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Review

Biomimetic-based odor and taste sensing systems to food quality and safety characterization: An overview on basic principles and recent achievements

Mahdi Ghasemi-Varnamkhasti [a,*], Seyed Saeid Mohtasebi [a], Maryam Siadat [b]

[a] Agricultural Machinery Engineering Department, Faculty of Agricultural Engineering and Technology, University of Tehran, P.O. Box 4111, Karaj 31587-77871, Iran
[b] Laboratoire Interfaces Composants et Microélectronique, LICM/CLOES/SUPELEC, Université de Metz 2, Rue E. Belin, 57070 Metz, France

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ABSTRACT

The appreciation of food is based on the perception of many senses; in fact for a total estimation the human senses are involved. Biomimetics as the 'abstraction of good design from nature' is to analyze and tap nature's huge reservoir of potential innovative solutions. These biological solutions are cost-efficient, multi-functional and environmentally friendly. Human sense inspired sensor technologies such as multi arrays of sensors are of interest to food industry for food control and sensory evaluation. These systems mimic the human sense to provide a decision on final food quality and safety. Nanotechnology techniques and biosensors are the recent advances in these systems. Odor and taste sensors are interestingly under consideration to food engineers and scientist for application in food processing tasks such as drying, packaging, sorting and so on. Soft computing together with computer development is the promising outlook to enhance the performance of these sensing systems to food quality and safety characterization. This paper deals with some aspects of such systems (odor sensor and taste sensor) and some of more recent applications and advances for food control in food research and technology are discussed as well.

Contents

1. Introduction

As is well known humans have five senses such as sight, hearing, touch, smell and taste. Humans act after receiving information from the outside world and this is why these senses are very important.

Fig. 1 illustrates the relevance between the biological system and the artificial system in the process of reception and consequent action. The ability of five organs, i.e., eye, ear, skin, nose and tongue, respectively, in the senses of sight, hearing, touch, smell and taste is organized by a sensor. We often use the term sensor in the global sense with combination of the data-processing part and the receptor part (i.e., the sensor in the narrow sense) and this phenomenon is practical due to computer development. So, the sensor plays roles of recognition as well as reception. This is the trend by which development of intelligent sensors is moving ahead.

* Corresponding author. Tel.: +98 261 2801011; fax: +98 0261 2808138.
E-mail addresses: ghasemymahdi@gmail.com, ghasemymahdi@ut.ac.ir, ghasemi@eis.uva.es (M. Ghasemi-Varnamkhasti).

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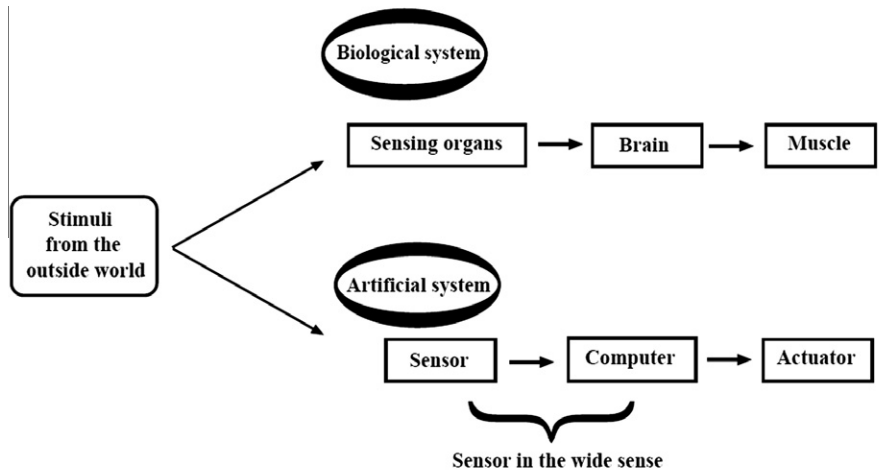

Fig. 1. Process of reception and the subsequent action in biological artificial systems (with kind permission from Toko, 2006).

Odor sensor and taste sensor are addressed as the senses of smell and taste, respectively. This is expected that these two kinds of sense can be realized at the reception level provided that good sensing materials are used satisfactorily. The quality of taste and chemical substances is perceived in gustatory and olfactory cells, respectively, to produce smell as a discrimination tool (Toko, 2006).

Nevertheless, taste or smell sense cannot be measured if many chemical sensors with high selectivity are developed for different chemical substances since we can extract more than 1000 in one kind of foodstuff. The original role of smell and taste was to detect and get information within an enormous mass of external information (large numbers of chemicals). There exist too many types of chemical substance included in producing taste and smell, therefore, it sounds important to get most important information quickly instead of discrimination a single chemical species among others. This attitude is seen in unicellular living organisms, which have no sight sense.

There is only a very limited correlation between the principles used to solve problems in technical artifacts and in biological systems. Vincent et al. (2006) have shown that only 12% similarity is between biology and technology fields in the principles that connect solutions to problems. This indicates the prosperity of inspiration in nature for how to solve technical problems. Bonser and Vincent (2007) has counted up the number of "biology-inspired" patents and pointed out that it has increased from 0 to 1200 in the last 20 years. It is feasible to directly facsimile solutions from nature, in particular for engineering purposes it is often more useful to use nature as inspiration source.

