

- Checking for visible traces of mold and mold odors;
- Checking for hidden mold (found behind wallpaper/panels, under carpets, on ceilings, or in wall recesses);
- Air sampling or surface samples—if necessary.

As it was mentioned before, one of the most common errors in building construction is made already at the design stage and is the improper selection of materials and protection against moisture and temperature changes, especially in the case of cellars and ceilings. These errors adversely affect the condition of the building at a later stage. The most common ones are shortened time of investment realization, installation of tight woodwork, and application of insulation systems, which significantly hinder drying of walls of the building [49].

Improper ventilation or total lack thereof leads to improper air circulation inside the building. Properly designed and manufactured ventilation should remove the spent air and provide fresh air. Its main task is to remove the carbon dioxide exhaled by people. In good quality air, it can be up to 0.1% of the volume. In higher concentrations, it is harmful to health or even lethal. The correct oxygen content is at least 20%. In a poorly ventilated bedroom, it can drop to 17%, which is also dangerous to health [30].

In order to improve the performance of natural ventilation, special ventilators should be designed in the window frames or walls. Another important goal in room ventilation is to remove the water vapor and to maintain air humidity between 40% and 60%. If the air is too dry, problems with breathing or itching in the throat may occur. If it is too wet, suitable conditions for the development of microorganisms will be created.

Technical progress brought about yet another problem, as air conditioning and mechanical ventilation systems have turned into convenient spots for microorganisms to develop. Pathogenic and toxin-producing fungi and bacteria grow fast where it is dark and humid, and HVAC systems seem to be the perfect environment for the growth and propagation of microbes. Lowered heat-transfer efficiencies, increased corrosion, and any possible odor issues are the consequence of intrinsic microbial biofilms found on air-handling exchanger coils. The United States Environmental Protection Agency (EPA) informs that contaminated HVAC systems are the breeding ground for fungi and bacteria and a hot spot for viruses and fungal as well as bacterial spores [47,50–52]. These environments on their own are not enough, as nutrients are necessary for any microbes to grow there, and these are often provided by the inherent dust which collects in the system and water. Liquid-state water is most often generated under normal operation of HVAC systems, as a result of water vapor condensation on cooling coils and fins of the exchangers. The condensate thus created may be aerosolized from surfaces with the subsequent contaminant deposition within ducts or occupied indoor spaces [52]. The contaminants in HVAC systems are accumulated on heat exchanger coils and fins, in condensate drain pans, on air filters, and in air ducts. As a consequence of such accumulation, indoor surfaces and building occupants can be exposed to bioaerosols. HVAC exchanger systems can be home to substantially large microbial populations. According to the research presented in Reference [52], automobile and household air conditioning units can produce up to 2500 CFU/m^3 of bacteria and 1000 CFU/m^3 of fungi above the ambient levels during initial startup. Asthma sufferers in houses with air conditioning were found to show significantly elevated asthma symptoms' rates compared to ones living in houses without an AC unit. In Sweden, there was a discussion pertaining to the problem of correlation between the moisture presence in the ventilation systems of single-family houses and SBS symptoms. It was observed that a large proportion of single-family houses have dampness problems in the foundation, and pollutants may enter the living space of the house and affect the health of the occupants. Moreover, compared to natural ventilation, living in a house with mechanical supply and exhaust ventilation was related to a lower prevalence of general symptoms and SBS symptoms [53].

A review of lower respiratory symptoms in the employees of the eighty office buildings surveyed by the National Institute of Occupational Safety and Health (NIOSH) in the U.S. has shown a correlation between moisture and pollution in ventilation systems and adverse effects on respiratory health [54].

Rainwater can also be a problem in the event of roofing leaks or sewerage system leaks, which can quickly lead to mold problems if not repaired properly and carefully. In some cases, an undiscovered roof leakage may cause issues, i.e., the growth of mold on generally accessible surfaces, e.g., walls and ceilings, and in places generally difficult to reach, e.g., on the wall behind the wallpaper or under the floor covering. Areas of moisture may also occur in the spaces between the wall and furniture [4,55,56].

2.4. Harmful Effects of Microbiological Contamination on Human Health

As it was mentioned before, indoor air quality has a greater impact on human and animal health than outdoor air, which may seem to be more polluted [15,57,58]. The SBS symptoms intensify as the time spent in the building increases, but they disappear or are significantly alleviated when people are away from the sick buildings [59]. Thus, the state of human health depends on the time of exposure to the type of agent and the number of microorganisms present in the air. Bioaerosols are the most common conveyor of biological agents in the air, which contain biological elements, water droplets, and other contaminants. Bioaerosols are ubiquitous in the environment due to their small particle size (up to 2.5 mm). Their presence in the air can cause diseases and infections [57,60].

People are exposed to direct contact with bioaerosols through the respiratory system, skin, eyes, and hair. However, the degree of exposure and the course of the disease varies among individuals and depends on many factors, including health condition, past diseases, and past therapies that increase the chances of infection [61,62].

During breathing, fungal spores enter the lungs and cause serious lung diseases in people suffering from allergies. Many residents suffer from various ailments (sleepiness; fatigue; nausea; dizziness; irritability; memory disorders; heaviness; quick and easy fatigue; long-lasting pains and frequent colds; irritation of eyes, nose, larynx, and throat; skin redness; and asthma-like symptoms: chest tightness and dyspnea) [63].

The list of symptoms associated with being in a sick building was published by WHO in 1987 [61]:

- Headaches and dizziness, fainting, nausea, difficult breathing, and unnatural fatigue;
- Allergic complaints: mucositis, chronic laryngitis, bronchitis, and dry cough;
- Mood-related symptoms: migraines, irritability, and concentration disorders;
- Dryness; redness; and flaking of the skin of the face, hands, and ears.

The problem of sick building syndrome is also connected with serious diseases, which people suffer from as a result of being in a polluted internal environment, e.g., skin irritation; dryness; redness; and flaking of the skin of the face, hands, and ears:

- Bronchial asthma;
- Legionnaires' disease and air-conditioning fever;
- Cancer, which occurs as a result of tobacco smoke, asbestos, and radon.

Contamination of the internal environment with fungi and, thus, increased occurrence of SBS is mainly caused by the presence of microbiological volatile organic compounds (MVOC), which are a subgroup of volatile organic compounds (VOC)—considered to be carcinogenic—mycotoxins, fungal spores, and fragments of mycelium [58,64–68]. These substances are secondary metabolites produced by fermentation and are volatile due to their physicochemical properties [69,70]. MVOCs with a characteristic mold smell indicate the presence of filamentous fungi in buildings. Generally, higher concentrations of MVOCs are recorded in rooms, mainly due to closed space and often due to a problem with ventilation [57,71,72]. Various health issues may arise as a result of release of compounds by developing microorganisms [45,73]. On the other hand, mycotoxins are fungi-produced toxic substances. The toxins thought to be the most harmful are produced by *Stachybotrys chartarum*, *Fusarium*, and *Aspergillus versicolor* genera [29,44]. The most toxic fungi-produced mycotoxins include ochratoxin A (OT), zearalenone (ZEN), aflatoxins (AF), trichothecenes, and fumonisins (F) [29,44]. Other fungi-produced toxins comprise ketones, alcohols, esters, terpenes, and sulphur compounds including the following substances [44,49,61,62]:

Ketones: 2-heptanone, 2-pentanone, and 3-octanone; alcohols: 2-methyl-1-butanol, 3-methyl-1-butanol, 2-methylpropanol, 3-octanol, 1-octen-3-ol, 1-hexanol, 1-pentanol, 2-methylisoborneol, and geosmin; terpenes and sesquiterpenes: limonene and pinene; furans: 3-methylfuran; sulphur: 296 compounds; and hydrocarbons: alkanes, olefins, diets, and trienes [74].

Mycotoxins are also products of secondary mold metabolism that interfere with cellular structures such as biomembranes and with important cellular processes such as protein, RNA, and DNA synthesis of Eucaryota. Therefore, they are also toxic to the cells of higher plants and animals, including humans. It should be noted that almost all mycotoxins have immunosuppressive effects, although the exact target in the immune system may vary. Many of them are also cytotoxic, so they have a way of inputting effects that can damage the intestines, skin, or lungs. Such cytotoxicity can affect the physical defense mechanisms of the respiratory tract, reducing its ability to purify particulate pollutants (including bacteria or viruses) or damaging the macrophages of alveoli, thereby preventing the elimination of pollutants from the deeper lungs. The result is increased susceptibility of a person exposed to an infectious disease and reduced defense against other contaminants [44].

The issues related to the fungal contamination of building elements, causing changes in air quality, are important from both medical and technical points of view. Early detection of fungal contaminants can help choosing the right preventive measures and removing the damage caused by the infestation. The renovation of a damp building cannot be professionally carried out without prior mycological evaluation of the building structure, interior decoration, and stored materials. In addition, the identification of fungi may indicate how dangerous the encountered type is.

2.5. Microorganisms Developing in the Building Envelopes

According to the literature on the subject, there may be even several hundred species of fungi and bacteria living in the indoor environment, including the following genera of fungi: *Cladosporium sphaerospermumn*, *Penicillium chrysogenum*, *Aspergillus niger*, *Aspergillus versicolor*, *Alternaria alternata*, *Stachybotrys chartarum*, and mycobacteria and Gram negative bacteria in the rooms [24,75,76].

There are more than a few dozen species of mold, which can be classified as the most serious pests of building materials, resulting from their widespread presence and low requirements for the development conditions. The main source of infestation of building partitions are the mold spores carried by air. The most frequently identified mold fungi are representatives of several types: *Penicillium*, *Aspergillus*, *Cladosporium*, *Alternalia*, and *Fusarium* [45].

Molds are the heterotrophic organisms of eukaryotic structure. They feed on dead or living organic matter, and their enzymes enable the decomposition of complex organic compounds. They have modest nutritional requirements, so they can develop on the substrates with low organic matter content, such as building partitions (Figure 1), walls, bricks, and stones. The conditions conducive to mold development are very diverse, as there are species that tolerate and exist at temperatures below 0 °C, but the largest group develops when the substrate or air is very humid (up to 70%) and the temperature is between 20 and 35 °C [77].



Figure 1. Microbiological infection in closed rooms: visible mold on the wall.

The most common microorganisms that can influence indoor air parameters and be combined with SBS symptoms are presented below.

2.5.1. Mold Genera

Aspergillus is one of the most harmful genera of mold. The *Aspergillus* species are commonly present in buildings with highly damp wall surfaces. This genus contains several toxic species, the most important of which are *Aspergillus pasiticus*, *Aspergillus flavus*, *Aspergillus fumigatus*, and *Aspergillus niger*. The aflatoxins produced by these species are among the most potent mycotoxins. These are some of the most toxic substances with particularly harmful properties for the liver, brain, kidneys, and heart; they are also highly teratogenic [39,76–78].

Another common genus of fungi is *Stachybotrys chartarum*. The fungi belonging of the *Stachybotrys chartarum* genus grows intensively under high humidity conditions. They are mesophilic organisms, developing in the range from 18 °C to 35 °C and in a much wider range [39,55,79].

2.5.2. Pathogenic Fungi

Pathogenic fungi belong to two subgroups: bagworms (*Ascomycetes*), especially class *Endomycetes* as well as formerly distinguished class of molds *Phycomycetes*, and imperfect fungi (*Deuteromycotina*). Among pathogenic fungi, the most important are dermatophytes (*Trichophyton*, *Epidermophyton*, and *Microsporum*), yeasts (*Candidia* and *Cryptococcus*), and others. These fungi cause superficial and deep mycoses in human skins [77].

2.5.3. Domestic Fungi

Domestic fungi, apart from decomposition of wood and other organic materials, are increasingly common on walls, bricks, and stones. Growing mycelium, encountering mechanical resistance of materials, penetrates gaps and fills open spaces. Domestic fungi cause an increase in humidity, colorful stains, bulges, mineral salt blooms, and flaking of plaster. The fungi of this species release water, carbon dioxide, organic acids, and other toxic compounds, thus causing biological corrosion [39].

