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Review

Electronic noses for food quality: A review

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The authors dedicate this review article to Prof. Silvia Coradeschi who sadly passed away in February 2014. Prof. Silvia was known for her unique leadership quality and dedication with unparalleled energy and enthusiasm. Her absence has made an unmatchable vacuum in our team. It is a great loss to us all and she is greatly missed.

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ABSTRACT

This paper provides a review of the most recent works in electronic noses used in the food industry. Focus is placed on the applications within food quality monitoring that is, meat, milk, fish, tea, coffee and wines. This paper demonstrates that there is a strong commonality between the different application area in terms of the sensors used and the data processing algorithms applied. Further, this paper provides a critical outlook on the developments needed in this field for transitioning from research platforms to industrial instruments applied in real contexts.

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Abbreviations: ANN, artificial neural network; APLSR, analysis of variance partial least squares regression; BP-MLP, back propagation multilayer perceptron; BPNN, back-propagation neural network; CA, cluster analysis; DA, discriminant analysis; DBN, deep belief network; DFA, discriminant factorial analysis; FNN, fuzzy neural network; LDA, linear discriminant analysis; LVQ, learning vector quantization; MGLH, multivariate general linear hypothesis; MLP, multi-layer perceptron; MOS, metal oxide semiconductor; MOSFET, metal oxide semiconductor field effect transistor; m-TDNN, multiple-time-delay neural networks; PCA, principal component analysis; PLS, partial least squares regression; PNN, probabilistic neural network; QDA, quadratic discriminant analysis; RBF, radial basis function; SQC, statistical quality control; SVM, support vector machines; VOCs, volatile organic compounds; KAMINA, Karlsruhe Micro. Nose.

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1. Introduction

Foodborne illnesses cause about 76 million cases of illnesses, 325,000 hospitalizations, and 5000 deaths in the United States each year (Hedberg, 1999). Common symptoms of foodborne illness include diarrhea, nausea, abdominal cramps, headache, dizziness and fever. In the developed/developing countries, surveillance of foodborne disease is a fundamental component of food safety systems (WHO). According to the estimates of US Centers for Disease Control and Prevention (CDC) in the year 2011, roughly 1 out of 6 Americans or 48 million people get sick, 128,000 are hospitalized and 3000 die of foodborne illnesses (CDC, 2011). Hence researchers started exploring better way for quality discrimination of perishable foods.

Highly perishable, muscle foods like fish, meat and poultry have become an integral part of human diet over many decades. However, in the past two decades awareness about the food safety from the point of specific pathogenic bacteria has exemplified the requirement for a rapid and accurate detection system for microbial spoilage in fish and meat (Frost, 2001; Haugen et al., 2006). In general fish and meat quality will be assessed either by examining the structure (texture, tenderness, flavor, juiciness, and color) or by detecting the microorganism and its count or by detecting the gas/VOCs generated by these microorganisms.

The practical application of human nose as a smell assessment instrument is severely limited by the fact that our sense of smell is subjective, gets tired easily, and is therefore difficult to use. Consequently, there is considerable need for an instrument that could mimic the human sense of smell and its use in routine industrial applications. To promote this technology to industrial application, metal oxide gas/odour sensors became exemplary candidates in areas like food industry, environment control, automobile industry, indoor air quality check and monitoring, industrial production, medicine and in safety aspects, to name a few – Scientific groups worldwide are investigating them giving due importance to the various aspects of gas/odour sensing properties.

Electronic nose instruments are attractive for a number of significant features: the relatively fast assessment of headspace, a quantitative representation or signature of a gas and cheap sensors which can be easily integrated in current production processes. Despite these features, there are still relatively few applications of electronic noses adopted in industry. This could be attributed to difficulties in robustness, selectivity and reproducibility of the sensors and to the need for pattern recognition algorithms which can cope with the complex signal analysis. Nonetheless, the use of electronic noses is rapidly expanding and there have been notable achievements relevant for the food industry, particularly in the past few years. Furthermore, this progress coincides with an increased understanding of the biological mechanisms behind the human olfactory system. Specifically, we now have a greater understanding not only of the genetics behind the olfactory receptors but also of the relationships between an odorant's molecular property and the quality of an odor. This paper focuses on the latest developments within key areas related to foodstuff where a quantitative approach to quality estimation is important as it regulates the economy of food (e.g. pricing) and quality control (e.g. detection of bacteria and spoilage). Specifically, this paper reviews the progress in the past decade for the following areas: milk, wine, coffee, tea, fish and meat.

A broad list of e-nose reviews can be found in the literature that are structured and focused on mass spectrometry based electronic noses (Peris and Escuder-Gilabert, 2009), biomedical and health care applications (Wilson and Baietto, 2011), agriculture and forestry applications (Wilson, 2013), microbial quality control of food products (Falasconi et al., 2012), pharmaceutical applications (Alam et al., 2012), for developing chemical sensor arrays (James et al., 2005). Our review is distinctive in a way that we focus on the methodologies which are common across the various applications. Therefore the motivation of this review is to make accessible to the various research groups not only the progress within their specific area but also in adjacent areas and most importantly common methodologies that can be used to solve related challenges in different fields. A secondary motivation is to promote the use of electronic noses for food quality monitoring fin an industrial setting by summarizing the extensive work in the past few years that indicates promising results with respect to the applicability of e-noses to a vast number of areas.

2. Electronic noses

During the 1980s research on machine olfaction lead to a generally accepted definition of an electronic nose as an instrument that comprises an array of heterogeneous electrochemical gas sensors with partial specificity and a pattern recognition system (Gardner and Bartlett, 1999; Persaud and Dodd, 1982). However, in more recent years, the term electronic nose has been used in a broader sense to refer to gas sensors that measure the ambient gas atmosphere based on the general principle that changes in the gaseous atmosphere alter the sensor properties in a characteristic way. A variety of different sensor types have been developed, to which three types of materials are commonly used: metal oxides, conducting polymers composites and intrinsically conducting polymers. Apart from conductive sensors, gas detection has also been done using optical sensors, surface acoustic wave sensors, gas sensitive field effect transistors and quartz microbalance (QMB) sensors. Micro-electro-mechanical systems (MEMS) plus nanotechnologies are the most promising emerging technologies in the area. The term electronic nose has also been used to characterize systems where ultra-fast gas chromatography or mass spectrometry is employed in the detection process. Once the data from the individual sensors from the array is collected, the electronic nose systems require a suitable post processing procedure to analyze and classify the data. Pre-processing of multivariate signals in sensor arrays represents an essential part of the measuring system. Data processing techniques used in post processing of pattern recognition routines include principal component analysis (PCA), linear discriminate analysis (LDA), partial least squares (PLS), functional discriminate analysis (FDA), cluster analysis (CA), fuzzy logic or artificial neural network (ANN) such as probabilistic neural network (PNN). Among these techniques, PCA, PLS, LDA, FDA and CA are based on a linear approach while fuzzy logic, ANN and PNN are regarded as nonlinear methods (Scott et al., 2006).

Particular to the food industry is the sample handling system used for exposing the volatile compounds present in the headspace (HS) to the sensor array in the e-nose. For some applications, specific techniques are used such as purge & trap (P&T), dynamic headspace (DHS), solid-phase microextraction (SPME) used by