Nature has always served as a model for mimicking and a source of inspiration to people in their efforts to improve their life (Singh et al., 2009). Adapting mechanisms along with the capabilities from nature and using scientific methods has resulted in effective materials, tools, algorithms, mechanisms, structures, processes, and many other merits. Biomimetics is an emerging domain that has this capability to facilitate major technical advances (Gebeshuber and Drack, 2008; Low, 2009; Lenau, 2009). Electronic nose and tongue (and more recently, bioelectronic nose and tongue) as the biomimetic systems are the tools mimicking the olfactory and gustatory systems of humans. These analytical instruments have a high potential to be used in food research and technology.

2. Biomimetic systems

Biomimetics is known as the 'abstraction of convenient design from nature'. Its central philosophy is that novel solutions have arisen in the natural world and these can be used as the basis for new technologies. Because nature has a tendency to be very economical with energy, bioinspired technologies have the potentials to create cleaner and greener solutions. It has to be mentioned that biomimetics does not try to copy nature. Biomimetics tries to apply processes and designs, constructional or developmental principles for technical applications.

The subject of copying and learning from biology was introduced as *Bionics* by Jack Steele, of the US Air Force in 1960 at a meeting at Wright-Patterson Air Force Base in Dayton, Ohio (Vincent, 2001) and Otto H. Schmitt made the term *Biomimetics* in 1969 (Schmitt, 1969). This field is increasingly identified with emerging subjects of science and engineering. The term is derived from *bios*, meaning life, and *mimesis*, meaning to imitate. This new science opens a window to the studies and imitation of nature's methods, designs and processes. Although some of nature's basic configurations and designs can be copied, there are many ideas from nature that are best adapted if they are to serve as inspiration using human-made capabilities.

The terms of bionics, bionik (german) and biomimetics have been coined in much more recent years. They all designate a study involving copying, imitating and learning from nature. The terms are derived from Greek "bios" meaning life, the suffix "in" meaning like and "mimeistai" meaning imitate. Some dictionaries describe the term bionics as constructed from "biology" and "electronics". There are excellent books on biomimetics discussing about both its history and many interesting examples (Bar-Cohen, 2006; Nachtigall, 2002; Kato and Kamimura, 2007).

Although this is a considerable difference between biological and artificial senses, however, electronic noses and tongues have the potential as promising tools to copy the human sensory system mechanism. There is this belief that electronic nose and tongue as the biomimetic systems are going to be increasingly employed in food control (Wang et al., 2007).

2.1. Application importance in food control

A very challenging problem in food processing is quality and safety control of food products, in such away much time and effort are spent on methods for this goal accordingly (Harker et al., 2008; Chung et al., 2010; Goni and Purlis, 2010; Bozkurt and Icier, 2010). Trained human sensory panels evaluating quality parameters are often employed but, however, this approach suffers from some drawbacks. Thus, discrepancy might occur due to human fatigue or stress, they are time-consuming, expensive and cannot be used for on line monitoring (Bleibaum et al., 2002; Ghasemi-Varnamkhasti et al., 2009). The development of replacement methods for sensory panels for objective measurement of food products in a consistent and cost effective manner is far attractive to food industry engineers (Zhang et al., 2007; Bhattacharyya et al., 2007; Farkas and Mohacsine, 2008; Lopez-Feria et al., 2008). As follows, biomimetics systems such as electronic tongue, electronic nose could be applicable in this regard.

2.2. The mechanism of human sensory system

Various stimuli can excite different receptors in the human senses (e.g., olfactory). These receptors transform the outer sphere stimulus into the nerve impulse to characterize them with specific frequency, and the nerve impulse will bring the signal of sense in the corresponding pallium sensory area pass through the separate nerve conduction channel. The current of sensory nerve impulse is, therefore, delivered to the primary pallium sensory area through the nerve conduction channel after integrating of complex information (Han, 2003).

The reception mechanism in taste sense is not yet obvious. Biological membrane of the taste cell as an epidermal cell receives chemical substances. At the first stage of chemical reception, the potential of the biological membrane is changed (Matsumura et al., 2009). The reception of chemical substances by taste and olfactory cells is illustrated in Fig. 2a. As depicted in Fig. 2b the process of reception of odorants is performed by olfactory cells and then doing the transduction of information to the brain. The olfactory cells directly elicit spike trains once the olfactory cilia receive an odor molecule, which happens when these have dissolved in the mucus layer.