2.5.4. Algae

Algae cause microbiological corrosion, observed on building facades (Figure 2) and should not be combined with SBS. On the other hand, they strongly influence the appearance of the threatened buildings. Algae form a large group of plants developing in aquatic and terrestrial environments subject to constant or periodic moisture. Algae are ubiquitous and form part of the plankton in the seas, oceans, and inland reservoirs (as phytoplankton). Algae also live outside water bodies in humid places: in and on the soil, on stones, on tree trunks, as well as on snow and ice; they are increasingly often found on the walls of buildings. Algae are green organisms which, owing to their chlorophyll content, are able to synthesize organic compounds. They take water and mineral salts from the substrate, often developing on building walls and roofs. During the development phase, they grow into the substrate to a depth of 1.0–2.0 mm [77]. In addition to the green stains which are difficult to remove, they can cause surface corrosion of materials by secreting acids and other substances. The façade may be infested by spores, which float in the air in substantial amounts. The infectious element develops rapidly when it comes into contact with the appropriate substrate and conditions. Once a certain degree of development has been reached, spore emission starts from the affected areas, which means that the neighboring façade surfaces and nearby buildings will become infected.

The microbiological contamination occurs in the form of bioaerosols, i.e., biological particles suspended in the air. There are various microorganisms and organic matter molecules coming from many sources. The source of bioaerosols involves the people and animals living in the apartment. The contaminants produced by fungi and molds in high concentrations originate mainly from the organisms growing in the dwelling [42,80,81]. According to Reference [61], the concentration of fungal spores in the contaminated buildings, expressed in colony-forming units (CFU), exceeds 1000 CFU/m^3,

while the permitted amount is 50 CFU/m^3 for mold fungi and 150 CFU/m^3 for mixed genera—with the exception of pathogens.



Figure 2. Algae covering the façade surfaces of one of the buildings found during field studies.

Cladosporium and *Alternaria* are permitted at 300 CFU/m^3, while the presence of Aspergillus fumigatus and *Stachybotrys chartarum* is not allowed at all [82]. According to Piotrowska and Żakowska [83], the dominant types in buildings are *Aspergillus versicolor*, *Penicillium chrysogenum*, and *Cladosporium cladosporoides*. For comparison, according to the studies conducted in the USA, an average mold concentration of 67,000 CFU/m^3 was detected in the buildings affected by floods during Hurricane Katrina [84,85]. The main molds identified were *Aspergillus niger*, *Penicllium* spp., *Trichoderma*, and *Paecilomyces*. In other studies, the amount of mold aerosols in bedding or carpets was determined, with values up to 260,000 CFU/m^3; among the detected species, *Aspergillus* and *Penicillium* were dominant [86].

3. Methods for Assessing the Degree of Pollution of the Internal Environment

Many analytical methods may be used to carry out quantitative or qualitative assessments of the microorganisms on a substrate. The choice of an appropriate method for microbial analysis depends not only on its duration and cost but also on the aim of the investigation. The following section describes the main analytical methods found in the literature concerning the microbial growth on building materials.

3.1. Microbiological Method

The microbiological method for the assessment of indoor air quality can be divided into traditional (mycological) and molecular methods.

Mycological evaluation is based on the macroscopic and microscopic observation of the collected and cultured microorganisms, determination of moisture in the collected samples, and evaluation of the efficiency of ventilation and other sanitary installations. This method is based on the determination of the presence of mold in air samples or swabs, calculation of the colony count, and determination of species or genus. Traditional techniques can be distinguished [27,87]:

- the Koch sedimentation method,
- the collision cascade method, which is based on the flow of polluted air through small openings.

The sedimentation method uses the phenomenon of dust and microorganisms settling on the surface of solid media on Petri dishes. The plates are exposed for a specified period of time and then, after covering, incubated at a specified temperature and time depending on the medium used. Colonies are counted in 1 m^3 of air, based on the assumption that, after 5 min, the number of organisms settled in about 100 cm^2 roughly corresponds to the number of organisms settled in 10 L of air [87].

The collision method consists in the fact that the air, flowing at high speed, which hits the surface of the nutrient medium, is forced to suddenly change the direction of movement and that, as a result, a

microorganism falls out of the air current and settles on the surface of the medium. The Petri dishes with media are incubated, the number of colonies on each plate is counted, and the number of colonies in 1 m^3 of air is calculated afterwards [27].

The cascade impactor (Figure 3) is a device for the determination of specific size distributions of any aerosol-forming dust. By means of properly profiled channels leading the aerosol, dust of different diameters settles in different places [27].

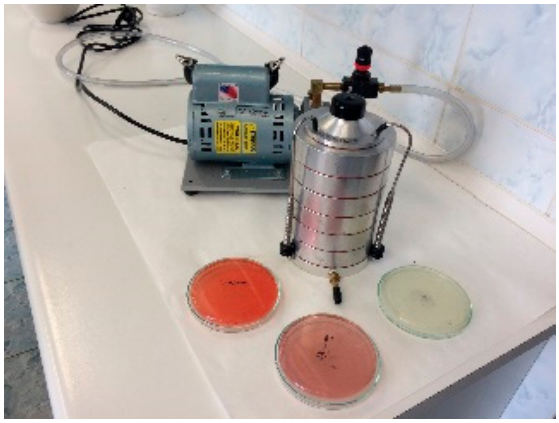


Figure 3. Photograph presenting the cascade impactor and Petri dishes.

The use of traditional microbiological techniques can take up to 43 days. They are the breeding techniques that require cultivation of fungal colonies, which is why they are so time-consuming.

3.2. Molecular Methods

Among the molecular methods for detection of microbiological infections, one can mention the Polymerase Chain Reaction (PCR) method, which is based on amplification of a DNA fragment as a result of heating and cooling the sample under laboratory conditions with the use of chemical reagents, oligonucleotides, and polymerase enzyme. PCR is a relatively costly and time-consuming method, but it offers unambiguous results [88,89].

NGS is a DNA sequencing technique used in genomic research that performs on the entire DNA or RNA isolated from the building material and enables the total description of the total community without the necessity of cultivation [90–92].

3.3. Chemical Methods

A wealth of information on the presence of microorganisms can be provided by various chemical methods. They are most often applied to provide metabolic activity estimates and, in consequence, microbial population's toxicity potential on a substrate. The possibilities are as follows:

- Detection of the chemical components forming the microbial cells such as components which make up the mycelium cells for fungi (chitin and ergosterol), adenosine triphosphate (ATP) being an energy-producing molecule, and cell-wall polysaccharides (β-D-glucane). The components' quantity can be connected with the number of microorganisms or correlated with the microbial species' type [76,77,93,94].
- Detection of the chemical compounds formed by microorganisms such as nitric oxide, various toxins (mycotoxins, endotoxins, etc.), and other substrate-sampled metabolites. Using this indirect method, it is possible to assess the metabolic (or biological) activity of microorganisms and, as a result, provide an estimate on microbial population. This method is mainly used to collect information on the quantity of potentially harmful compounds (volatile compounds or metabolites on substrates) and to identify the pathogenic potential of the sampled environment and resulting health hazards [76,93,95].

The chemical methods enable the identification of selected markers that are the products of metabolites such as mycotoxins or volatile organic compounds. Among all the methods, the most popular ones are [96]

- Gas chromatography mass spectrometry,
- High-performance liquid chromatography.

Both methods require a complex sample preparation process that requires a lot of manual work [97–99].

The chemicals found in abundance in indoor air (in mg/m^3) can be measured in real time using the active methods. In this way, for example, the concentrations of carbon dioxide, carbon monoxide, and ozone are measured. The use of active methods is difficult for, e.g., the pollutants from the VOC group, which are found in indoor air in low concentrations (in $\mu g/m^3$) [100]. Their determination often requires sampling with simultaneous concentration. When determining the VOC concentrations, total air samples or the samples with simultaneous concentration by means of passive or dynamic dosimetry are usually taken. Regardless of the sample collection and concentration method, the next step is chemical or thermal desorption followed by analysis based on UV spectrophotometry or liquid and/or gas chromatography with different detection systems. The qualitative and quantitative analysis procedures are therefore quite complicated, time consuming, and expensive [101].

Chromatographic methods are a helpful tool in the detection of volatile organic compounds. These are GC-MS (Gas Chromatography-Mass Spectrometry), SESI-MS (Secondary Electrospray Ionization-Mass Spectrometry), IMS (Ion Mobility Spectrometry), SIFT-MS (Selected Ion Flow Tube Mass Spectrometry) and PTR-MS (Proton Transfer Reaction Mass Spectrometry). The first method is the gas chromatography mass spectrometry. GC-MS consists of two main construction blocks: a gas chromatograph and a mass spectrometer. The gas chromatograph uses a capillary column which is dependent on the column dimensions (length, diameter, and film thickness) and phase properties (e.g., 5% polysiloxane phenyl). The difference in the chemical properties between the different molecules in a mixture and their relative affinity to the stationary phase of the column will cause the separation of molecules as the sample moves along the column length. Particles are retained by the column and then removed from the column at different times (known as the retention time), allowing the mass spectrometer below to capture, ionise, accelerate, deflect, and detect ionised particles separately. The mass spectrometer does this by breaking down each molecule into ionised fragments and by detecting these fragments using their mass-to-charge ratio. These two elements, when used together, allow for a much more accurate identification of the substance than any of the units used separately. The second method is the secondary electrospray ionization mass spectrometry, which is an environmental ionisation technique for the analysis of trace vapour concentrations, where nano-electrosprays produce charging agents which collide with the analyte molecules directly in the gas phase. In the next reaction, the charge is transferred and the vapours are ionised, and most of the molecules are protonised (in positive mode) and deposited (in negative mode). Another technique is the ion mobility spectrometry, which is the analytical technique used to separate and identify ionised particles in the gaseous phase by their mobility in the carrier buffer gas. IMS instruments are highly sensitive stand-alone devices but are often combined with mass spectrometry, gas chromatography, or high-performance liquid chromatography to achieve multidimensional separation. They are available in different sizes, from a few millimetres to several metres depending on the specific application, and are capable of operating in a wide spectrum of conditions. There is also the technique connected with chromatography—the selected ion flow tube mass spectrometry—which is a quantitative mass spectrometry technique for trace gas analysis which involves the chemical ionisation of trace volatile compounds by selected cations in a strictly defined period of time along a flow tube. The last technique is the proton transfer reaction mass spectrometry. This analytical chemistry technique uses gas-hydron phase ions as the ion source. PTR-MS is used for online monitoring of volatile organic compounds in ambient air. PTR-MS consists of an ion source connected directly to the drift tube (unlike SIFT-MS,

no mass filter is connected) and an analysis system [102]. The main disadvantage which may be found in all of the above described methods is the problem with sample desorption. Solid phase microextraction (SPME) should be used to avoid this problem. In these methods, the sorbent is applied to a thin glass or quartz fibre inside a steel needle. The frequently used sorbents are polyacrylate (PA), polydimethylsiloxane (PDMS), polydimethylsiloxane–polydivinylbenzene (PDMS/DVB), Carbowax, and Carboxen [103].

3.4. Quick Detection with Multi-Sensor Array

Many types of fungi produce a specific range of volatile substances [27,104–106]. This profile (gas fingerprint) can be used for the early detection of fungal contamination of the affected materials. Electronic or optoelectronic nasal technology has been previously used in many branches, for example, food [104,105,107], medicine, pharmaceutical, cosmetics [27,107–109], or the environmental industry [110–112]. Therefore, the possibility to identify the fungal contamination of samples and their types based on the analysis of the superficial phase is relevant both from the scientific and practical points of view. Such studies are important especially during the early stages of fungal development, when their presence is not yet visible, the spore concentration is low, and there is no obvious mycelium development. Therefore, the use of electronic noses based on a gas sensor array to quickly evaluate and identify samples contaminated with various fungi—including those typically found in construction—seems to be a promising approach.

Fast detection enables recognizing different types of particles contained in the environment or their characteristics, i.e., alkalinity, acidity, and specific chemical bonds. This information allows determining the chemical composition of the environment.

4. Gas Sensor Array

The gas sensor array constitutes the basis for the electronic nose. It is a multi-sensor device used for testing air quality in addition to recognizing specific products due to their smell. Multi-sensor gas analysers are employed for monitoring specific air pollutants. Multi-sensor systems are also applied for measuring the degree of microbiological contamination of buildings. In comparison with chromatography or olfactometry, the application of multi-sensor systems is characterised by lower cost of equipment and by performing analyses [113,114]. The use of e-noses significantly shortens the time required for an odor analysis, which was performed by means of olfactometric technique or with the use of gas chromatography coupling and mass spectrometry (GC-MS). Conducting tests with the use of the aforementioned techniques lasts up to several hours. In contrast, the analysis carried out with the use of an e-nose only takes about a few minutes [115].