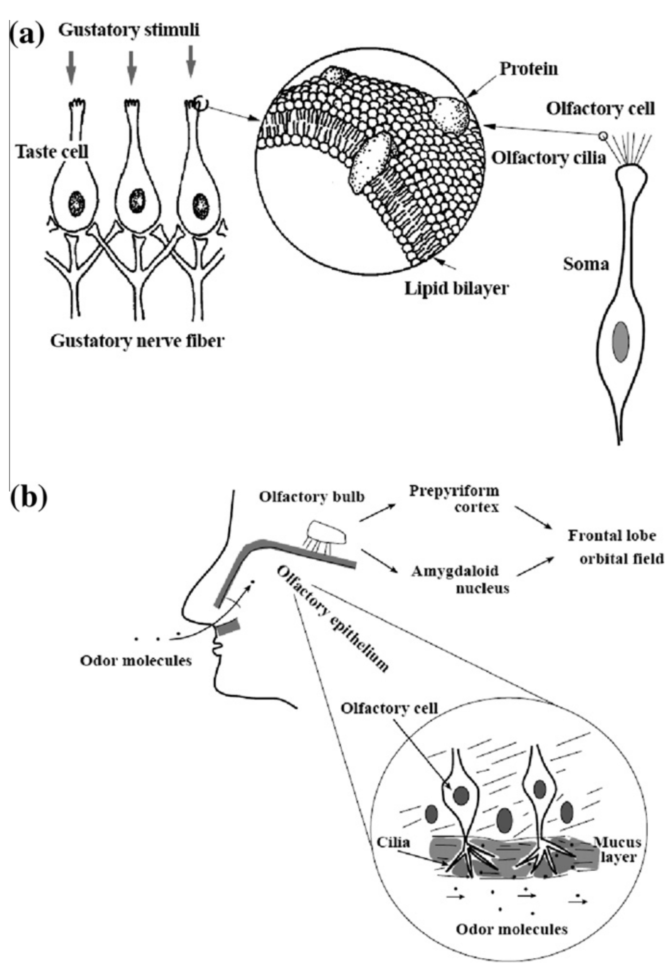

Fig. 2. (a) Taste and smell reception. (b) Nose receptors for odor substances (with kind permission from Toko, 2006).

2.3. Taste sensor (electronic tongue)

Taste sensor or electronic tongue is an analytical tool including an array of non-specific, low selective chemical sensors with partial specificity (cross-sensitivity) to different components in solution accompanied by an appropriate method of pattern recognition and/or multivariate calibration for the data-processing. The stability of sensor behavior and enhanced cross-sensitivity is a critical criterion, which is understood as reproducible response of a sensor to as many species in solution as possible. If properly configured and trained (calibrated), the electronic tongue has the potential to determine quantitative composition (the content on multiple components) and to recognize (distinguish, classify, identify) complex liquids of different nature. The sense of taste may have two meanings. One aspect devotes to the five basic tastes of the tongue; sour, salt, bitter, sweet, and 'umami'. These tastes are sensed from different, discrete regions on the tongue including specific receptors known papillae. The other aspect denotes the perception obtained when food enters the mouth. The basic taste is then combined with the information from the olfactory receptors, when aroma from the food enters the nasal cavities via the inner passage. A unique feature in application of taste sensor is the possibility to maintain a correlation between the output of the electronic tongue and human perception. After calibration as acceptable as possible, the electronic tongue can produce results in the same manner a human sensory panel does: as marks or assessments of various simple and complex features of taste and flavor of different products. The electronic tongue can easily taste raw substances, and also new entitles that maybe have the hazards for human consumption.

Different sensing principles are used in electronic tongues or taste sensors, such as electrochemical methods (e.g., potentiometry or voltammetry), optical methods, mass change detection based on some principals like quartz-crystals. Unlike traditional analytical methods, electronic tongue do not obtain information on the nature of the compounds under consideration, but only present a digital fingerprint of the food material. These fingerprints can be subsequently used in chemometrics tools included in the system. The latter issue maybe said a weakness for electronic tongue.

Since electronic tongues are going to characterize the food products and this issue is very important for human health, the fabrication technology of integrated multisensor devices like electronic tongue that can employ several modes of measurement should be carefully adapted. The main aspect of that technology should be the possibility of easy formation of transducer structure and spreading of the chemosensitive material on its surface. The device material should be chemically inert and the preparation process of the final structure should be cost effective. There are many methods and materials to prepare the sensors included in a taste sensing system. Among these materials, the unique semiconducting, optical and electrochemical properties of radical lanthanide bisphthalocyanines make them ideal materials for sensing applications. Resistive sensors based on bisphthalocyanines change their conductivity when exposed to a variety of volatile organic compounds. Because bisphthalocyanines are intrinsic semiconductors, the conductivity of their thin films is higher than the conductivity of metallophthalocyanine thin films. This facilitates the electrical measurements and enhances the sensitivity of the taste sensors. Such materials have been successfully exploited in quality control, classification, freshness evaluation and authenticity assessment of a variety of food, mainly wines and olive oils as reviewed by Rodriguez-Mendez et al. (2009). Moreover, physicochemical properties of nanostructured Langmuir–Blodgett thin films based on phthalocyanines and their applications in food quality assessment are of interest to researchers working on electronic tongue. Films of a variety of phthalocyanine molecules including several metallophthalocyanines, lanthanide double decker phthalocyanines and heteroleptic derivatives have been prepared and reported by Rodriguez-Mendez and de Saja (2009). However, description and explanation of other materials and taste sensor fabrication procedures is beyond on the aim of this article. So, we can consider an instance describing an electrochemical method; four rare-earth bisphthalocyanines ($LnPc_2$) with different central lanthanide ions were synthesized and used in the work of Parra et al. (2006). The $LnPc_2$ included in the study were: lutetium (III) bisphthalocyaninate ($LuPc_2$), gadolinium (III) bisphthalocyaninate ($GdPc_2$) and the gadolinium octa-*tert*-butyl substituted derivative ($GdPc^t_2$). A sensor based on cobalt (II) monophthalocyanine was also included in the array. These materials were mixed with carbon ink in 80:20 (w:w) ratio for phthalocyanine powders and 85:15 (w:w) in case of perylene derivatives. This mixture was homogenised by thoroughly hand mixing. Cyclohexanone was then added until a paste of adequate viscosity was obtained. The mixture was deposited onto the gold electrodes by using a semiautomatic fluid dosificator, and thermally dried at 100 °C for 4 h.

Another feature of fabrication is the possibility of scaling down the device that would be advantageous, because it allows to obtain miniaturized total analysis systems (Ciosek et al., 2007; Winquist et al., 2008; Twomey et al., 2009). In some cases, the compatibility of the chosen fabrication technique with the other microsystem technologies should also be considered in order to create appropriate module realizing, e.g., each step in multistage analytical procedure. Nanotechnology techniques also have been reported in the literature to fabricate the sensors with high performance to be used in electronic tongue (Martins et al., 2008).

Recently the concept of biosensor array has been considered in food quality and safety characterization known as bioelectronic tongue. If an array of biosensors is used in exposure to the food, each biosensor recognizes one or group of analytes as well as the quantity of analyte in the sample, and then with chemometric tools, very accurate characterization of the sample can be achieved. Utilization of these tools has shown promising results, a valuable review paper on application of such instruments is found in literature (Zeravik et al., 2009). Sensitivity improvement has been of interest to the researchers working on taste quantification and so many technological techniques are being employed for this purpose (Lorenz et al., 2008; Ciosek et al., 2009; Rodriguez-Mendez et al., 2009; Liyama et al., 2009; Woertz et al., 2010). At present, usage of nanotechnology in biosensor preparation is interestingly under consideration to enhance selectivity and sensitivity and biosensor performance accordingly (Darder et al., 2009; Lima et al., 2009; Siqueira et al., 2010).

Although the development of electronic tongues is still fairly in the early stages, several applications have already been described (Deisingh et al., 2004). These include model analyses, food and beverage analysis and water monitoring. In this article we consider some applications focusing on the more recent ones. Kataoka et al. (2004) evaluated the taste of 20 bottled nutritive drinks, both in human gustatory sensation tests and using a multi-channel taste sensor. An appropriate correlation between the results of human gustatory sensation tests and taste sensor data for sourness and bitterness, and the palatability component pungency was reported. Kaneda et al. (2003) conducted a work for measuring astringency of beverages using a quartz-crystal microbalance with the aim of finding the components most responsible for beer astringency. They found the specific interactions of the tannin–peptide complexes with the lipid membranes involved in the astringent perceptions, then, they proposed a new mechanism for the astringent perception. The authors developed two astringency measurement systems for wines, teas, and beers. They strongly pointed out there is a danger that the peptide-immobilized QCM may react to not only astringent polyphenols but also non astringent polyphenols, while the lipid membrane sensor only responds to astringent polyphenols. They concluded that the comparison of these sensor responses to several beverages could result in better clarification of the relationship between polyphenols and astringency. Recently in order to rapid assessment of taste and flavor of beer, Rudnitskaya et al. (2009) evaluated an electronic tongue system. In their work, 50 Belgian and Dutch samples of different types (lager beers, ales, wheat beers, etc.) were used. Sensory evaluation data was considered as a reference data and electronic tongue measurement was based on potentiometric chemical sensors. Their electronic tongue had this capability to recognize the main differences among beer samples and to predict the sensory attributes of beer (bitter, sweet, sour, fruity, caramel, artificial, burnt, intensity and body). More recent date, the possibility of the electronic tongue for prediction of instrumental parameters of beer quality was evaluated by Polishin et al. (2010). For this purpose, they fabricated an electronic tongue with 18 potentiometric chemical sensors and said their system is so fast and easily applicable. Little sample preparation and only a relatively small amount of sample for the analysis was the merit of the system used. The electronic tongue was able for predicting physicochemical parameters such as real extract, alcohol and polyphenol content and bitterness. Table 1 summarizes some of the recent works. The readers for more study on such applications are referred to Vlasov et al. (2008) and Scampicchio et al. (2008).

2.4. Odor sensor (electronic nose)

The electronic nose originates its name because in several aspects, this system tries to mimic the human nose. Human olfactory perception is based on chemical interaction between volatile odor compounds and the olfactory receptors (primary neurons) in the nasal cavity. The signals are transferred to the brain through synapses and secondary neurons and further went to the limbic system in the cortex where recognition of odor occurs based on neural network pattern recognition. In fact, the chemical sensors of the electronic nose resemble the primary neurons with different sensitivity to different odors. By chemical interaction between odor compounds and the chemical sensors, a change either physical or chemical is took place, so giving rise to electrical signals which are recorded by the instrument analogue with the secondary neurons. As a consequence, the signals from the individual sensors involved in the system show a pattern which is unique for the compound used and is, thereafter, analyzed by chemometrics tools. Samples with similar odors generally but not always give rise to similar patterns and samples with different odors represent differences in their patterns. When the sensor patterns for a series samples are compared, differences can be correlated with the perceived sample odor (Ghasemi-Varnamkhasti et al., 2009). Electronic systems appear to be very promising for a number of reasons. The main ones are that these systems are based on inexpensive, non-specific solid-state sensors, which are sensitive to the gases that are emitted by food samples. Moreover, once an electronic system has been trained, we do not need to have an expert operator and can get the results as soon as possible accordingly. In the electronic nose system, a pattern recognition engine, as the system brain, enables the system to analyze huge data relevant to the sensor signals. When the aim is the classification of a given sample, analysis of the volatile fraction of the sample is faster and simpler. In food analysis, this fact is also advantageous where the quality of a commercial product (e.g., cheese, coffee, wine, olive oil, and dairy products) is evaluated from specific flavor standpoint.