The e-nose principle is based on a primitive model of a biological olfactory analyser. The array is made of a plate on which several or several dozen different sensors are placed, reacting selectively to the presence of different compounds or groups of chemical compounds [88]. Owing to the application of many sensors of different sensitivity and selectivity, each time it is possible to create a unique combination of signals, so-called gas fingerprints, which are characteristic for the given gas sample. Depending on the type of sensors used (specific or nonspecific), they are capable of recognizing individual components of the sample or a group of components, which enables the combination of readings with different parameters. After receiving the measurement data, special selected analytical methods are employed to obtain specific information about the tested gas [116]. For the analysis, a set of profiles is selected, which includes the responses of the individual elements of the matrix. Different sensors recognise different compounds; hence, different signals are generated, which together form a certain combination [88,117]. Therefore, information on the possibility of certain compounds in the gas under analysis is necessary for proper calibration of the array [117].

Electronic noses can be constructed using various commercially available detectors, including electrochemical (EC), metal oxide semiconductor (MOS), nondispersive infrared sensors (NDIR), thermal sensor, and Photoionization Sensor (PID) [118]. Numerous scientific units are working on

improving the piezoelectric sensors with surface acoustic wave (SAW) or bulk acoustic wave (BAW) like quartz crystal microbalance (QCM, known also as QMB). The optical sensors which utilize surface plasmon resonance (SPR) are applied as well [119].

Table 1 presents general information about the sensors most commonly applied in the e-nose systems. MOS constitutes one of the widespread types of sensors, which stems from their easy implementation and the sensitivity range enabling a versatile application in measurement environments. They are widely used in the considered arrays, utilizing semiconductor metal oxides, usually tin dioxide (SnO_2) with additives such as silver, gold, and platinum (used to improve the selectivity of the gas-sensitive layer) [120]. The MOS sensors are characterized by the range from 1 ppm to approximately 1%. The electrochemical sensors enable the improvement of LOD (Limit of detection) to about 0.1 ppm, and the detection range is lower than in the case of MOS [118]. The application of a Photoionisation Detector PID, which is characterized by high sensitivity from about 1 ppb to 200 ppm depending on the detector type, is a good solution [121,122].

Table 1. General characteristic of most commonly applied gas sensors [117,118,123].

Sensor Type	Sensor Advantages	Sensor Disadvantages
calorimetric	fast sensor reaction, short return time to the baseline	high operating temperature, sensitive only to oxygen-containing compounds
catalytic	small sensor sizes, low measurement costs	requires environmental control, baseline drift, low sensitivity to ammonia and carbon dioxide
conductive polymers	low measuring temperature, sensitive to many volatile organic compounds, fast sensor reaction, various sensor coverings, inexpensive	susceptibility to poisoning the sensor, sensitive to moisture and temperature, sensors can be supersaturated by some compounds, limited, short sensor life
electrochemical	low operating temperature, low energy consumption, sensitive to many volatile organic compounds	significant sensor size, limited sensitivity for simple compounds or low molar mass
oxide semiconductor (MOS)	high sensitivity, rapid sensor response, return of the signal to the baseline for compounds with low molar mass	high operating temperature, high energy consumption, susceptible to sulphur poisoning and weak acids, limited types of sensor coverings, sensitive to dampness, poor precision
optical	high sensitivity, ability to distinguish individual compounds in a mixture, ability to measure many parameters	complicated sensor array systems, expensive to run, susceptible to mechanical damage, limited mobility
quartz microbalances (QMB)	high precision, wide range of active element covers, high sensitivity	complicated electronics, low signal-to-noise ratio, sensitive to humidity and temperature
surface acoustic wave (SAW)	sensitivity, good response time, inexpensive, small, sensitive to many compounds	complicated electronic circuits

Biosensors are highly useful in laboratory investigations. Currently, it constitutes a dynamically developing branch of science connected with sensors. They are characterized by a low limit of detection (LOD), well below 1 ng·mL^{-1} [124,125]. Generally, biosensors comprise a biologically sensing layer, which specifically interacts with the target analyte. The sensing biological layer is deposited on different transducers, depending on the sensor type. The generated signal is proportional to the selectively adsorbed specific analytes. Piezoelectric sensors, as well as many types of electrochemical sensors, are often employed as transducers [74]. The odorant-binding proteins (OBP) derived from different organisms are applied for this purpose [126]. Different cells or specially isolated nanovesicles were examined as well [127,128]. The biosensors formed in this way exhibit high sensitivity and selectivity. However, there are certain issues that hamper the practical application of biosensors. One of them is the lack of reproducibility of biomaterial deposition on the carrier as well as the difficulties in obtaining stable and reproducible measurement results.

Literature describes the application of biosensors for the detection of fungal infestation, mainly of foodstuffs. This is indirectly connected by the maximum permissible content of mycotoxins in

particular products, such as aflatoxins (AFB1, AFB2, and AFG2), ochratoxins A (OTA), patulins (PAT), deoxynivalenol (DEN), zearalenon (ZEN), fuminisins, as well as T-1 and HT-2 toxins [74]. Increasingly accurate methods of detecting trace pollutants. Table 2 presents the selected cases.

Table 2. Recent application of biosensors for mycotoxin contamination mainly in foodstuff.

Mycotoxin	Sensor Type	Sensing Element	Sensibility	Ref.
AFB1	Piezoelectric (QCM)	Antibody	1.625 ng mL^{-1}	[129]
AFB2	Optical (SPR)	Aptamer	0.19 ng mL^{-1}	[130]
OTA	Piezoelectric (QCM)	Antibody	0.16 ng mL^{-1}	[124]
T-2	Optical (SPR)	Antibody	1.2 ng mL^{-1}	[131]
PAT	Potentiometric (EIS/DPV)	Aptamer	0.27 pg mL^{-1}	[132]
ZEN	Amperometric (CV/DPV)	Aptamer	0.17 pg mL^{-1}	[133]

The majority of studies described so far pertained to the application of e-noses for product quality control (e.g., food or pharmaceutical) [134,135], detection of various ailments [136], or the assessment of odor nuisance [137]. They are also useful for the continuous measurements of the degree of pollution of environmental samples (water and air) as well as for evaluating the effectiveness of sewage and waste gas treatment [98]. Recently, electronic noses have been increasingly often used to test the quality of indoor air and to control the microbiological infestation phenomenon.

The main e-nose application hindrance corresponds to very low MVOC and mycotoxin concentrations. These are mainly trace concentrations reaching a few ppb or nanograms [74,138]. In numerous cases, this value is below the limit of detection of the utilized sensors. Direct measurements conducted in rooms, especially by means of an e-nose, may be used for a general and preliminary evaluation of the fungal infestation of a building [89,139]. In such cases, clear symptoms of infestation significantly exceeding the standard values can already be observed. Two solutions can be employed in order to improve LOD of devices: preconcentration on solid sorbents [140] as well as decreasing the sample to air volume ratio by tightly sealing it in a small vessel. The techniques of trap and desorption for LOD enhancement were adopted from gas chromatography. Mainly solid sorbents are used, including Tenax TA, Tenax GR, Carbopack B, Carbotrap, Carboxen 569, and Carbosieve SIII [141]. Numerous e-nose devices require the flux in the range of 150–400 mL min^{-1} over at least several dozen seconds [112,142–144]. Therefore, the application of SPME fiber is limited, e.g., when other detection types are employed like mass spectrometry (MS) [104]; however, the SPME fibers can be used even in the case of MOS sensors [145]. Preconcentration requires the exposure of the sorbent in the investigated room for a certain period of time. According to Sawoszczuk et al. [103], it can range from 1 to 24 h for the SPME fibers. The other method is commonly employed under laboratory conditions for the analysis of fungal infestation of building materials [112,146] or other samples, e.g., foodstuffs. The samples are placed in glass containers or laboratory chambers with the volume from several dozen mL (e.g., 20 mL vials) [146] to several liters (Table 2) (Figaro gas test box 5.4 L) [144].

Two approaches can be distinguished among e-nose users: investigations conducted using the commercially available sensors [147,148] as well as construction of custom sensor arrays, like the one presented in Figure 4. The former is characterized by numerous advantages because such devices are pre-calibrated, pre-configured, and usually provided with software for data acquisition and analysis. When custom arrays are configured, the e-nose startup as well as management of the acquired data is labor-intensive; however, such a sensor array may be optimized for a specific application. Numerous investigations, i.e., the ones enumerated in Table 3, confirm the high efficiency of the custom arrays.



Figure 4. Different versions of e-noses developed at Lublin University of Technology: Top left shows laboratory version 7×MOS (Metal Oxide Semiconductor) with undercover sensor chamber; top right is the portable device 8×MOS undercover sensor chamber (1-8 Figaro gas sensors and temperature and relative humidity sensors); bottom left is laboratory version 16×MOS with 2 switching inlets (flushing air and sample); bottom right is laboratory version 17×MOS with 4 multiplexed inlets (flushing air and 3 samples).

Table 3. Chosen application of e-nose for fungal contamination assessment [1].

Application	e-Nose	Sampling Details	Description	Ref.
Building materials	12×MOS	sampling 3 min @ 200 mL min^{-1}, cleaning 50 min @ 200 mL min^{-1}	Possibility to detect *Aspergillus* versicolor growing on different building materials (classification rate in range 80 and 89%); the classification ability is assessed in a second dataset collected 4 and 5 months later.	[112,140]
	8×MOS	100 mL/mn; 2 min flushing/5 min measurement	Ability to distinguish between the non-contaminated and contaminated samples, shortly after fungal contamination, typically occurs with indoor environment (*Penicillium*, *Aspergillus*, *Acremonium*, *Paecilomyces*, and *Cladosporium*)	[139]
	32×MOS	SPME sampling	Building timber infection with *Serpula lacrimans*, discrimination between infected and uninfected samples	[145]
Building assessment	15×MOS	sampling 60 s, 30 s cleaning, 240 ns reference sample	E-noses can detect and classify 5 common fungi species; correct classification was achieved at 24 h of growth.	[140]
	8×MOS	sampling 5 min @100 mL/mn	Discrimination between buildings with different levels of mold stroke.	[27,89]
Fungi species discrimination	αFox-3000 AlphaM.O.S. (12×MOS) with a HS-100 auto sampler	20 mL flask, 500 µL sample injected into sensor chamber; air flux 150 mL/min; 2 min measurement/2 min recovery	Ability to correctly identify closely related fungi	[146]
Library paper	BH114 Bloodhound Sensors (14×CP) and eNOSE 4000 Marconi Applied Technologies (12×CP)	sampling from bags 500 mL and vials 50 mL, flushing with air (BH114) and nitrogen (eNOSE4000)	Possibility of *Aspergillus terreus*, *A. holandicus*, and *Eurotium chevalieri* differentiation after 20 h of incubation; possible differentiation between particular species as well as paper growing substrate.	[106,149]
Rapeseed	Cyranose 320 Sensigent (32×CP)	gas box 5.4 L, 10 s baseline purge, 40 s sample draw-in, 5 s laboratory air purge, >120 s sample purge	Distinction between species of spoiled and unspoiled rapeseeds, colony forming units, and ergosterol content; the electronic nose provided responses correctly corresponding to the level of spoilage.	[145]
	6×MOS	10 s baseline purge, 40 s sample draw-in, 5 s laboratory air purge and 140 s sample purge	Possibility of rapeseed spoilage examination	
Human pathogenic influence	6×MOS; and 2nd based on GC column	0.4 L/min;4.6 mL/min	Classification correction of *Penicillium chrysogenum*, *Cladosporium herbarum*, *Rhizopus oryzae*, and *Alternaria alternate* species was respectively 55–100% and 80–100% for MOS- and GC-based e-nose	[150,151]
Bakery	MS	SPME fiber desorption	ergosterol level prediction, 87–96% accuracy of *Eurotium* and *Aspergillus* and 46% accuracy for *Penicillium* species detection	[143]
Fruits	PEN3 Airsense (10×MOS)	sampling 60 s @ 150 mL min^{-1}, cleaning 120 s	Successfully discriminated after 48 h of storage, 90% discrimination accuracy among *Botrytis cinerea*, *Monilinia fructicola*, and *Rhizopus stolonifer* contamination in peaches.	[104]
	PEN3 Airsense (10×MOS)	sampling 50 s @ 200 mL min^{-1}, cleaning 60 s@ 400 mL min^{-1}	Prediction of OTA content in *Aspergillus carbonarius* cultured grape-based medium; all the OTA level samples were positively classify using e-nose; comparison to GC-MS analysis	[152]
Cereals	PEN2 Airsense (10×MOS)	sampling 90 s @ 200 mL min^{-1}, cleaning 60 s@ 600 mL min^{-1}	Fungal species and counts in rice could be classified and predicted with 96.4% accuracy; early detection of *Aspergillus spp.* contamination in rice is feasible	[142]

[1.] MS—mass spectrometry, MOS—metal oxide semiconductor, SPME—solid phase microextraction, OTA—ochratoxin A, CP—conducting polymer.