Table 1
Some more recent applications of electronic tongue in food quality and safety characterization.

Application case	Aim of use	Researcher(s)
Tomato	Analysis of tomato taste	Beullens et al. (2008)
Wine	Age prediction and organic acids and phenolic compounds quantification	Rudnitskaya et al. (2010)
Beer	Assessment of bitterness intensity and suppression effects	Legin et al. (2009)
	Quantification of real extract, real fermentation degree, alcohol content, pH, bitterness, color, polyphenol and CO_2 content	Polishin et al. (2010)
Mineral water	Classification	Men et al. (2009)
Minced meat	Prediction of NaCl, nitrate and nitrite contents	Labrador et al. (2010)
Tunisian water	Discrimination among samples	Sghaier et al. (2009)
Olive oil	Evaluation of the phenolic content of extra virgin olive oils	Rodriguez-Mendez et al. (2008)
	Characterization with different degree of bitterness	Apetrei et al. (2010)
Tea	Classification of black tea taste	Palit et al. (2009)
	Discrimination of Xihulongjing tea grade	Xiao and Wang (2009)
Milk	Classification of milk originating from various producers	Ciosek and Wroblewski (2008)
	Identification of goat milk adulteration with bovine milk	Dias et al. (2009)
	Adulteration recognition	Paixao and Bertotti (2009)
	Monitoring changes in probiotic fermented milk during storage	Hruskar et al. (2010)
Wine consumed with seafood	Evaluation of effect of sulfur dioxide on formation of fishy off-odor and undesirable taste	Fujita et al. (2010)
Orange juice	Citric acid assessment	Medeiros et al. (2009)
Soybeans	Identification and discrimination of different soybeans cultivars with genetically distinct characteristics	Gregorut et al. (2009)
Non-alcoholic beverage	Evaluation of juice level	Peres et al. (2009)
Water	Study of water quality in fish tank	Chang et al. (2008)
Honey	Classification of honey samples of different floral origins and geographical origins	Wei et al. (2009)
Natural water	Recognition and prediction of common anions chloride, sulfate and bicarbonate	Labrador et al. (2009)
Chinese tea	Correlation with sensory properties and classification according to geographical origin and grade level	He et al. (2009)
Fish	Freshness monitoring	Gil et al. (2008)
Edible oils	Discriminating oils on the basis of their quality and geographical origin	Oliveri et al. (2009)
Chicken carcass	*Salmonella typhimurium* detection	Lan et al. (2008)
Beverage types	Determining taste-causing compounds	Sun et al. (2008)
	Recognition among the types	Ciosek et al. (2009)
Sport drinks	Evaluation of salt region	Wu et al. (2008)
Green tea	Determination of caffeine content and main catechins contents	Chen et al. (in press)
Soft drink	Semi-quantitative and quantitative analysis for differentiation among the beverage based on fruit juice contents	Dias et al. (in press)

There are already commercial gas sensor devices used for identification of specific contaminants or common mixtures. Based on the different operation principles, a variety of solid-state gas sensors have been developed, such as metal oxide semiconductor, photothermal, optical and fiber-optic-based, piezoelectric, pyroelectric, and thermal devices. Like previous section for electronic tongue, we consider only one type (metal-oxide sensors) of the sensor used in electronic noses. Metal-oxide sensors have fairly good sensitivity, in particular for polar analytes such as ethanol. The selectivity can be shifted to different classes of compounds to some degree either by changing the operating temperature of the sensors or by modifying the films by incorporating different amounts of noble-metal catalysts during the fabrication process. Metal oxides such as SnO_2, ZnO, Fe_2O_3 and WO_3 are an intrinsically n-type semiconductor. These types of metal oxide semiconductors respond to reducible gases such as H_2, CH_4, CO, C_2H_5 or H_2S and increase their conductivity. In contrast, p-type semiconductors such as CuO, NiO and CoO respond to oxidizable gases such as O_2, NO_2 and Cl_2. The above issues are considered in fabrication of this type of electronic nose system (Belkova et al., 2010; Park et al., 2010; Wen and Tian-mo, 2010). For study on the other types, the reader is referred to Pearce et al. (2003).

The cell-based biosensors are another kind of sensing element used in artificial olfactory system known as bioelectronic nose. The cell-based biosensor uses living cells that express olfactory receptors as the biological sensing elements and the protein-based biosensor uses the olfactory receptor protein. Diverse methods like optic devices are employed for measurement of the binding of odorant molecules to the olfactory receptors. So, combining the biological sensing elements with these non-biological devices, a bioelectronic nose can be implemented. The potential application of bioelectronic nose to food quality and safety characterization is heavily dependent on the development of highly sensitive and selective biosensors. Recent advances in the development of bioelectronic nose have been documented in the valuable paper of Lee and Park (2010).

The performance of existing electronic nose devices is much more dependent on the sensor's aging and, especially, the sensor's replacement and frequently requires a recalibration to account for change. Moreover, current electronic nose devices based on metal oxide semiconductors or conducting polymers that specifically identify gaseous odorants are typically large and expensive and thus not adequate for use in micro- or nano-arrays that could mimic the performance of the natural olfactory system. Nanotechnology is seen as a key in advancing e-nose devices to a level that will match the olfactory systems developed by nature (Chen et al., 2008; Krivetsky et al., 2009; Xie et al., 2010). Nanowire chemiresistors are seen as critical elements in the future miniaturization of electronic noses. It is now also believed that single crystal nanowires are most stable sensing elements what will result in extending of life-time of sensors and therefore the recalibration cycle. The application of semiconductor oxide nanowires as solid-state chemical sensors is an area of apparent technological promise. With the great progress achieved recently in the development of the effective growth techniques and proven sensing performance the focus in research is shifted towards the better understanding of the fundamentals of surface reactivity of low dimensional nanostructures. To make this kind of device operational one has to use an array of sensing elements which have a, at least somewhat, different response to the same target gas (Chen et al., 2009). That is why along with pristine SnO_2 and In_2O_3 nanowires it also can be fabricated and tested sensing properties of new nano- and meso structures such as TiO_2 single crystal whiskers and SnO_2 nanowires doped with Ni/NiO nanoparticles to diversify the responses in the array of sensors.

Such systems are being used in food science and technology that several cases are discussed herein. In a study conducted by Rajamaki et al. (2006), the potential application of an electronic nose for the quality and safety control of modified atmosphere (MA) packaged broiler chicken cuts was assessed in different temperature levels. The electronic nose results were then compared with those obtained by microbiological, sensory and headspace GC analyses. They suggested that the electronic nose could clearly distinguish broiler chicken packages with deteriorated quality from fresh packages either earlier than or at the same time as the sensory quality deteriorated. The results indicated that the electronic nose was capable to detect even early signals of spoilage in MA packed poultry meat. Similar work was reported by Balasubramanian et al. (2008) for predicting the *Salmonella* populations in fresh beef. Some more recent applications of electronic nose in food control are given in Table 2. In These research efforts, the authors have employed either commercial electronic nose or implemented ones in their laboratories. Some new commercially available electronic noses, models and technologies have been introduced in the literature (Wilson and Baietto, 2009).

As discussed earlier, the brain of the electronic noses is pattern recognition algorithm. Artificial neural networks (ANNs) have been extensively used to perform this pattern recognition, and good results have been reported previously in the classification of foodstuffs, such as eggs (Dutta et al., 2003), coffees (Gardner et al., 1992), meat (Schweizer-Berberich et al., 1994; Balasubramanian et al., 2009), milk (Labreche et al., 2005), wine (Gozzoline et al., 2008). In a study, Penza and Cassano (2004) used an electronic nose comprising four metal oxide semiconductor thin-film sensors to characterize the volatile compounds present in the nine samples of Italian wines from different denominations of origin. Principal component analysis and artificial neural networks were applied to the generated patterns to achieve various classification tasks. Finally the authors suggested that their work demonstrates the feasibility of an electronic nose for wines discrimination.

3. Pattern recognition models

As stated earlier, the sensors of electronic tongue and nose with the help of chemometrics tools can perform a characterization work on the food products under investigation. Chemometrics has been defined as the science of relating measurements made on a chemical system to the state of the system through application of mathematical or statistical methods. The use of chemomet-

Table 2
Recent cases of electronic nose application to food quality and safety characterization.

Application case	Aim of use	Researcher(s)
Egg	Monitoring storage time and quality attributes	Yongwei et al. (2009)
Meat	Freshness assessment	Musatov et al. (2010)
	Qualitative and quantitative detection of beef fillets spoilage	Argyri et al. (2010)
	Shelf life prediction and modeling	Limbo et al. (2010)
Hard cheeses	Differentiation based on either age or geographical origin and discrimination based on cheese variety	Gursoy et al. (2009)
Tomato	Assessment of microbial contamination in processed tomatoes	Concina et al. (2009)
	Storage shelf life monitoring	Gomez et al. (2008)
	Monitoring changes of tomato aroma during drying	Pani et al. (2008)
Carrot	Volatile monitoring and control in microwave drying	Li et al. (2009a)
Milk	Identification of different milk flavorings	Wang et al. (2010)
Breast milk	Antioxidant capacity and aroma quality and safety assessment	Li et al. (2009d)
Japanese green tea	Identification of tea types and their particular flavor	Yang et al. (2009)
Wine	Discrimination among types of wine	Lozano et al. (2008)
	Threshold detection of aromatic compounds	Santos et al. (2010)
	Classification according to geographic origin	Cynkar et al. (2010)
Olive oil	Identifying the geographical origin of Liguria extra virgin olive oil	Casale et al. (2010)
	Detection of adulteration with rapeseed and sunflower oils	Mildner-Szkudlarz and Jelen (2010)
Virgin olive oil	Monitoring of oxidative status evolution and sensory analysis of oil with different phenolic content	Lerma-Garcia et al. (2009)
Alcoholic beverage	Off-flavor detection	Ragazzo-Sanchez et al. (2009)
Wine grape	Postharvest dehydration assessment of the grapes	Santonico et al. (2010)
Honey	Geographical origin characterization	Cacic et al. (2009)
Apricot	Monitoring of the storage period	Defilippi et al. (2009)
	Evaluation of quality and breeding perspectives	Gatti et al. (2009)
Sea bass	Freshness decay and shelf life predictive modeling	Limbo et al. (2009)
Pear	Prediction of acidity, soluble solids and firmness	Zhang et al. (2008)
Blueberry	Disease detection and classification	Li et al. (2010a)
Wheat	Analysis of fungal volatile	Perkowski et al. (2008)
	Discrimination of storage age	Pang et al. (2008)
Rice	Differentiation among rice varieties	Zheng et al. (2009)
Chickpea	Recognition among varieties with different milling and physicochemical properties	Ravi and Harte (2009)
Pineapple	Shelf life evaluation of fresh-cut fruit	Torri et al. (2010)
Peach	Characterization of peach cultivars and monitoring ripening stage during shelf life	Benedetti et al. (2008)
	Peach quality attribute evaluation	Zhang and Wang (2009)
Citrus juice	Classification based on fruit type, cultivar and treatment	Reinhard et al. (2008)
Mango fruit	Discrimination of mango fruit maturity	Lebrun et al. (2008)
	Ripeness and rot evaluation	Li et al. (2009c)
Coffee	Discrimination of complex mixtures	Suslick et al. (2010)
	Quality control through the detection of defects in cup tests	Rodriguez et al. (2010)
Fish	Freshness monitoring	Barat et al. (2008)
Virgin coconut oil	Detecting the adulteration	Marina et al. (2010)
Feeding fat	Classification	Van Ruth et al. (2010)
Octopus	Spoiling and formaldehyde-containing characterization	Zhang et al. (2009)
Bread	Aroma monitoring during baking	Ponzoni et al. (2008)
Infant cereals	Evaluation of antioxidant properties and aroma quality	Li et al. (2010b)