5. Analysis of Received Signals

In gas sensor arrays, the output signal of a sensor forms components of a vector. Therefore, for chemical sensors, feature extraction evaluates certain parameters from a signal stream, which represent the information pertaining to the objective of classification. It is of key significance, since it governs the sensor output used in estimating the measured quantities [153].

In order to conduct the statistical analysis from a gas sensor array, appropriate parameters should be selected first. These are usually statistical values obtained for a stabilized signal, presented in absolute or relative form. The static response can be determined as a change is resistance ΔR of particular sensors, most often expressed as the $R_S - R_O$ difference, R_S/R_O relative value, relative difference $(R_S - R_O)/R_O$, and logarithmic relative value $\ln(R_S/R_O)$ [154], where R_S is sensor signal in particular time, R_O is baseline, and sensor signal is for zero gas. This is so-called baseline correction. Its advantage includes partial leveling of the changes in sensor characteristics in time, caused by poisoning [155].

However, the application of dynamic parameters describing signal variability in time is enjoying increasing attention. It enables to shorten the analysis time because it does not require signal stabilization. Extraction of dynamic features can be employed especially in the case of impulse sampling or sample injection to a gas sensor array. The signal properties may involve half width of the impulse, kurtosis, and impulse field or skewness [156]. The rate of sorption/desorption is different for particular gases, which also enables inferring additional information on the samples.

Moreover, transformation, centering, or scaling can be applied for signal processing. Transformation involves presenting the measurement data in a new form. The data are presented as logarithms or the first or second derivative is calculated [157,158]. Centering is employed to subtract a fixed value from the response of a single sensor in an array. It is carried out on a data matrix by subtracting the mean value of elements in a given column from each column element [159]. In turn, scaling enables to approximate results to a homogenous numerical value, facilitating their interpretation [159]. Scaling is employed especially in the cases where the variables representing a significant property are subject to slight changes in small range in comparison with the remaining variables [160,161].

The measurement data from sensor arrays are multidimensional; therefore, it is difficult to derive important information on the investigated gas sample without the application of appropriate analysis methods. In a dataset pertaining to the number of measurements, the explanatory techniques, employed following the feature extraction, as well as preprocessing and normalization, are used to investigate the characteristics of data and discover its internal properties [153]. The exploratory analysis of data indicates the adequateness of the sensor array for a given task; then, supervised classification can be carried out to build a model for predicting the class membership of the investigated samples. Among the exploratory analyses, representation and clustering can be highlighted. The former involves the algorithms that are employed to provide representation of the data in lower space of dimension than the original one [162,163].

Among the dimensionality reduction and classification methods, the most popular ones include Principal Component Analysis (PCA) [164], Linear Discriminant Analysis (LDA) [165], Quadratic Discriminant Analysis (QDA) [166], Support Vector Machine (SVM) [167], Cluster Analysis (CA) [168], Factorial Discriminant Analysis (FDA) [169], Canonical Discriminant Analysis (CDA) [170], Hierarchical Clustering (HC) [171], and Artificial Neural Network (ANN) [120,164,172]. In turn, the concentration of samples is usually determined with Partial Least Squares (PLS) [173], Multiple Linear Regression (MLR) [174], Ridge Regression (RR), or regression ANN. In the scientific literature on sensor arrays, the application of PCA, both for the preliminary assessment of measurement results as well as the main method of data analysis, is very common [164,175].

Numerous types of cluster analysis can be indicated; the main classification is into the hierarchical and non-hierarchical CA [176]. Cluster analysis (clustering) is based on grouping a set of objects that are similar to each other (in a certain way) rather than to other clusters [177]. CA does not

constitute an unambiguous algorithm; instead, it is a task for solving. Different algorithms can be used, varying in terms of understanding what a cluster is [177,178]. Hierarchical cluster analysis is an unsupervised learning method in statistics, which can be used to divide objects into groups, and Ward's method with Euclidean metrics can be used as one of many methods of agglomeration [163,179]. The non-hierarchical cluster analysis employs a distance matrix in a multidimensional space to find homogenous data clusters [97,177]. Fuzzy clustering, which is a special type of CA, can be employed as well for tasks of signal analysis from sensor matrices exposed for air from mold-contaminated buildings [180]. The hard approach to clustering is not always effective and sufficient to tackle the real-life complexity; thus, fuzzy clustering becomes useful is such scenarios [181,182]. In the case of the fuzzy k-means (fkm) algorithm, objects are grouped into clusters to a varying degree, i.e., in accordance with the gray-scale approach. Generally, fkm can be employed in direct practical applications, but there are some extensions which further enhance its performance [183]. A limited number of homogenous clusters may be found by applying fuzzy clustering. In order to include objects into clusters, the membership degrees, ranging in the interval, are used [184].

A review of the literature indicated that the most popular methods of analyzing the sensor readout involve PCA, CA, and the supervised learning techniques [185]. The statistical method often used for analyzing multidimensional signals involves data grouping through selection of new variables that best describe the information profile from the matrix. Thus, the multidimensionality of data is reduced (compressed), enabling their presentation on charts [186]. Some of the original data is lost in the course of transformations; however, they can be reversed, thus restoring the information [187]. Importantly, the mentioned methods can be implemented into the control structure; additionally, the measurements of smell nuisance can be subjected to transformation while still being conducted [178].

PCA is performed to consistently portray a set of data in a representation space [188]. In mathematical terms, it can be considered a linear transformation described as S = WX, where X is the original set of data, W denotes the transformation matrix, while S corresponds to the data in the representation space [153]. PCA is the most straightforward and commonly employed multivariate analysis method. In PCA, the set of data is represented on a subspace of reduced dimensionality [89,189]; the statistical properties characterizing the original set of data are preserved there in some proportion. The data set from a chemical sensor array can be reliably represented in subspaces of smaller dimension because individual sensors are correlated among themselves. The number of dimensions can be established based on Kaiser criterion [190] or another method, like scree plot and the level of cumulative proportion of explained variance by k principal components. From the practical point of view, the described method entails selecting new variables (axes) which are mutually independent as well as describing the variability of the analyzed set of data in a thorough manner [191] and seeing the original data from a new viewpoint [179,192]. The designated variables lack physical significance per se and have no unit. Their contribution in the total covariance of the dataset constitutes the only marked value, which is expressed in percent. The advantage is that plotting indicates the relations and differences between the analyzed data, which cannot be seen in multidimensional datasets [89]. Afterwards, the data obtained in the course of measurements with gas sensors can be assigned to groups, also enabling a graphical representation of the results [193]. In mathematical terms, PCA involves finding an orthogonal basis in which the correlations between sensors are absent. The statistical properties characterizing a set of data can only be retained if the statistical data distribution is assumed. In PCA, Gaussian distribution is used to describe the multivariate data; PCA is subsequently calculated only taking into account the second moment of the data probability distribution (covariance matrix).

Principal component analysis and cluster analysis are commonly used for visualization of multidimensional observations in space and unsupervised classification [98,139,177,186]. In turn, the supervised learning methods can be employed to confirm the hidden structure (i.e., homogenous clusters of data) for the purpose of classification. The classification tree technique is an example of predictive supervision carried out by means of by the machine learning method [178,194,195]. Classification sets, containing the input and output classes can be used to describe each of the tested

systems. The input parameters comprise preconditions, environmental states, as well as other rare parameters [196]. In each classification, there can be any number of separable classes which describe the parameter occurrence. The classes are usually selected in line with the partitioning equivalence principle for the abstractions of the test case and limit value analyses for specific test cases [185,197]. When these classifications are combined, a classification tree is formed. Classifications can create compositions for the semantic purposes.

Partial Least Squares Discriminant Analysis (PLS-DA) [198] and Generalized Linear Models with Regularized Path (GLMNET) [199] also can be applied as the supervised methods of machine learning for analysis of multidimensional signal form gas sensors array. These methods are chosen when large similarities or even redundancies between the sensors readout were obtained. The techniques differ in that the PLS method is utilized for reduce the space dimensionality, when GLMNET eliminates the matrix singularity of the discriminant model, by necessary penalties adding into likelihood loss function [163].

According to certain authors, Artificial Neural Networks (ANN) are considered superior [196]. ANN is based on the concept of a complex network formed by interconnected brain neurons; in this network, the information is collected by dendrites from the neighboring cells while the transformed data is passed further by means of axons. Thus, artificial neural network operates as a mathematical model in which data processing is performed in line with the aforementioned scheme [98]. A procedure known as "learning by algorithms" is carried out to couple ANN and a multi-sensor array. Depending on how complex the input and output data relations are, the number of neuron layers is determined. The system created in such way can be compared to the mammal olfactory sense [116,178,197,200].

6. Conclusions

The climate of the rooms in which a person spends a significant part of their time (i.e., about 90% of the day) has a colossal impact on their health and well-being. Often, designers and users do not realize how the microbiological infestation can lower the standard of living and become an unexpected source of various diseases and illnesses. The use of an electronic nose may significantly shorten the time of air analysis, which was performed using olfactometric technique or using gas chromatography coupling and mass spectrometry (GC-MS). Examination with the use of the above-mentioned techniques lasts up to several hours, while the electronic nose can analyze the air within a dozen or so minutes. Modern electronic noses are increasingly often used to test air quality indoors and to control the phenomenon of microbiological infestation. They are also useful during continuous measurements of the degree of pollution of environmental samples (air and water) as well as the evaluation of the effectiveness of waste gas and wastewater treatment. Microbiological corrosion should be treated not only from the point of view of material damage but also in terms of the overall health condition of the society.

Author Contributions: Z.S. and G.Ł. developed the concept of the article and wrote the outline of the paper draft; M.G., A.M., and S.D.-S. worked mainly on Sections 2 and 3; G.Ł. worked mainly on Section 4; G.Ł. worked mainly on Section 5; Z.S. and G.Ł analyzed information and improved the paper draft. S.D.-S. formatted the manuscript. All authors of this article provided substantive comments. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially supported by Ministry of Science and Higher Education in Poland, within the statutory research of particular scientific units.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Oszust, K.; Panek, J.; Pertile, G.; Siczek, A.; Oleszek, M.; Frąc, M. Metabolic and genetic properties of Petriella setifera precultured on waste. *Front. Microbiol.* **2018**, *9*, 115. [CrossRef] [PubMed]
2. Husman, T. Health effect of indoor-air microorganisms. *Scand. J. Work Environ. Health* **1996**, *22*, 5–13. [CrossRef] [PubMed]