rics implies the use of multivariate data analysis that is based on the fact that complex systems need multiple parameters to be described and thus more information about the analyzed system can be retrieved by using a multivariate approach (Ni and Kokot, 2008; Ghasemi-Varnamkhasti et al., 2009). Those methods such as linear discriminant analysis (LDA), principal component analysis (PCA), and partial least squares (PLS) are helpful for dimensionality reduction of a data set, therefore, it can be examined in a two- or three-dimensional plot. Since LDA, PCA, and PLS are all linear methods, they are the best choices in cases where sensor arrays respond linearly. These methods can be also used with nonlinear data; however, interpretation should be accomplished accurately for such an analysis. This is a merit for such methods that little calibration data is required for model generation. In electronic noses and tongues, the pattern recognition is often performed by using artificial neural networks (ANNs) (Gutierrez-Osuna, 2002; Pioggia et al., 2008). Any non-linearity of data could be modeled by these methods. A potential disadvantage of NN approaches is that no statistical information can be created to express the models. Furthermore, the number of training samples as well as the training time required to analyze are much more dependent on the number of adjustable parameters for a NN. The more adjustable parameters increase the training sample and training time.

The concept of ANNs is to resemble the structure and workings of the human brain through mathematical models. ANNs possess an adaptable knowledge that is distributed over many neurons in such a manner it can communicate with one another. The network topology, the structure of the single neuron model together with the adaptation or learning rule have to considered in order to define the ANN architecture. The neurons are single elements and comprise a connection function, an input function, an activation (transfer) function and an output function. A neuron receives signals by means of several input connections and acts as a processing unit. These are weighted at the input to a neuron by the connection function. The weights define the coupling strength (synapses) of the respective connections and are established by a learning process, in the course of which they are modified according to given pattern sand a learning rule. For supervised learning, besides the input patterns, the desired corresponding output patterns are also given to the network in the training phase while in the case of unsupervised learning, the a classification criteria independently is found in the network for the input patterns.

In stochastic learning methods, random processes and probability distributions are used to minimize a suitably defined energy function of the network. Enormous numbers of neural models now exist, and each of these models is available in various forms. The Integrand-and-Fire (IF) neuron model (KinneBrock, 1992) is often employed to establish ANNs suitable for classification and forecast objectives. However, when dealing with ANNs, as underscored by Goodner et al. (2001), the risk of data over-fitting can result in counterfeit classifications. They suggested that the ratio between samples and variables should be greater than 6 in order to achieve reliable results. As found in the literature (Jurs et al., 2000; Lu et al., 2000; Li, 2004; Li et al., 2007; Peris and Escuder-Gilabert, 2009) numerous methods exist for computational analysis of data obtained from arrays employed in electronic noses and tongues. With advances in array fabrication (e.g., miniaturization of sensor allowing more responses to be recorded in a shorter time), demands on computational methods will be increased. Moreover, computational feature will have a critical role in allowing sensor array to be used in monitoring a wide range of chemically similar analytes. Past success using cross-reactive multiarray sensors integrated to computational techniques to recognize and quantify analytes of interest ensures that this area of research will continue to receive profound attention in the future (Wang et al., 2009). Presently, we can find many diverse data analysis techniques in literature, such as Wavelet, Support Vector Machine (SVM) in order to enhance the performance of electronic noses and tongues (Berrueta et al., 2007; Pardo and Sberveglieri, 2008; Gutierrez et al., 2008; Barbri et al., 2009; Wang et al., 2009; Phaisangittisagul et al., 2010; Laghi et al., 2010; Singh et al., 2010). It seems data analysis couple with soft computing such as fuzzy logic, artificial neural networks, genetic algorithms, and decision trees would open a promising window in application of biomimetic-based systems to food quality and safety characterization in the next years (Ghasemi-Varnamkhasti et al., 2009; Caesarendra et al., 2010).

4. Future trend and perspective

Sensor-based electronic noses and tongues today generally suffer from significant weaknesses limiting their widespread application in food quality and safety assessment. For instance, their sensing ability is heavily affected by environmental factors: humidity (in the case of electronic nose) and background noise, general drift caused by temperature, sensor variations and sensor poisoning. These problems, in addition to often wanting to detect very low concentrations (below ppm) of the odor or analyte, make the implementation of an electronic noses and tongues complicated even with providing expensive auto samplers. Against this challenge, innovative devices are being designed to tackle these concerns and improve detection thresholds and classification success rates; examples include combining an electronic nose array with a gas chromatography column or mass spectrometer (Ragazzo-Sanchez et al., 2009; Berna et al., 2009; Vera et al., 2010). These analytical instruments are large and expensive and have marked limitations influencing on their application and potential market. Nonetheless, the future for such systems seems promising particularly for the electronic nose which can fulfill niche analyses. This is because researchers throughout the world are increasing their attempts in several laboratories to develop innovative instrumental tools. Even the early instruments have performed well for some applications and it is believed that the newer prototypes will advance the field (Brudzewski et al., 2010). Some of these innovative achievements include the *artificial olfactory microsystem* (*e-mucosa*). This is a new type of electronic nose that mimics nasal chromatograph effect and have wealthier information content and so will enable a higher level of discrimination than present electronic nose systems (Che Harun et al., 2009a, 2009b; Taylor et al., 2009).

The electronic tongues are very useful in the food industry. However, the detection ability of the sensors employed largely depends on absorbability or catalysis of those sensitive materials to special ions. Although some advances have been achieved, this method still has limitations in sensitivity and specificity compared with the biology binding of specific odorants and tastants to the olfactory and taste receptor cells. Thus, the study of taste is still at an early stages. Only a few kinds of taste sensors system are in commercial use. Therefore, the research of artificial taste system is still very exciting for the future. Recently, there have been attempts to integrate electronic noses and tongues to obtain improved classifications and detection of foods (Apetrei et al., 2010). It can thus also be expected that the combination of both systems is useful, especially for measurement situations involving changes in both the aqueous and gas phase. It is worth to mention that, however, since both methods alone could fairly separate the samples, the combination of the methods can improve the classification properties only to a certain limit. It can be expected, though, that for other samples that are not easily classified with a single method, the combination would have a larger effect.

From general point of view, the choice of the best model for describing the data set is not a hand-key procedure and needs for a high level of skills from the operator. This point remains a major constraint in the use of electronic nose and tongue and most of the time this choose is made by the constructor of the apparatus during a feasibility study performed by the supplier for him. The experience showed that most of industries or firms that make acquisition of electronic nose and tongue for quality and safety control analyses on foods or other matrices do not have sufficient statistical knowledge to verify the adequacy of the statistical model or procedure used by the electronic noses and tongues and the linearity or non-linearity of the sensors response that produce their data. So, this point is a big problem which needs to be much more resolved in the future to allow for a greater expansion of the electronic noses and tongues utilization.

At the end of this paper, beside the great challenge to develop artificial systems mimicking the chemical senses of humans, research on electronic noses and tongues immediately has addressed practical utilizations. Opportunities for industrial applications arise from the fact that human senses are of primary importance in many fields where sensory analysis is used to handle the information extracted from human perceptions. It is worth mentioning the possibility to train electronic noses and tongues with different panels and the comparison of panel evaluation and the portability of different panel evaluation is a matter in food industries specifically for liquid food and beverage and this subject could be addressed in future research. This new approach could offer a valid alternative to the tedious and time-consuming traditional analytical methods and could be a useful tool for on line monitoring to food quality and safety characterization.

5. Conclusion

Biomimetic systems such as electronic nose and electronic tongue could be used extensively in food research and technology. These systems are known as human sense inspired sensor array technologies. As a summary, it can be said that the sensors used for smell and taste should have a fabrication principle different from the physical sensors or the conventional chemical sensors. Nowadays, developed taste and odor sensors have outputs well correlated with the human sensory panels, and the taste sensor especially has an intelligent capability to break down the information included in chemical substances to the basic information of taste quality. It is expected odor sensors (electronic noses) and taste sensors (electronic tongues) as the biomimetic systems would be increasingly of interest in food science and technology. Currently, the biggest market for such systems is in the food industry so that the applications of odor and taste sensors in food industry are numerous. They include: Inspection of food by odor and taste, grading quality and safety of food by odor and taste, checking mayonnaise for rancidity, fish inspection, automated flavor control, beverage container inspection, fermentation control monitoring cheese ripening, microwave over cooking control and so on.

On-line odor and taste sensors could have a key role in the automation of food control and processing (Maiti et al., 2009; Trincavelli et al., 2009; Li et al., 2009b). In near future, when the basic challenges of these sensors are solved, we will see more online e-noses and e-tongues installed in the line of food quality and safety characterization. For each application, however, technical problems have to be solved for implementation on-line. One interesting feature for the future would be to have a fully automated platform of different kinds of sensors to monitor the vital information needed for the characterizing the quality of the raw material, process or product (Infante et al., 2010). Odor and taste sensors would make up an important part of such a multisensor system. This prospective concept may be realized for food control in the food industries in close future.

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