3. Fung, F.; Hughson, W.G. Health effects of indoor fungal bioaerosol exposure. *Appl. Occup. Environ. Hyg.* **2003**, *18*, 535–544. [CrossRef] [PubMed]
4. Crook, B.; Burton, N.C. Indoor moulds, sick building syndrome and building related illness. *Fungal. Biol. Rev.* **2010**, *24*, 106–113. [CrossRef]
5. Guo, H.; Lee, S.C.; Chan, L.Y. Indoor air quality investigation AT air-conditioned and non-air-conditioned markets in Hong Kong. *Sci. Total Environ.* **2004**, *323*, 87–98. [CrossRef]
6. Jadud, M.A.; Rock, B.A. Tobacco smoking policy and indoor air quality: A case study. *Energy Build.* **1993**, *20*, 143–150. [CrossRef]
7. Harrison, J.; Pickering, C.A.C.; Faragher, E.B.; Austwick, P.K.C.; Little, S.A.; Lawton, L. An investigation of the relationship between microbial and particulate indoor air pollution and the sick building syndrome. *Respir. Med.* **1992**, *86*, 225–235. [CrossRef]
8. Ross, C.S.; Lockey, J.E. Indoor air quality medicolegal issues. *J. Allergy Clin. Immunol.* **1994**, *94*, 417–522. [CrossRef]
9. Andersen, I.; Gyntelberg, F. Modern indoor climate research in Denmark from 1962 to the early 1990s: An eyewitness report. *Indoor Air* **2011**, *21*, 182–190. [CrossRef]
10. Sundell, J. Reflections on the history of indoor air science, focusing on the last 50 years. *Indoor Air* **2017**, *27*, 708–724. [CrossRef]
11. Tietjen, G.E.; Khubchandani, J.; Ghosh, S.; Bhattacharjee, S.; Kleinfelder, J. Headache symptoms and indoor environmental parameters: Results from the EPA BASE study. *Ann. Indian. Acad. Neurol.* **2012**, *15*, 95–99. [CrossRef]
12. Pierpaoli, M.; Ruello, M.L. Indoor air quality: A bibliometric study. *Sustainability* **2018**, *10*, 3830. [CrossRef]
13. Klepeis, N.E.; Nelson, W.C.; Ott, W.R.; Robinson, J.P.; Tsang, A.M.; Switzer, P.; Behar, J.V.; Hern, S.C.; Engelmann, W.H. The National Human Activity Pattern Survey (NHAPS): A Resource for assessing exposure to environmental pollutants. *J. Expo. Anal. Environ. Epidemiol.* **2001**, *11*, 231–252. [CrossRef] [PubMed]
14. Połednik, B. Variations in particle concentrations and indoor air parameters in classrooms in the heating and summer seasons. *Arch. Environ. Prot.* **2013**, *39*, 15–28. [CrossRef]
15. Suchorab, Z.; Sobczuk, H.; Guz, Ł.; Łagód, G. The possibility of building classification for mould threat using gas sensors array. *Adv. Mater. Res.* **2015**, *1126*, 161–168. [CrossRef]
16. Maddalena, R.; Mendell, M.J.; Eliseeva, K.; Chan, W.R.; Sullivan, D.P.; Russell, M.; Satish, U.; Fisk, W.J. Effects of ventilation rate per person and per floor area on perceived air quality, sick building syndrome symptoms, and decision-making. *Indoor Air* **2015**, *25*, 362–370. [CrossRef]
17. Polizzi, V.; Adams, A.; Picco, A.M.; Adriaens, E.; Lenoir, J.; Van Peteghem, C.; De Saeger, S.; De Kimpe, N. Influence of environmental conditions on production of volatiles by Trichoderma atroviride in relation with the sick building syndrome. *Build. Environ.* **2011**, *46*, 945–954. [CrossRef]
18. Huo, X.; Sun, Y.; Hou, J.; Wang, P.; Kong, X.; Zhang, Q.; Sundell, J. Sick building syndrome symptoms among young parents in Chinese homes. *Build. Environ.* **2019**, *169*, 106283. [CrossRef]
19. Berglund, B.; Lindvall, T. Sensory and hyperreactivity reactions and their significance to public health. Sensory reactions to "sick buildings". *Environ. Int.* **1986**, *12*, 147–159. [CrossRef]
20. Sundell, J.; Anderson, B.; Anderson, K.; Lindvall, T. Volatile organic compounds in ventilating air in buildings at different sampling points in the buildings and their relationship with the prevalence of occupant symptoms. *Indoor Air* **1993**, *3*, 82–93. [CrossRef]
21. Chester, A.C.; Levine, P.H. The natural history of concurrent sick building syndrome and chronic fatigue syndrome. *J. Psychiatr. Res.* **1997**, *31*, 51–57. [CrossRef]
22. Burge, P.S. Sick Building Syndrome. *Occup. Environ. Med.* **2004**, *61*, 185–190. [CrossRef] [PubMed]
23. Lim, F.L.; Hashim, Z.; Md Said, S.; Than, L.T.; Hashim, J.H.; Norback, D. Sick building syndrome (SBS) among office workers in a Malaysian university—Associations with atopy, fractional exhaled nitric oxide (FENO) and the office environment. *Sci. Total Environ.* **2015**, *536*, 353–361. [CrossRef] [PubMed]
24. World Health Organization. *WHO Guidelines for Indoor Air Quality: Dampness and Mould*; WHO: Geneva, Switzerland, 2009.
25. Lu, C.Y.; Lin, J.M.; Chen, Y.Y.; Chen, Y.C. Building-related symptoms among office employees associated with indoor carbon dioxide and total volatile organic compounds. *Int. J. Environ. Res. Public Health* **2015**, *12*, 5833–5845. [CrossRef]

26. Lu, C.Y.; Tsai, M.C.; Muo, C.H.; Kuo, Y.H.; Sung, F.C.; Wu, C.C. Personal, psychosocial and environmental factors related to sick building syndrome in official employees of Taiwan. *Int. J. Environ. Res. Public Health* **2018**, *15*, 7. [CrossRef] [PubMed]
27. Suchorab, Z.; Sobczuk, H.; Guz, Ł.; Łagód, G. Gas sensors array as a device to classify mold threat of the buildings. In *Environmental Engineering V*, 1st ed.; Pawlowska, M., Pawlowski, L., Eds.; CRC Press: Lublin, Poland, 2017; pp. 203–210.
28. Dutkiewicz, J.; Górny, R. Biological factors hazardous to human health: Classification and criteria of exposure assessment. *Med. Pr.* **2002**, *53*, 29–39. [PubMed]
29. Żukiewicz-Sobczak, W.; Sobczak, P.; Imbor, K.; Krasowska, E.; Zwoliński, J.; Horoch, A.; Wojdyła, A.; Piątek, J. Fungal hazards in buildings and flats—Impact on the human organism. *Med. Ogólna Nauki Zdr.* **2012**, *18*, 141–146.
30. Wolkoff, P. Indoor air humidity, air quality, and health—An overview. *Int. J. Hyg. Environ. Health* **2018**, *221*, 376–390. [CrossRef]
31. Lu, C.; Deng, Q.; Li, Y.; Sundell, J.; Norbäck, D. Outdoor air pollution, meteorological conditions and indoor factors in dwellings in relation to sick building syndrome (SBS) among adults in China. *Sci. Total Environ.* **2016**, *560–561*, 186–196. [CrossRef]
32. Van Tilborg, M.M.; Murphy, P.J.; Evans, K.S. Impact of dry eye symptoms and daily activities in a modern office. *Optom. Vis. Sci.* **2017**, *94*, 688–693. [CrossRef]
33. Blaszczok, M.; Baranowski, A. Thermal improvement in residential buildings in view of the indoor air quality—Case study for polish dwelling. *Archit. Civ. Eng. Environ.* **2018**, *11*, 121–130. [CrossRef]
34. Kemp, P.C.; Neumeister-Kemp, H.-G.; Esposito, B.; Lysek, G.; Murray, F. Changes in airborne fungi from the outdoors to indoor air; large HVAC systems in nonproblem buildings in two different climates. *Am. Ind. Hyg. Assoc. J.* **2003**, *64*, 269–275. [CrossRef] [PubMed]
35. Pasanen, A.; Juutinen, T.; Jantunen, M.; Kalliokoski, P. Occurrence and moisture requirements of microbial growth in building materials. *Int. Biodeterior. Biodegrad.* **1992**, *30*, 273–283. [CrossRef]
36. Brzyski, P.; Barnat-Hunek, D.; Fic, S.; Szeląg, M. Hydrophobization of lime composites with lignocellulosic raw materials from flax. *J. Nat. Fibers* **2017**, *14*, 609–620. [CrossRef]
37. Brzyski, P.; Barnat-Hunek, D.; Suchorab, Z.; Łagód, G. Composite Materials Based on Hemp and Flax for Low-Energy Buildings. *Materials* **2017**, *10*, 510. [CrossRef] [PubMed]
38. Siddiquee, S.; Al Azad, S.; Bakar, F.A.; Naher, L.; Kumar, S.V. Separation and identification of hydrocarbons and other volatile compounds from cultures of Aspergillus niger by GC–MS using two different capillary columns and solvents. *J. Saudi Chem. Soc.* **2015**, *19*, 243–256. [CrossRef]
39. Isaksson, T.; Thelandersson, S.; Ekstrand-Tobin, A.; Johansson, P. Critical conditions for onset of mould growth under varying climate conditions. *Build. Environ.* **2010**, *45*, 1712–1721. [CrossRef]
40. Ważny, J.; Karyś, J. *Protection of the Buildings against Biological Corrosion*, 1st ed.; Arkady: Warsaw, Poland, 2001. (In Polish)
41. Belanger, K.; Bracken, M.B.; Leaderer, B.P. The relation between fungal propagules in indoor air and Home characteristic. *Allergy* **2001**, *56*, 419–424. [CrossRef]
42. Hroudova, J.; Zach, J. Acoustic and thermal insulating materials based on natural fibres used in floor construction. *World Acad. Sci. Eng. Technol. Int. J. Civ. Environ. Eng.* **2014**, *8*, 1152–1155.
43. Adamczyk, J.; Dylewski, R. Recycling of construction waste in terms of sustainable building. *Probl. Ekorozw.* **2010**, *5*, 125–131.
44. Morath, S.U.; Hung, R.; Bennett, J.W. Fungal volatile organic compounds: A review with emphasis on their biotechnological potential. *Fungal Biol. Rev.* **2012**, *26*, 73–83. [CrossRef]
45. Kuske, M.; Romain, A.C.; Nicolas, J. Microbial volatile organic compounds as indicators of fungi. Can an electronic nose detect fungi in indoor environments? *Build. Environ.* **2005**, *40*, 824–831. [CrossRef]
46. European Agency for Safety and Health at Work. Expert Forecast on Emerging Biological Risks Related to Occupational Safety and Health. *European Risk Observatory Report.* 2007. Available online: https://osha.europa.eu/en/publications/report-expert-forecast-emerging-biological-risks-related-occupational-safety-and-health (accessed on 20 November 2019).
47. US EPA. *EPA 402-F-91-102: Building Air Quality, a Guide for Building Owners and Facility Managers*; United States Environmental Protection Agency: Washington, DC, USA, 1991. Available online: https://www.epa.gov/indoor-air-quality-iaq (accessed on 20 November 2019).

48. AIHA. *The American Industrial Hygiene Association Indoor Environmental Quality Committee*; Gunderson, E.C., Ed.; The IAQ Investigator's Guide Fairfax: Fairfax, VA, USA, 2006.
49. Samson, R.; Flannigan, B.; Flannigan, M.; Verhoeff, A.; Adan, O.; Hoekstra, E. *Health Implications of Fungi in INDOOR Environments*, 1st ed.; Elsevier Science & Technology: Oxford, UK, 1994.
50. Simmons, R.B.; Rose, L.J.; Crow, S.A.; Ahearn, D.G. The occurrence and persistence of mixed biofilms in automobile air conditioning systems. *Curr. Microbiol.* **1999**, *39*, 141–145. [CrossRef] [PubMed]
51. Rose, L.J.; Simmons, R.B.; Crow, S.A.; Ahearn, D.G. Volatile organic compounds associated with microbial growth in automobile air conditioning systems. *Curr. Microbiol.* **2000**, *41*, 206–209. [CrossRef] [PubMed]
52. Schmidt, M.G.; Attaway, H.H.; Terzieva, S.; Marshall, A.; Steed, L.L.; Salzberg, D.; Hamoodi, H.A.; Khan, J.A.; Feigley, C.E.; Michels, H.T. Characterization and Control of the Microbial Community Affiliated with Copper or Aluminum Heat Exchangers of HVAC Systems. *Curr. Microbiol.* **2012**, *65*, 141–149. [CrossRef]
53. Smedje, G.; Wang, J.; Norbäck, D.; Nilsson, H.; Engvall, K. SBS symptoms in relation to dampness and ventilation in inspected single-family houses in Sweden. *Int. Arch. Occup. Environ. Health* **2017**, *90*, 703–711. [CrossRef]
54. Mendell, M.J.; Naco, G.M.; Wilcox, T.G.; Sieber, W.K. Environmental risk factors and work-related lower respiratory symptoms in 80 office buildings: An exploratory analysis of NIOSH data. *Am. J. Ind. Med.* **2003**, *43*, 630–641. [CrossRef]
55. Sessa, R.; Di Pietro, M.; Schia Voni, G.; Santino, I.; Atieri, A.; Pinelli, S.; Del Piano, M. Microbiological indoor air quality in healthy buildings. *New Microbiol.* **2002**, *25*, 51–56.
56. Lugauskas, A.; Krikstaponis, A. Filamentous fungi isolated in hospitals and some medical institutions in Lithuania. *Indoor Built. Environ.* **2004**, *13*, 101–108. [CrossRef]
57. Garcia-Alcega, S.; Nasir, Z.A.; Ferguson, R.; Whitby, C.; Dumbrell, A.J.; Colbeck, I.; Gomes, D.; Tyrrel, S.; Coulon, F. Fingerprinting outdoor air environment using microbial volatile organic compounds (MVOCs)—A review. *TrAC Trend. Anal. Chem.* **2017**, *86*, 75–83. [CrossRef]
58. Chen, X.; Li, F.; Liu, C.; Yang, J.; Zhang, J.; Peng, C. Monitoring, human health risk assessment and optimized management for typical pollutants in indoor air from random families of university staff, Wuhan City, China. *Sustainability* **2017**, *9*, 1115. [CrossRef]
59. Guo, P.; Yokoyama, K.; Piao, F.; Sakai, K.; Khalequzzaman, M.; Kamijima, M.; Nakajima, T.; Kitamura, F. Sick building syndrome by indoor air pollution in Dalian, China. *Int. J. Environ. Res. Public Health* **2013**, *10*, 1489–1504. [CrossRef] [PubMed]
60. Sharma, A.; Clark, E.; McGlothlin, J.D.; Mittal, S.K. Efficiency of airborne sample analysis platform (ASAP) bioaerosol sampler for pathogen detection. *Front. Microbiol.* **2015**, *6*, 512. [CrossRef] [PubMed]
61. Eggleston, P.A.; Bush, R.K. Environmental allergen avoidance: An overview. *J. Allergy Clin. Immunol.* **2001**, *107*, 403–405. [CrossRef] [PubMed]
62. Gardner, J.W.; Shin, H.W.; Hines, E.L. An electronic nose system to diagnose illness. *Sens. Actuator B Chem.* **2000**, *70*, 19–24. [CrossRef]
63. Frąc, M.; Jezierska-Tys, S.; Yaguchi, T. Occurrence, detection, and molecular and metabolic characterization of heat-resistant fungi in soils and plants and their risk to human health. *Adv. Agron.* **2015**, *132*, 161–204. [CrossRef]
64. Norbäck, D.; Hashim, J.H.; Hashim, Z.; Ali, F. Volatile organic compounds (VOC), formaldehyde and nitrogen dioxide (NO_2) in schools in Johor Bahru, Malaysia: Associations with rhinitis, ocular, throat and dermal symptoms, headache and fatigue. *Sci. Total Environ.* **2017**, *92*, 153–160. [CrossRef]
65. Liu, Y.; Zhou, X.; Wang, D.; Song, C.; Liu, J. A prediction model of VOC partition coefficient in porous building materials based on adsorption potential theory. *Build. Environ.* **2015**, *93*, 221–233. [CrossRef]
66. Zhou, X.; Liu, Y.; Song, C.; Liu, J. A study for predicting the VOC emission characteristic of adsorbent blended building materials. *Procedia Eng.* **2017**, *205*, 519–525. [CrossRef]
67. Zhou, X.; Liu, Y.; Song, C.; Liu, J. Impact of Temperature and Microstructure on the Emission Characteristics of VOC in Porous Building Materials. *Procedia Eng.* **2015**, *121*, 1065–1075. [CrossRef]
68. Gross, A.; Mocho, P.; Plaisance, H.; Cantau, C.; Kinadjian, N.; Yrieix, C.; Desauziers, V. Assessment of VOCs material/air exchanges of building products using the DOSEC®-SPME method. *Energy Procedia* **2017**, *122*, 367–372. [CrossRef]

69. Schenkel, D.; Lemfack, M.C.; Piechulla, B.; Splivallo, R. A meta-analysis approach for assessing the diversity and specificity of belowground root and microbial volatiles. *Front. Plant. Sci.* **2015**, *6*, 707. [CrossRef] [PubMed]
70. Zhou, X.; Liu, Y.; Song, C.; Liu, J. A study on the formaldehyde emission parameters of porous building materials based on adsorption potential theory. *Build. Environ.* **2016**, *106*, 254–264. [CrossRef]
71. Gallego, E.; Roca, F.J.J.; Perales, J.F.F.; Sánchez, G.; Esplugas, P. Characterization and determination of the odorous charge in the indoor air of a waste treatment facility through the evaluation of volatile organic compounds (VOCs) using TD–GC/MS. *Waste Manag.* **2012**, *32*, 2469–2481. [CrossRef]
72. Araki, A.; Kanazawa, A.; Kawai, T.; Eitaki, Y.; Morimoto, K.; Nakayama, K.; Shibata, E.; Tanaka, M.; Takigawa, T.; Yoshimura, T.; et al. The relationship between exposure to microbial volatile organic compound and allergy prevalence in single-family homes. *Sci. Total Environ.* **2012**, *423*, 18–26. [CrossRef]
73. Sun, Y.; Hou, J.; Cheng, R.; Sheng, Y.; Zhang, X.; Sundell, J. Indoor air quality, ventilation and their associations with sick building syndrome in Chinese homes. *Energy Build.* **2019**, *197*, 112–119. [CrossRef]
74. Oliveira, I.S.; Galdino da Silva, A., Jr.; Souza de Andrade, C.A.; Oliveira, M.D.L. Biosensors for early detection of fungi spoilage and toxigenic and mycotoxins in food. *Curr. Opin. Food Sci.* **2019**, *29*, 64–79. [CrossRef]
75. Gutarowska, B.; Żakowska, Z. Elaboration and application of mathematical model for estimation of mould contamination of some building materials based on ergosterol content determination. *Int. Biodeterior. Biodegrad.* **2002**, *49*, 299–305. [CrossRef]
76. Verdier, T.; Coutand, M.; Bertron, A.; Roques, C. A review of indoor microbial growth across building materials and sampling and analysis methods. *Build. Environ.* **2014**, *80*, 136–149. [CrossRef]
77. Gutarowska, B. Metabolic activity of moulds as a factor of building materials biodegradation. *Pol. J. Microbiol.* **2010**, *59*, 119–124. [CrossRef]
78. Chambers, S.T.; Bhandari, S.; Scott-Thomas, A.; Syhre, M. Novel diagnostics: Progress toward a breath test for invasive Aspergillus fumigatus. *Med. Mycol. Off. Publ. Int. Soc. Hum. Anim. Mycol.* **2011**, *49*, 54–61. [CrossRef]
79. Sun, D.; Wood-Jones, A.; Wang, W.; Vanlangenberg, C.; Jones, D.; Gower, J.; Simmons, P.; Baird, R.E.; Mlsna, T.E. Monitoring MVOC profiles over time from isolates of Aspergillus flavus using SPME GC-MS. *J. Agric. Chem. Environ.* **2014**, *3*, 48–63. [CrossRef]
80. Hung, R.; Lee, S.; Bennett, J.W. Fungal volatile organic compounds and their role in ecosystems. *Appl. Microbiol. Biotechnol.* **2015**, *99*, 3395–3405. [CrossRef] [PubMed]
81. Ghosh, B.; Lal, H.; Srivastava, A. Review of bioaerosols in indoor environment with special reference to sampling, analysis and control mechanisms. *Environ. Int.* **2015**, *85*, 254–272. [CrossRef]
82. Lacey, J. Indoor aerobiology and health. In *Building Mycology: Management of Decay and Health in Buildings*, 1st ed.; Jagjit, S., Ed.; Taylor and Francis: London, UK, 1995; pp. 75–120.
83. Piotrowska, M.; Żakowska, Z.; Gliścińska, A.; Bogusławska-Kozłowska, J. The role of outdoor air on fungal aerosols formation in indoor environment. In Proceedings of the II International Scientific Conference: Microbial Biodegradation and Biodeterioration of Technical Materials, Łódź, Poland, 30–31 May 2001; pp. 113–118. (In Polish).
84. Rao, C.Y.; Riggs, M.A.; Chew, G.L.; Muilenberg, M.L.; Thorne, P.S.; Van Sickle, D.; Dunn, K.H.; Brown, C. Characterisation of airborne molds, endotoxins, and glucans in homes in New Orleans after Hurricanes Katrina and Rita. *Appl. Environ. Microbiol.* **2007**, *73*, 1630–1634. [CrossRef]
85. Riggs, M.A.; Rao, C.Y.; Brown, C.M.; Van Sickle, D.; Cummings, K.J.; Dunn, K.H.; Deddens, J.A.; Ferdinands, J.; Callahan, D.; Moolenaar, R.L.; et al. Resident cleanup activities, characteristics of flood-damaged homes and airborne microbial concentrations in New Orleans, Louisiana, October 2005. *Environ. Res.* **2008**, *106*, 401–409. [CrossRef]
86. Adhikari, A.; Jung, J.; Reponen, T.; Lewis, J.S.; DeGrasse, E.C.; Grimsley, L.F.; Chew, G.L.; Grinshpun, S.A. Aerosolization of fungi, (1→3)-β-d glucan, and endotoxin from flood-affected materials collected in New Orleans homes. *Environ. Res.* **2009**, *109*, 215–224. [CrossRef]
87. Wiejak, A. The assessment of air contamination with the mould fungi spores as an essential factor of mycological report. *Build. Res. Inst. Quart.* **2011**, *40*, 3–12.
88. Guz, Ł.; Sobczuk, H.; Suchorab, Z. Odor measurement by using a portable device with semiconductor gas sensors array. *Przem. Chem.* **2010**, *89*, 378–381.

89. Łagód, G.; Suchorab, Z.; Guz, Ł.; Sobczuk, H. Classification of buildings mold threat using electronic nose. *AIP Conf. Proc.* **2017**, *1866*, 030002-1–030002-5. [CrossRef]
90. Mendell, M.J.; Adams, R.I. The challenge for microbial measurements in buildings. *Indoor Air* **2019**, *29*, 523–526. [CrossRef] [PubMed]
91. Otlewska, A.; Adamiak, J.; Gutarowska, B. Clone-based comparative sequence analysis of 16S rRNA genes retrieved from biodeteriorating brick buildings of the former Auschwitz II–Birkenau concentration and extermination camp. *Syst. Appl. Microbiol.* **2015**, *38*, 48–55. [CrossRef] [PubMed]
92. Oszust, K.; Gryta, A.; Ziemiński, K.; Bilińska-Wielgus, N.; Gałązka, R.; Frąc, M. Characterization of microbial functional and genetic diversity as a novel strategy of biowaste ecotoxicological evaluation. *Int. J. Environ. Sci. Technol.* **2018**, *16*, 4261–4274. [CrossRef]
93. Andersson, M.A.; Nikulin, M.; Köljalg, U.; Andersson, M.C.; Rainey, F.; Reijula, K.; Hintikka, E.L.; Salkinoja-Salonen, M. Bacteria, molds, and toxins in water-damaged building materials. *Appl. Environ. Microbiol.* **1997**, *63*, 387–393. [CrossRef]
94. Szponar, B.; Larsson, L. Determination of microbial colonisation in waterdamaged buildings using chemical marker analysis by gas chromatography–mass spectrometry. *Indoor Air* **2000**, *10*, 13–18. [CrossRef]
95. Andersen, B.; Nielsen, K.F.; Jarvis, B.B. Characterization of Stachybotrys from water-damaged buildings based on morphology, growth, and metabolite production. *Mycologia* **2002**, *94*, 392–403. [CrossRef]
96. Wei, G.L.; Zeng, E.Y. Gas chromatography-mass spectrometry and high-performance liquid chromatography-tandem mass spectrometry in quantifying fatty acids. *TrAC Trend. Anal. Chem.* **2011**, *30*, 1429–1436. [CrossRef]
97. Fornal, E.; Parfieniuk, E.; Czeczko, R.; Bilinska-Wielgus, N.; Frac, M. Fast and easy liquid chromatography–mass spectrometry method for evaluation of postharvest fruit safety by determination of mycotoxins: Fumitremorgin C and verruculogen. *Postharvest Biol. Technol.* **2017**, *131*, 46–54. [CrossRef]
98. Guz, Ł.; Łagód, G.; Jaromin-Gleń, K.; Suchorab, Z.; Sobczuk, H.; Bieganowski, A. Application of gas sensor arrays in assessment of wastewater purification effects. *Sensors* **2015**, *15*, 1–21. [CrossRef]
99. Murphy, K.R.; Wenig, P.; Parcsi, G.; Skov, T.; Stuetz, R.M. Characterizing odorous emissions using new software for identifying peaks in chemometric models of gas chromatography-mass spectrometry datasets. *Chemom. Intell. Lab. Syst.* **2012**, *118*, 41–50. [CrossRef]
100. Tiebe, C.; Hübert, T.; Koch, B.; Ritter, U.; Stephan, I. Investigation of gaseous metabolites from moulds by ion mobility spectrometry (IMS) and gas chromatography-mass spectrometry (GC–MS). *Int. J. Ion. Mobil. Spectrom.* **2010**, *13*, 17–24. [CrossRef]
101. Połednik, B. *Zanieczyszczenia a Jakość Powietrza Wewnętrznego w Wybranych Pomieszczeniach*, 1st ed.; Polska Akademia Nauk: Lublin, Poland, 2013; Volume 116.
102. Wang, Y.; Li, Y.; Yang, J.; Ruan, J.; Sun, C. Microbial volatile organic compounds and their application in microorganism identification in foodstuff. *TrAC Trend. Anal. Chem.* **2016**, *78*, 1–16. [CrossRef]
103. Sawoszczuk, T.; Syguła-Cholewińska, J.; del Hoyo-Meléndez, J.M. Optimization of headspace solid phase microextraction for the analysis of microbial volatile organic compounds emitted by fungi: Application to historical objects. *J. Chromatogr. A* **2015**, *1409*, 30–45. [CrossRef] [PubMed]
104. Marin, S.; Vinaixa, M.; Brezmes, J.; Llobet, E.; Vilanova, X.; Correig, X.; Ramos, A.J.; Sanchis, V. Use of a MS-electronic nose for prediction of early fungal spoilage of bakery products. *Int. J. Food Microbiol.* **2007**, *114*, 10–16. [CrossRef]
105. Otlewska, A.; Adamiak, J.; Gutarowska, B. Application of molecular techniques for the assessment of microorganism diversity on cultural heritage objects. *Acta Biochim. Pol.* **2014**, *61*, 217–225. [CrossRef]
106. Canhoto, O.; Pinzari, F.; Fanelli, C.; Magan, N. Application of electronic nose technology for the detection of fungal contamination in library paper. *Int. Biodeterior. Biodegrad.* **2004**, *54*, 303–309. [CrossRef]
107. Guz, Ł. Metodyczne Aspekty Pomiaru Lotnych Zanieczyszczeń Powietrza za Pomocą Urządzenia Wieloczujnikowego. Ph.D. Thesis, Faculty of Environmental Engineering Lublin University of Technology, Lublin, Poland, 2 July 2018.
108. Zhang, Y.; Askim, J.R.; Zhong, W.; Orlean, P.; Suslick, K.S. Identification of pathogenic fungi with an optoelectronic nose. *Analyst* **2014**, *139*, 1922–1928. [CrossRef]
109. Magan, N.; Evans, P. Volatiles as an indicator of fungal activity and differentiation between species, and the potential use of electronic nose technology for early detection of grain spoilage. *J. Stored. Prod. Res.* **2000**, *36*, 319–340. [CrossRef]

110. Tothill, I.E.; Magan, N. Rapid Detection Method for Microbial Contamination. In *Rapid and Online Instrumentation for Food Quality Assurance*, 1st ed.; Tothill, I.E., Ed.; CRC Press: New York, NY, USA, 2003; pp. 136–160.
111. Van Deventer, D.; Mallikarjunan, P. Optimizing an electronic nose for analysis of volatiles from printing inks on assorted plastic films. *Innov. Food Sci. Emerg.* **2002**, *3*, 93–99. [CrossRef]
112. Kuske, M.; Padilla, M.; Romain, A.; Nicolas, J.; Rubio, R.; Marco, S. Detection of diverse mould species growing on building materials by gas sensor arrays and pattern recognition. *Sens. Actuator B Chem.* **2006**, *119*, 33–40. [CrossRef]
113. Demyttenaere, J.C.R.; Morina, R.M.; Pat, S. Monitoring and fast detection of mycotoxinproducing fungi based on headspace solid-phase microextraction and headspace sorptive extraction of the volatile metabolites. *J. Chromatogr. A* **2003**, *985*, 127–135. [CrossRef]
114. Scotter, J.M.; Langford, V.S.; Wilson, P.F.; McEwan, M.J.; Chambers, S.T. Real-time detection of common microbial volatile organic compounds from medically important fungi by Selected Ion Flow Tube-Mass Spectrometry (SIFT-MS). *J. Microbiol. Methods* **2005**, *63*, 127–134. [CrossRef] [PubMed]
115. Zarra, T.; Galang, M.G.; Ballesteros, F.; Belgiorno, V.; Naddeo, V. Environmental odour management by artificial neural network—A review. *Environ. Int.* **2019**, *133*, 105189. [CrossRef] [PubMed]
116. Craven, M.A.; Gardner, J.W.; Bartlett, P.N. Electronic noses—Development and future prospects. *Trends Anal. Chem.* **1996**, *15*, 486–493. [CrossRef]
117. Wilson, A.D.; Baietto, M. Applications and advances in electronic-nose technologies. *Sensors* **2009**, *9*, 5099–5148. [CrossRef]
118. Szulczyński, B.; Gębicki, J. Currently Commercially Available Chemical Sensors Employed for Detection of Volatile Organic Compounds in Outdoor and Indoor Air. *Environments* **2017**, *4*, 21. [CrossRef]
119. Kuchmenko, T.A.; Lvova, L.B. A Perspective on Recent Advances in Piezoelectric Chemical Sensors for Environmental Monitoring and Foodstuffs Analysis. *Chemosensors* **2019**, *7*, 39. [CrossRef]
120. Krivetskiy, V.; Malkov, I.; Garshev, A.; Mordvinova, N.; Lebedev, O.I.; Dolenko, S.; Efitorov, A.; Grigoriev, T.; Rumyantseva, M.; Gaskov, A. Chemically modified nanocrystalline SnO_2-based materials for nitrogen-containing gases detection using gas sensor array. *J. Alloys Compd.* **2017**, *691*, 514–523. [CrossRef]
121. Alphasense. PID-AH2 Sensor Datasheet. Available online: www.alphasense.com (accessed on 20 November 2019).
122. Alphasnese. PID-A12 Sensor Datasheet. Available online: www.alphasense.com (accessed on 20 November 2019).
123. James, D.; Scott, S.M.; Ali, Z.; O'Hare, W.T. Chemical sensors for electronic nose systems. *Microchim. Acta* **2005**, *149*, 1–17. [CrossRef]
124. Karczmarczyk, A.; Haupt, K.; Feller, K.H. Development of a QCM-D biosensor for Ochratoxin A detection in red wine. *Talanta* **2017**, *166*, 193–197. [CrossRef]
125. Gu, Y.; Wang, Y.; Wu, X.; Pan, M.; Hu, N.; Wang, J.; Wang, S. Quartz crystal microbalance sensor based on covalent organic framework composite and molecularly imprinted polymer of poly(o-aminothiophenol) with gold nanoparticles for the determination of aflatoxin B1. *Sens. Actuator B Chem.* **2019**, *291*, 293–297. [CrossRef]
126. Di Pietrantonio, F.; Cannatà, D.; Benetti, M.; Verona, E.; Varriale, A.; Staiano, M.; D'Auria, S. Detection of odorant molecules via surface acoustic wave biosensor array based on odorant-binding proteins. *Biosens. Bioelectron.* **2013**, *41*, 328–334. [CrossRef] [PubMed]
127. Wasilewski, T.; Gębicki, J.; Kamysz, W. Advances in olfaction-inspired biomaterials applied to bioelectronic noses. *Sens. Actuator B Chem.* **2018**, *257*, 511–537. [CrossRef]
128. Wasilewski, T.; Gębicki, J.; Kamysz, W. Bioelectronic nose: Current status and perspectives. *Biosens. Bioelectron.* **2017**, *87*, 480–494. [CrossRef]
129. Ertekin, Ö.; Öztürk, S.; Öztürk, Z.Z. Label free QCM immunobiosensor for AFB1 detection using monoclonal IgA antibody as recognition element. *Sensors* **2016**, *16*, 1274. [CrossRef]
130. Wu, W.; Zhu, Z.; Li, B.; Liu, Z.; Jia, L.; Zuo, L.; Chen, L.; Zhu, Z.; Shan, G.; Luo, S.Z. A direct determination of AFBs in vinegar by aptamer-based surface plasmon resonance biosensor. *Toxicon* **2018**, *146*, 24–30. [CrossRef]
131. Hossain, M.Z.; McCormick, S.P.; Maragos, C.M. An imaging surface plasmon resonance biosensor assay for the detection of t-2 toxin and masked t-2 toxin-3-glucoside in wheat. *Toxins* **2018**, *10*, 119. [CrossRef]
132. He, B.; Dong, X. Aptamer based voltammetric patulin assay based on the use of ZnO nanorods. *Microchim. Acta* **2018**, *185*, 462. [CrossRef] [PubMed]

133. He, B.; Yan, X. An amperometric zearalenone aptasensor based on signal amplification by using a composite prepared from porous platinum nanotubes, gold nanoparticles and thionine-labelled graphene oxide. *Microchim. Acta* **2019**, *186*, 383. [CrossRef]
134. Baldwin, E.; Bai, J.; Plotto, A.; Dea, S. Electronic noses and tongues: Applications for the food and pharmaceutical industries. *Sensors* **2011**, *11*, 4744–4766. [CrossRef]
135. Chilo, J.; Pelegri-Sebastia, J.; Cupane, M.; Sogorb, T. E-nose application to food industry production. *IEEE Instrum. Meas. Mag.* **2016**, *19*, 27–33. [CrossRef]
136. Wilson, A.D. Applications of electronic-nose technologies for noninvasive early detection of plant, animal and human diseases. *Chemosensors* **2018**, *6*, 45. [CrossRef]
137. Szulczyński, B.; Gębicki, J. Electronic nose—An instrument for odour nuisances monitoring. *E3S Web Conf.* **2019**, *100*, 79. [CrossRef]
138. Chauhan, R.; Singh, J.; Sachdev, T.; Basu, T.; Malhotra, B.D. Recent advances in mycotoxins detection. *Biosens. Bioelectron.* **2016**, *81*, 532–545. [CrossRef] [PubMed]
139. Suchorab, Z.; Frąc, M.; Guz, Ł.; Oszust, K.; Łagód, G.; Gryta, A.; Bilińska-Wielgus, N.; Czerwiński, J. A method for early detection and identification of fungal contamination of building materials using e-nose. *PLoS ONE* **2019**, *14*, e0215179. [CrossRef] [PubMed]
140. Kuske, M.; Rubio, R.; Romain, A.C.; Nicolas, J.; Marco, S. Fuzzy k-NN applied to moulds detection. *Sens. Actuator B Chem.* **2005**, *106*, 52–60. [CrossRef]
141. Li, Z.; Wang, N.; Vigneault, C. Electronic nose and electronic tongue in food production and processing. *Stewart Posthar. Rev.* **2006**, *2*, 1–5. [CrossRef]
142. Zhang, X.; Li, M.; Cheng, Z.; Ma, L.; Zhao, L.; Li, J. A comparison of electronic nose and gas chromatography–mass spectrometry on discrimination and prediction of ochratoxin A content in Aspergillus carbonarius cultured grape-based medium. *Food Chem.* **2019**, *297*, 124850. [CrossRef]
143. Gębicki, J.; Szulczyński, B. Discrimination of selected fungi species based on their odour profile using prototypes of electronic nose instruments. *Measurement* **2018**, *116*, 307–313. [CrossRef]
144. Gancarz, M.; Wawrzyniak, J.; Gawrysiak-Witulska, M.; Wiącek, D.; Nawrocka, A.; Rusinek, R. Electronic nose with polymer-composite sensors for monitoring fungal deterioration of stored rapeseed. *Int. Agrophys.* **2017**, *31*, 317–325. [CrossRef]
145. Persaud, K.C.; Wareham, P.D. Hand-Held Electronic Nose (HHEN) for dry rot detection in buildings. In *Digest of Technical Papers—International Conference on Solid State Sensors and Actuators and Microsystems, TRANSDUCERS 2005*; IEEE: Seoul, Korea, 2007; pp. 1947–1950.
146. Karlshøj, K.; Nielsen, P.V.; Larsen, T.O. Differentiation of closely related fungi by electronic nose analysis. *J. Food Sci.* **2007**, *72*, 187–192. [CrossRef] [PubMed]
147. Wilson, A.D. Review of electronic-nose technologies and algorithms to detect hazardous chemicals in the environment. *Procedia Technol.* **2012**, *1*, 453–463. [CrossRef]
148. Vanneste, E.; Geise, H.J. Commercial electronic nose instruments. In *Handbook of Machine Olfaction: Electronic Nose Technology*; Pearce, T.C., Ed.; Wiley-VCH: Chichester, UK, 2003; pp. 161–179.
149. Pinzari, F.; Fanelli, C.; Canhoto, O.; Magan, N. Electronic nose for the early detection of moulds in libraries and archives. *Indoor Built Environ.* **2004**, *13*, 387–395. [CrossRef]
150. Rusinek, R.; Gancarz, M.; Krekora, M.; Nawrocka, A. A Novel Method for Generation of a Fingerprint Using Electronic Nose on the Example of Rapeseed Spoilage. *J. Food Sci.* **2019**, *84*, 51–58. [CrossRef] [PubMed]
151. Gancarz, M.; Wawrzyniak, J.; Gawrysiak-Witulska, M.; Wiącek, D.; Nawrocka, A.; Tadla, M.; Rusinek, R. Application of electronic nose with MOS sensors to prediction of rapeseed quality. *Measurement* **2017**, *103*, 227–234. [CrossRef]
152. Liu, Q.; Zhao, N.; Zhou, D.; Sun, Y.; Sun, K.; Pan, L.; Tu, K. Discrimination and growth tracking of fungi contamination in peaches using electronic nose. *Food Chem.* **2018**, *262*, 226–234. [CrossRef]
153. Di Natale, C.; Martinelli, E.; Pennazza, G.; Orsini, A.; Santonico, M. *Data analysis for chemical sensor arrays In Advances in Sensing with Security Applications*, 1st ed.; Byrnes, J., Ostheimer, G., Eds.; Springer: Ammsterdam, The Netherlands, 2006; pp. 147–169. [CrossRef]
154. Distante, C.; Leo, M.; Siciliano, P.; Persaud, K.C. On the study of feature extraction methods for an electronic nose. *Sens. Actuator B Chem.* **2002**, *87*, 274–288. [CrossRef]
155. Gutierrez-Osuna, R. Pattern analysis for machine olfaction: A review. *IEEE Sens. J.* **2002**, *2*, 189–202. [CrossRef]

156. Brudzewski, K.; Ulaczyk, J. An effective method for analysis of dynamic electronic nose responses. *Sens. Actuator B Chem.* **2009**, *140*, 43–50. [CrossRef]
157. Roussel, S.; Forsberg, G.; Grenier, P.; Bellon-Maurel, V. Optimisation of electronic nose measurements. Part II: Influence of experimental parameters. *J. Food Eng.* **1999**, *39*, 9–15. [CrossRef]
158. Tomic, O.; Eklöv, T.; Kvaal, K.; Haugen, J.E. Recalibration of a gas-sensor array system related to sensor replacement. *Anal. Chim. Acta* **2004**, *512*, 199–206. [CrossRef]
159. Bro, R.; Smilde, A.K. Centering and scaling in component analysis. *J. Chemometr.* **2003**, *17*, 16–33. [CrossRef]
160. Skov, T.; Bro, R. A new approach for modelling sensor based data. *Sens. Actuator B Chem.* **2005**, *106*, 719–729. [CrossRef]
161. Scott, S.M.; James, D.; Ali, Z. Data analysis for electronic nose systems. *Microchim. Acta* **2006**, *156*, 183–207. [CrossRef]
162. Kohonen, T. The self-organizing map. *Neurocomputing* **1998**, *21*, 1–6. [CrossRef]
163. Łagód, G.; Majerek, D.; Guz, Ł.; Nabrdalik, M. Analysis of gas sensors array signals for evaluation of mold contamination in buildings. *AIP Conf. Proc.* **2018**, *1988*, 020022. [CrossRef]
164. Fu, J.; Huang, C.; Xing, J.; Zheng, J. Pattern classification using an olfactory model with PCA feature selection in electronic noses: Study and application. *Sensors* **2012**, *12*, 2818–2830. [CrossRef]
165. González Martín, Y.; Pérez Pavón, J.L.; Moreno Cordero, B.; García Pintob, C. Classification of vegetable oils by linear discriminant analysis of Electronic Nose data. *Anal. Chim. Acta* **1999**, *384*, 83–94. [CrossRef]
166. Dixon, S.J.; Brereton, R.G. Comparison of performance of five common classifiers represented as boundary methods: Euclidean Distance to Centroids, Linear Discriminant Analysis, Quadratic Discriminant Analysis, Learning Vector Quantization and Support Vector Machines, as dependent on. *Chemometr. Intell. Lab.* **2009**, *95*, 1–17. [CrossRef]
167. Pardo, M.; Sberveglieri, G. Classification of electronic nose data with support vector machines. *Sens. Actuator B Chem.* **2005**, *107*, 730–737. [CrossRef]
168. Gardner, J.W. Detection of vapours and odours from a multisensor array using pattern recognition Part 1. Principal component and cluster analysis. *Sens. Actuator B Chem.* **1991**, *4*, 109–115. [CrossRef]
169. Monakhova, Y.B.; Godelmann, R.; Kuballa, T.; Mushtakova, S.P.; Rutledge, D.N. Independent components analysis to increase efficiency of discriminant analysis methods (FDA and LDA): Application to NMR fingerprinting of wine. *Talanta* **2015**, *141*, 60–65. [CrossRef] [PubMed]
170. Aronzon, A.; Hanson, C.W.; Thaler, E.R. Differentiation between Cerebrospinal Fluid and Serum with Electronic Nose. *Otolaryngol. Head Neck Surg.* **2005**, *133*, 16–19. [CrossRef] [PubMed]
171. Hong, X.; Wang, J.; Qi, G. Comparison of spectral clustering, K-clustering and hierarchical clustering on e-nose datasets: Application to the recognition of material freshness, adulteration levels and pretreatment approaches for tomato juices. *Chemometr. Intell. Lab.* **2014**, *133*, 17–24. [CrossRef]
172. Schaller, E.; Bosset, J.O.; Escher, F. "Electronic Noses" and Their Application to Food. *LWT Food Sci. Technol.* **1998**, *31*, 305–316. [CrossRef]
173. Lozano, J.; Santos, J.P.; Arroyo, T.; Aznar, M.; Cabellos, J.M.; Gil, M.; del Carmen Horrillo, M. Correlating e-nose responses to wine sensorial descriptors and gas chromatography–mass spectrometry profiles using partial least squares regression analysis. *Sens. Actuator B Chem.* **2007**, *127*, 267–276. [CrossRef]
174. Nayak, M.S.; Dwivedi, R.; Srivastava, S.K. Application of iteration technique in association with multiple regression method for identification of mixtures of gases using an integrated gas-sensor array. *Sens. Actuator B Chem.* **1994**, *21*, 11–16. [CrossRef]
175. Tian, X.Y.; Cai, Q.; Zhang, Y.M. Rapid classification of hairtail fish and pork freshness using an electronic nose based on the PCA method. *Sensors* **2012**, *12*, 260–277. [CrossRef]
176. Fraley, C.; Raftery, A.E. Model-based clustering, discriminant analysis, and density estimation. *J. Am. Stat. Assoc.* **2002**, *97*, 611–631. [CrossRef]
177. MacQueen, J. Some methods for classification and analysis of multivariate observations. In Proceedings of the Fifth Berkeley Symposium on Mathematical Statistics and Probability, Berkeley, CA, USA, 21 June–18 July 1965; University of California Press: Berkeley, CA, USA, 1967.
178. Łagod, G.; Duda, S.M.; Majerek, D.; Szutt, A.; Dołhańczuk-Śródka, A. Application of Electronic Nose for Evaluation of Wastewater Treatment Process Effects at Full-Scale WWTP. *Processes* **2019**, *7*, 251. [CrossRef]

179. Majerek, D.; Guz, Ł.; Suchorab, Z.; Łagód, G.; Sobczuk, H. The application of the statistical classifying models for signal evaluation of the gas sensors analyzing mold contamination of the building materials. *AIP Conf. Proc.* **2017**, *1866*, 040024. [CrossRef]
180. Łagód, G.; Majerek, D. Application of fuzzy clustering model for interpretation of gas sensors array signals from mold-contaminated buildings. *AIP Conf. Proc.* **2019**, *2133*, 020022. [CrossRef]
181. Ruspini, E.H. A new approach to clustering. *Inform. Control.* **1969**, *15*, 22–32. [CrossRef]
182. Wee, W.G.; Fu, K.S. A formulation of fuzzy automata and its application as a model of learning systems. *IEEE Trans. Syst. Sci. Cybern.* **1969**, *5*, 215–223. [CrossRef]
183. Gustafson, D.E.; Kessel, W.C. Fuzzy Clustering with A Fuzzy Covariance Matrix. In Proceedings of the THOMAS IEEE Conference on Decision and Control, San Diego, CA, USA, 10–12 January 1979; pp. 761–766.
184. Ferraro, M.B.; Giordani, P. On possibilistic clustering with repulsion constraints for imprecise data. *Inform. Sci.* **2013**, *245*, 63–75. [CrossRef]
185. Henry, P. *The Testing Network an Integral Approach to Test Activities in Large Software Projects*; Springer: Berlin, Germany, 2008; p. 87.
186. Thomas, M.C.; Romagnoli, J. Extracting knowledge from historical databases for process monitoring using feature extraction and data clustering. *Comput. Aided Chem. Eng.* **2016**, *38*, 859–864. [CrossRef]
187. Everitt, B.S.; Landau, S.; Leese, M.; Stahl, D. *Cluster Analysis, Wiley Series in Probability and Statistics*, 5th ed.; John Wiley & Sons: Chichester, UK, 2008.
188. Cattell, R.B. The Scree Test for the Number of Factors. *Multivar. Behav. Res.* **1966**, *1*, 245–276. [CrossRef]
189. Rajagopal, R.; Ranganathan, V. Evaluation of effect of unsupervised dimensionality reduction techniqueson automated arrhythmia classification. *Biomed. Signal. Process.* **2017**, *34*, 1–8. [CrossRef]
190. Kaiser, H.F. A Note on Guttman's lower bound for the number of common factors. *Br. J. Stat. Psychol.* **1961**, *14*, 1–2. [CrossRef]
191. Krzanowski, W.J. *Principles of Multivariate Analysis: A User's Perspective*, 1st ed.; University Press Inc.: Oxford, NY, USA, 2008.
192. Khun, M.; Johnson, K. *Applied Predictive Modeling*, 1st ed.; Springer: New York, NY, USA, 2013.
193. Łagód, G.; Guz, Ł.; Sabba, F.; Sobczuk, H. Detection of Wastewater Treatment Process Disturbances in Bioreactors Using the E-Nose Technology. *Ecol. Chem. Eng. S* **2018**, *25*, 405–418. [CrossRef]
194. Bergman, L.E.; Wilson, J.M.; Small, M.J.; VanBriesen, J.M. Application of classification trees for predicting disinfection by-product formation targets from source water characteristics. *Environ. Eng. Sci.* **2016**, *33*, 455–470. [CrossRef]
195. Breiman, L.; Friedman, J.H.; Olshen, R.A.; Stone, C.J. *Classification and Regression Trees*; Wadsworth Statistics/Probability Series; Wadsworth Advanced Books and Software: Belmont, CA, USA, 1984.
196. Mette, A.; Hass, J. *Guide to Advanced Software Testing*; Artech House: Boston, FL, USA, 2008; pp. 179–186.
197. Persaud, K.C.; Dodd, G. Analysis of discrimination mechanisms in the mammalian olfactory system using a model nose. *Nature* **1982**, *299*, 352–355. [CrossRef] [PubMed]
198. Brereton, R.G.; Lloyd, G.R. Partial least squares discriminant analysis: Taking the magic away. *J. Chemometr.* **2014**, *28*, 213–225. [CrossRef]
199. Friedman, J.H.; Hastie, T.; Tibshirani, R. Regularization paths for generalized linear models via coordinate descent. *J. Stat. Softw.* **2010**, *33*, 1–22. [CrossRef]
200. Gardner, J.W.; Bartlett, P.N. Electronic Noses. Principles and applications. *Meas. Sci. Technol.* **2000**, *11*, 1087. [CrossRef]



© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).